SPOOL

Cyber-physical Architecture #5

Interdisciplinary Data-integrated Approaches

V9/#1

ISSN 2215-0897
E-ISSN 2215-0900

VOLUME 9 . ISSUE 1

SPOOL

VOLUME 9 . ISSUE 1

Cyber-Physical Architecture #5

Editorial

Articles

SPOOL - Journal of Architecture and the Built Environment

SPOOL is a journal initiative in the field of 'architecture and the built environment'. It puts a strong emphasis on specific topics, so-called threads: Science of Architecture; Landscape Metropolis; Energy Innovation, Cyber-physical Architecture, Narratives and Expo. These topics refer to existing and upcoming research programmes/interests in Europe and beyond, and ensure a steady stream of potential copy. Treating these topics as threads within one journal allows SPOOL to focus on the interrelationship between the fields, something that is often lost in specialised journals. SPOOL welcomes within this framework original papers and associated open data on research that deal with interventions in architecture and the built environment by means of design, engineering and/or planning.

ISBN
978-94-6366-570-4

Cover images
Front: Design-to-Robotic-Production and -Operation process.
Back: Voronoi structure that facilitates the creation of convex and concave areas that offer opportunities for capturing or repelling sun and rain and fostering animal and plant species.

Publisher
TU Delft

Contact
Principal: Frank van der Hoeven (info@openaccess.ac)

Design
Sirene Ontwerpers, Rotterdam, NL

ISSN 2215-0897
E-ISSN 2215-0900

www.spool.ac

EDITORIAL

Interdisciplinary Data-integrated Approaches

Michael Hensel [1], **Henriette Bier** [2]

[1] *TU Wien*
Vienna, Austria
[2] *Delft University of Technology*
Delft, the Netherlands

Rapid urbanization with the associated land cover and land use change, as well as resource depletion, contribute to the degradation of ecosystems and biodiversity and have a negative impact on human health and well-being. Societal calls for responses and results pose a significant challenge for research and education in the various fields concerned with the environment. Alongside the current environmental crisis there is a pressing need for developing 'green solutions' for the built environment with the help of data-driven methods, workflows and tools.

In view these developments, a shift from narrow disciplinary and domain-specific approaches towards broader interdisciplinary, multi-domain and multi-scalar strategies is required. This includes data-acquisition, data-sharing and data-integration, as well as data-driven modelling to enable the complexity of sustainability problems arising from rapid urbanization to be tackled. While there have been efforts to address the challenges of multi-domain approaches, for instance in the fields of sustainability, the urban and architectural sciences, as well as the interoperability of methods and tools, the actual problem goes deeper, requiring interdisciplinary knowledge exchange to develop adequate shared paradigms, concepts, methods and tools.

Cyber-physical Architecture (CpA) issue 5 addresses these challenges by engaging with experts from a range of disciplines involved in environmental concerns while utilizing data-acquisition, data-sharing and integration, and data-driven modelling in a discourse that identifies modalities for a broader interdisciplinary, multi-domain and multi-scalar approach.

Nicholson et al. present an integrated ecological perspective that recognizes the importance of knowledge exchange in tackling the complexity of urban environments. Projects drawn from MIT Senseable City Lab and CRA-Carlo Ratti Associati demonstrate how data can be used as a tool in developing ecological design solutions. Sensors, data and networks link the artificial and natural elements of urban environments to connect citizens and decision makers and to integrate ecological solutions into the built environment.

Sunguroglu Hensel et al. pursue the development of an interdisciplinary approach, computational framework, and related workflows for multi-domain and trans-scalar modelling that integrate planning on a territorial scale with design on an architectural scale. They outline two lines of research, the first focusing on understanding environments for the purpose of discovering, recovering and adapting land knowledge to different conditions and contexts, the second on designing environments while developing computational workflows for data-integrated planning and design. Finally, the convergence of analytical and generative data-driven computational workflows is discussed with the aim of integrating architectures and environments.

Van Ameide presents an approach to monitoring people's location data, movement and activity patterns aimed at enabling analysis of user behaviours to inform the planning of evidence-based urban developments. This paper focuses on a series of experiments that serve to develop user-driven generative design processes and to explore new computational tools for site analysis and monitoring that can enable data-driven urban place studies.

Oskam et al. describe a specific data-driven design approach that provides microclimatic modulation in support of biodiversity and social accessibility of leftover spaces. By introducing small-scale urban interventions existing and new life is supported. These interventions were developed by means of Design-to-Robotic-Production and -Operation (D2RP&O). This approach links computational design to robotic production and Artificial Intelligence (AI) supported operation processes to establish a bio-cyber-physical feedback loop.

Alavi et al. discuss their approach to predicting and preventing high concentrations of air pollutants in indoor environments that can have adverse impact on health and well-being, cognitive performance and productivity. This approach is based on algorithmic AI-enabled methods. The article outlines design implications and presents design proposals and interactive solutions for preventing high concentrations of indoor air pollutants.

Papers published in this issue were originally presented at the Adaptive Environments symposium on 9-10 September 2021 organized by Michael Hensel (TU Vienna), Henriette Bier (TU Delft), Margherita Pillan (PoliMi), and Keith Green (Cornell) and have been single-blind reviewed. They reflect the engagement of an international network of researchers investigating modalities for a data-driven, interdisciplinary, multi-domain and multi-scalar approach aimed at addressing environmental concerns.

Eds. Michael Hensel (TU Vienna) and Henriette Bier (TU Delft)

DOI

https://doi.org/10.47982/spool.2022.1.00

‘Greening’ the Cities

How Data Can Drive Interdisciplinary Connections to Foster Ecological Solutions

Sinéad Nicholson [1], **Marika Tomasi** [1,2], **Daniele Belleri** [1], **Carlo Ratti** [1,3], **& Marialena Nikolopoulou** [1,2]

[1] *CRA-Carlo Ratti Associati, Torino (Italy)*
[2] *School of Architecture and Planning, University of Kent, Canterbury (UK)*
[3] *Massachusetts Institute of Technology, Cambridge (USA)*

Abstract

We are facing an urgent global environmental crisis that requires a reframing of traditional professional and conceptual boundaries within the urban environment. Complex and multidisciplinary issues need complex and multidisciplinary solutions, which result from the collaboration of many different disciplines concerned with the urban environment. A more integrated ecological perspective that recognizes the complexity of urban environments and resituates our ‘artificial’ or human-made world within its natural ecosystem can facilitate this shift towards greater knowledge exchange. C40 Cities case studies provide a framework within which to understand the disciplines and scales encompassed by ecological solutions, while projects at MIT Senseable City Lab and CRA-Carlo Ratti Associati highlight how data is used as a tool in driving ecological solutions. The artificial world of sensors, data and networks creates a bridge between the ‘artificial’ and ‘natural’ elements of our urban environments, allowing us to fully understand the present condition, connect city users and decision makers, and better integrate ecological solutions into the built environment.

Keywords

Ecological Solutions, Data-driven Design, Ecological Perspective, Urban Environmental Degradation, Artificial-natural

DOI

https://doi.org/10.47982/spool.2022.1.01

Introduction

Cities cover only 1% of the earth's total land surface (Ritchie, 2018). Yet they are responsible for 76% of global CO_2 emissions, 50% of global waste and consume 75% of the world's natural resources (Organisation for Economic Co-operation and Development (OECD, 2020, 2020). These statistics would seem to imply a conflict between 'city' and 'nature'. Environmental degradation is one of the greatest impacts of urbanization. According to the C40 Cities organization, a global network of 97 cities committed to taking action on a broad range of urban environmental issues, cities must address loss of biodiversity, greenhouse gas emissions, water, air and soil pollution and the Urban Heat Island (UHI) effect in order to begin to reverse environmental degradation and consequently build resilience for the future (Attstrom et al., 2020). These issues present decision makers tasked with finding solutions with multi-scalar and multidisciplinary challenges and so the solutions require cross-disciplinary and cross-scalar knowledge transfer between stakeholders: citizens, planners, designers, scientists and technicians (Heymans et al., 2019). This means recognizing the connections between and consequences of urban activities at every scale: between disciplines, between users and city, and between the city and its landscape. There is growing agreement that we need a shift in work practices towards a more integrated and collaborative approach. But to enable this shift we also need a change of perspective on the human/nature relationship, as previously argued by practitioners and thinkers such as Ian McHarg, Timothy Morton and Janine Benyus (Benyus, 2015; McHarg & Steiner, 2006; Morton, 2018): an ecological perspective that recognizes human beings as just another species *within* the natural environment. Through this lens we can perceive the city as it is – an ecosystem, complete with its flows of energy, matter and information, living and non-living components, and their constant interactions and exchanges, from the micro to the global scale (Odum & Barret, 2005).

If these interactions and exchanges were visible to us, we might rethink the 'natural' versus 'artificial' perspective that seems to divide the city and its landscape, and that has been obscuring the environmental consequences of urbanization. Perhaps counter-intuitively, the digital revolution, which could be considered the epitome of artificiality, is providing us with the means to do this. Via new digital technologies, data-acquisition, data-sharing and data integration, are making the invisible, visible. Data can turn seeming chaos into legible patterns, can connect action and response and drive the feedback loops that ensure adaptability and resilience (O'Connor et al., 2019). On this premise, the design practice CRA-Carlo Ratti Associati has been exploring an architecture that 'senses and responds': using data to connect users and their environment; merging the 'artificial' and the 'natural' (Ratti & Belleri, 2020). By blurring this distinction and resituating our artificial or 'human-made' built environments within their 'natural' ecosystems, we as designers can begin to recognize the relationships between what were previously considered separate disciplines and scales, and so effectively implement 'green solutions'.

This article illustrates how 'green solutions' to environmental degradation can be applied using data as a tool to both understand the problems at hand, and better integrate solutions into the urban ecosystem. We begin by introducing C40 Cities as a practical representation of multi-scalar and interdisciplinary data-driven action that can help us define what 'green solutions' actually encompass. We then explore the use of data in sensing projects from MIT Senseable City Lab, which can be employed in better understanding some of the issues highlighted by C40 in a local context, and finally examine the Vitae building in Milan (IT) as an example of the integration of data and 'green solutions' in practice. Through these examples, the article also illustrates how data-facilitated connections encourage a broader and more balanced ecological approach to urban planning and design.

What are green solutions?

The term 'green solutions' carries the implicit assumption that 'green' is always good. However, this can strengthen the natural versus artificial divide and lead to a form of greenwashing, where 'natural' elements such as trees or plants are used in design as symbolic gestures, sometimes with little understanding of how they can affect the project (see Budds, 2020). Though vegetation in general can be one of the most effective solutions to urban environmental degradation, when applied without considering the effects within the larger system or across disciplines, vegetation can also lead to unintended consequences. The recent popularity in planting street trees as a climate change adaptation measure is an example. In some cities mass planting of street trees is believed to have contributed to a rise in human health problems due to severe pollen allergies: many cities use the male variety of certain species popular for urban planting since they are 'tidier' and produce only pollen, not fruit and seeds like their female counterparts (Hirschlag, 2020; Sierra-Heredia et al., 2018). Street trees, when planted in areas exposed to high levels of air pollution such as busy roads can also worsen air pollution as well as heat stress since the tree canopies can reduce ventilation and trap pollutants and rising hot air (Coutts et al. 2016). While we believe the use of urban greenery as a 'green solution' can make significant contributions to the overall ecological health of a site, as these examples suggest, addressing environmental degradation requires a more balanced and interdisciplinary understanding than the oversimplified emphasis on 'green' may produce. For this reason we suggest reframing the term as 'ecological solutions' to better reflect its scope.

There is a need, then, for a more interdisciplinary understanding of ecological solutions in design and planning. The C40 Cities organization is a good place from which to understand what the term could encompass at the large scale. While emphasizing climate action, C40 recognizes the complexity of environmental degradation and directs cities to address the sectors of Energy & Buildings, Transportation & Urban Planning, Food, Waste & Water, Air Quality and Adaptation and Implementation in their solutions (C40 Cities, 2021b). It focuses on providing quantifiable targets and facilitating knowledge transfer between cities, experts and citizens and emphasizes 'Measuring and Monitoring' as the first step in any initiative.

The projects presented in Table 1 provide a selection of solutions C40 cities have implemented to tackle environmental degradation. The projects presented are a result of a filtered search for green solutions within the C40 database of case studies and are reviewed for their specific outcomes as well as their overall contribution to the aforementioned issues (i.e., loss of biodiversity, greenhouse gas emissions, water, air and soil pollution and the UHI effect).

The strategies mentioned in Table 1 cover multidisciplinary solutions, implemented by private and public stakeholders, acting across multiple scales. They highlight the results of what can be considered 'ecological solutions,' effectively bridging disciplines, scales or domains. They range from the use of 'cool' materials on city roofs to alleviate the UHI effect as well as to reduce energy consumption, communication campaigns to reduce waste, the capture of landfill emissions for electricity production, renovation of street-level drainage systems to include nature-based drainage elements, and the use of vegetation in the form of green roofs, walls and planters. The Zero Waste project in Buenos Aires is an example of connecting stakeholders through top-down and bottom-up action. The project was able to reduce landfill by 78% in two years through a combination of government policy and a public communication campaign (*C40 Good Practice Guides*, 2016).

Another successful example of an interdisciplinary approach to addressing urban environmental degradation is Hong Kong's updated stormwater system: in redesigning its stormwater drainage system, Hong Kong was able to significantly reduce areas of high flood risk while also reducing freshwater consumption through combined policy interventions and a design that captured and treated stormwater for non-potable uses.

STRATEGIES	CITY	NAME	DESCRIPTION	RESULTS	ISSUE
Greening the building	Toronto	Eco-Roof Incentive Programme	Fees paid by developers under the cash-in-lieu policy of the Green Roof Bylaw make this project self-sustaining. Funding is granted for building owners to install green and cool roofs.	233,000 m^2 of eco-roof space (cool+green).[a]	● ○ ○ ●
	London	Greening the BIDs	The project has supported 15 green infrastructure audits; demonstration projects were partially funded to catalyst urban greening in central London.	1 million m^2 of new potential green cover, correspondent to 300 rain gardens, 200 green walls and 100+ ha of green roofs, and small-scale interventions such as planters and window boxes.[a]	● ○ ○ ●
Cool roof	New York	NYC °CoolRoofs Programme	The programme encourages and facilitates both private and public installations of cool materials on New York City's rooftops.	The programme has coated 626 buildings with a white, reflective coating, for a total of around 530,000 m^2 of rooftop. Buildings' cooling costs are reduced by 10-30%.[a]	○ ● ○ ●
Zero waste	San Francisco	Zero Waste by 2020	Policy initiative that aims to eliminate waste sent to landfill or incineration.	From 1990 to 2013, the waste diverted from landfill has increased from 35% to 80%; the recycling rate is 78%.[a]	○ ○ ● ○
	Buenos Aires	Municipal Solid Waste Reduction Project	Project to reduce waste sent to landfills by increasing citizens' awareness, as well as the realization of "Green Centres" and a Mechanical Biological Treatment plant.	The achieved disposal reduction was 44% in 2013, 78% in 2014.[a]	○ ○ ● ○
Landfill restoration	Wuhan	Project of Daijiahu Park	Transformation of a site of industrial waste in an urban park, with specific attention to water management and landscape.	Transformation of a previously polluted lake into a "green lung" for the city: greening rate of 91.8%, 80+ ha of public green space, 827 tons of CO_2 and 200+ tons of dust absorbed per year.[b]	● ● ● ●
	Johannesburg	Landfill Gas Project	Electricity generation from methane gas harvested from landfill sites.	CO_2 reduction of 1,813 tons in June 2018 (-13%).[b]	○ ● ● ○
Stormwater management	Hong Kong	Stormwater Storage Scheme	Expansion and improvement of the existing drainage, pumping and storage systems. Sustainability and ecology are included in the design.	Reduce areas of high flood risk from 90 (1995) to 6 (2019). Annual water savings of more than 240,000 m^3. Expected to increase to 3.4million m^3 with ongoing works.[b]	● ○ ● ○

TABLE 1 C40 'green solutions' and related strategies for urban environmental degradation issues (source: https://www.c40.org/case_studies) Results updated at [a] 2016, [b] 2020.

Legend

- ● Loss of biodiversity
- ● Greenhouse gas emissions
- ● Water, air and soil pollution
- ● Urban Heat Island

Thanks to the redesigned system, five of the city's rivers, previously polluted by their use as stormwater channels, are being restored to public use as parkland and planted with native vegetation, thereby contributing to biodiversity and human well-being (*C40*, 2020). Private/public funding mechanisms such as described in the Eco-Roof Incentive Programme help sustain these programmes, highlighting the shifting and necessary economic values essential to successful ecological solutions.

Sensing

The examples above highlight some of the cross-scalar and multidisciplinary solutions that can be implemented to address environmental degradation in cities. The solutions are supported by, and direct further action through, data acquisition, data-driven modelling, and data sharing and integration. Definitions of data vary according to the discipline, but broadly speaking, data are simply units of information, collected as observations or measurements (Australian Bureau of Statistics, 2021). Data acquisition begins with the human sensory system and is extended by new technologies that include environmental sensors, simulation software and wireless networks. This 'artificial' world of sensors, networks, data and software allows us to visualize and analyse large amounts of information so that we can begin to understand the complexity of the urban ecosystem. This information is key to understanding the issues to be addressed and the consequent effects of any interventions. In the context of the CRA and MIT Senseable City Lab sense/respond paradigm, sensing plays a major part in many of CRA and MIT Senseable City Lab projects. The following projects are examples of sensing applied across different scales to better understand specific urban issues related to environmental degradation.

City Scanner – data acquisition

City Scanner transforms everyday urban vehicles into sensing nodes that can inform planners and policymakers about the environmental conditions of their cities, including the C40 issues of air pollution, greenhouse gas emissions and the UHI effect. Examples of data collected include thermal conditions, sensors for particulate matter in the air, temperature and humidity, and accelerometers, which together can provide information about a wide range of urban concerns including those already mentioned, but also other important indicators like road quality (from vibrations detected by the accelerometer) or building energy efficiency (from thermal imagery) (MIT Senseable City Lab, 2018). Drive-by sensing can significantly improve the spatial coverage and time resolution of data collected, overcoming recognized limitations of stationary and remote sensing approaches (Anjomshoaa et al., 2018). The data collection campaign is performed by low-cost devices supporting multiple sensors, with little deployment requirements on the hosting vehicle (Mora et al., 2019). The sensing devices are installed on vehicles already present on urban streets, such as garbage trucks (Fig. 1a). The number of sensors can be optimized by studying street coverage using scheduled and unscheduled vehicles (Anjomshoaa et al., 2018). A web application provides a tool to navigate the resulting data (available at http://senseable.mit.edu/cityscanner/app; Fig. 1b)

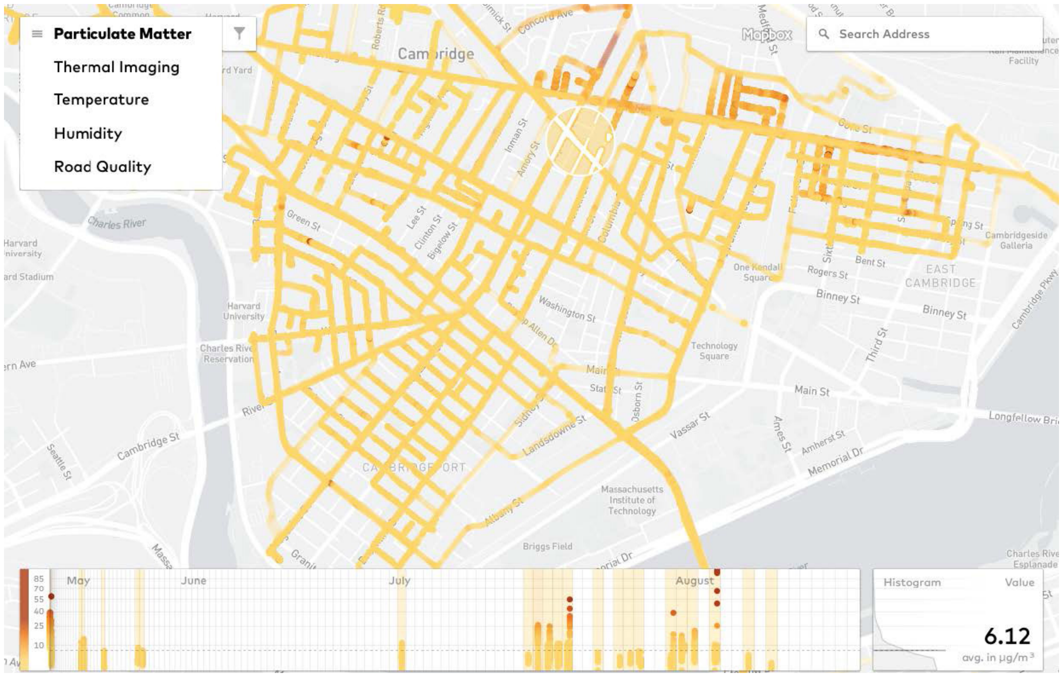


FIGURE 1 City Scanner: *Screenshot of the City Scanner web application (source: Anjomshoaa et al., 2018)*

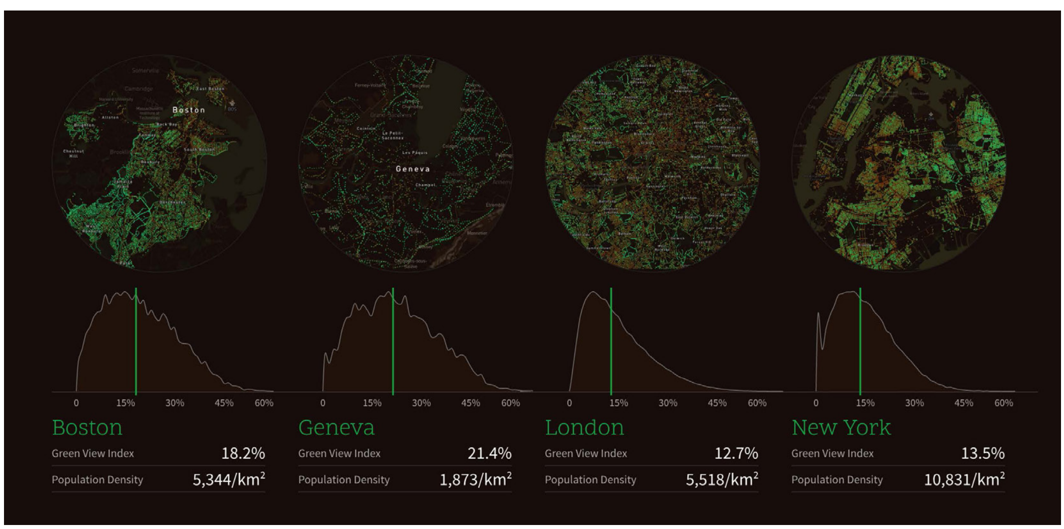


FIGURE 2 Treepedia maps showing the resulting green coverage and GVI comparison for four major cities (source: Zhu et al., 2020)

Treepedia – data integration and sharing

A second project is Treepedia which makes use of Google Street View (GSV) images to detect urban vegetation. MIT Senseable City Lab has developed this tool to measure and compare green canopy coverage in urban areas at street level. This allows urban vegetation to be assessed from the pedestrian perspective, which gives a fuller picture of the green coverage in the city and connects the citizen's experience of urban vegetation to planning on a larger scale (Li & Ratti, 2018). Specifically, GSV images are downloaded and processed to extract and visualize the amount of street greenery in an urban area; the proposed index (GVI

–Green View Index; Li et al., 2015) and the resulting maps (Fig. 2) provide not only a clear communication method to foster public awareness, but also form a valuable dataset on the presence of vegetation in the urban environment. The results can inform urban planners as well as citizens and are relevant to addressing all the C40 issues identified.

Solar Cities - Data-driven modelling and data sharing

From roaming sensors to street-scale imagery, to large-scale urban modelling, Solar Cities maps the annual irradiation across a city's urban surfaces (Fig. 3) with the intention of providing a tool to 'support local governments in strategising urban developments and provide decision making support for energy harvesting initiatives' (MIT Senseable City Lab, 2021). By facilitating the use of clean energy in the form of photovoltaics, which can also double as passive shading, it addresses C40's identified issues of greenhouse gas emissions and the UHI effect. The project quantifies just one relationship – solar potential (Wh/m^2) – but considers it across the entire city, from 'rooftop to street level'. It can pinpoint which building facades have the greatest energy potential, allowing cities to make more efficient use of resources, and provides a visual resource to aid city planners, designers and decision makers in understanding the energy potential of their city as well as how future developments might impact that potential.

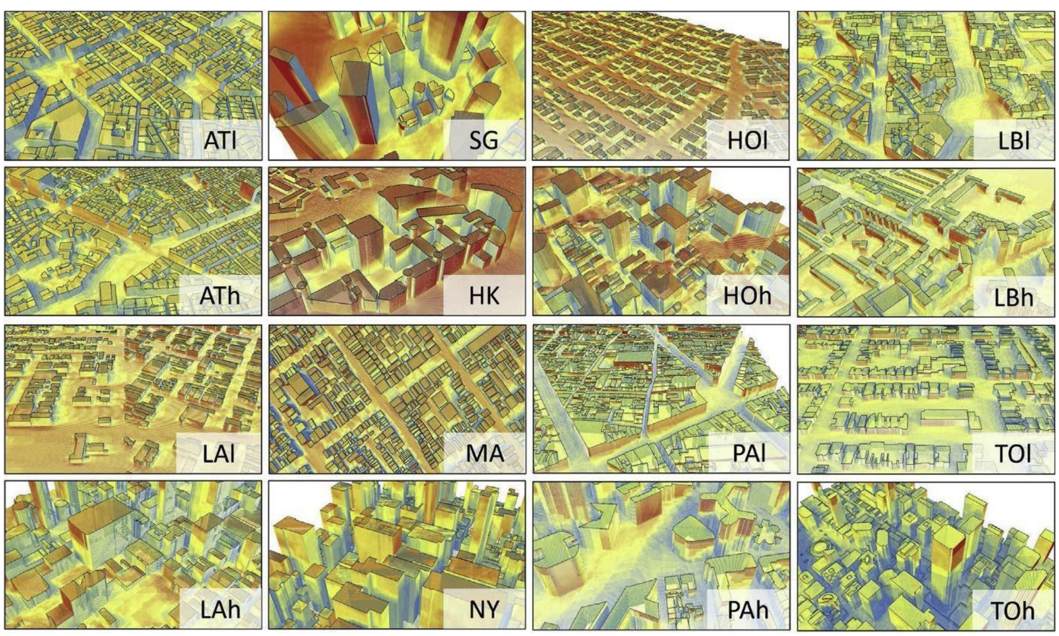


FIGURE 3 Solar Cities: analysis of annual solar irradiation across urban surfaces in sixteen study areas (source: MIT Senseable City Lab, 2020)

Responding

Sensors and the resulting data analysis allow us to simultaneously 'zoom' in and out, spatially and temporally, on the urban ecosystem, highlighting patterns and relationships between different urban issues. From this extended perspective, we gain the more nuanced understanding (and justification) that we need to address the complex problem that is environmental degradation. Backed by this data-driven knowledge, initiatives like C40 can provide pressure and support from 'above' to implement interdisciplinary and multi-scalar work that comprehensively addresses environmental degradation. At the same time, small projects that address these issues at a local scale provide valuable examples of how designers can apply data and the related technology to implement ecological solutions when supported by initiatives like C40.

Reinventing Cities, organized by the C40 Cities Climate Leadership Group, is a competition that seeks to bolster sustainable and resilient building developments in underutilized areas of cities across the globe (C40 Reinventing Cities, 2021b). The C40 framework – distilled in the Reinventing Cities challenges (available at https://www.c40reinventingcities.org/en/professionals/guidelines/) – calls for projects that provide solutions to environmental degradation at the single building scale. By uniting multiple scales, disciplines and stakeholders in the pursuit of those shared goals it also encourages an ecological paradigm that is as necessary as the technology employed in the projects in addressing environmental degradation. The winning projects highlight a broader 'ecological' approach to design, where every project involves specialists from multiple and diverse fields, as well as private and public stakeholders to address the specific environmental challenges identified by C40.

Vitae

Our case study Vitae (Fig. 4 *Vitae*, 2019), designed for the C40 Reinventing Cities competition, involved 14 partners from a range of disciplines including design, energy engineering, agriculture, psychology and education. The project lead, Covivio, is a real estate developer, while CRA acted as architect and project manager and Habitech as environmental expert (C40 Reinventing Cities, 2021a). Vitae's environmental aims are twofold: to address the identified C40 challenges in a concrete way, but also to encourage a (re)connection between city and 'nature' for users by building on the theory of Biophilia – the innate link humans have with the natural environment and other living organisms (see Edward O. Wilson's Biophilia theory (1984)). This more intangible goal, like the more technical goals, is supported by data and the artificial 'realm'.

FIGURE 4 Rendered image of Vitae design proposal for C40 Reinventing Cities Competition (source: Vitae Presskit, available on https://www.c40reinventingcities.org/data/sites_134e6/fiche/39/projects_memo_-_vitae_-_milan-_serio_f9b88.pdf)

Vitae is designed as a combined private/public building providing office space, research centre, public green space and urban agriculture within an area of Milan currently in the process of transforming from an industrial to an 'innovation' district. The project began in 2019 and has just entered the construction phase, but the design process itself highlights several ways in which data was used to advance the C40 goals. The following highlights some examples of how data was used in the design process to facilitate an integrated, interdisciplinary design approach as well as to support the implementation of vegetation, which is key to Vitae's ecological approach. Figure 5 shows how data acquisition and data-driven modelling were used to help connect project stakeholders during the design phase as well as to merge various building disciplines to address the C40 challenges.

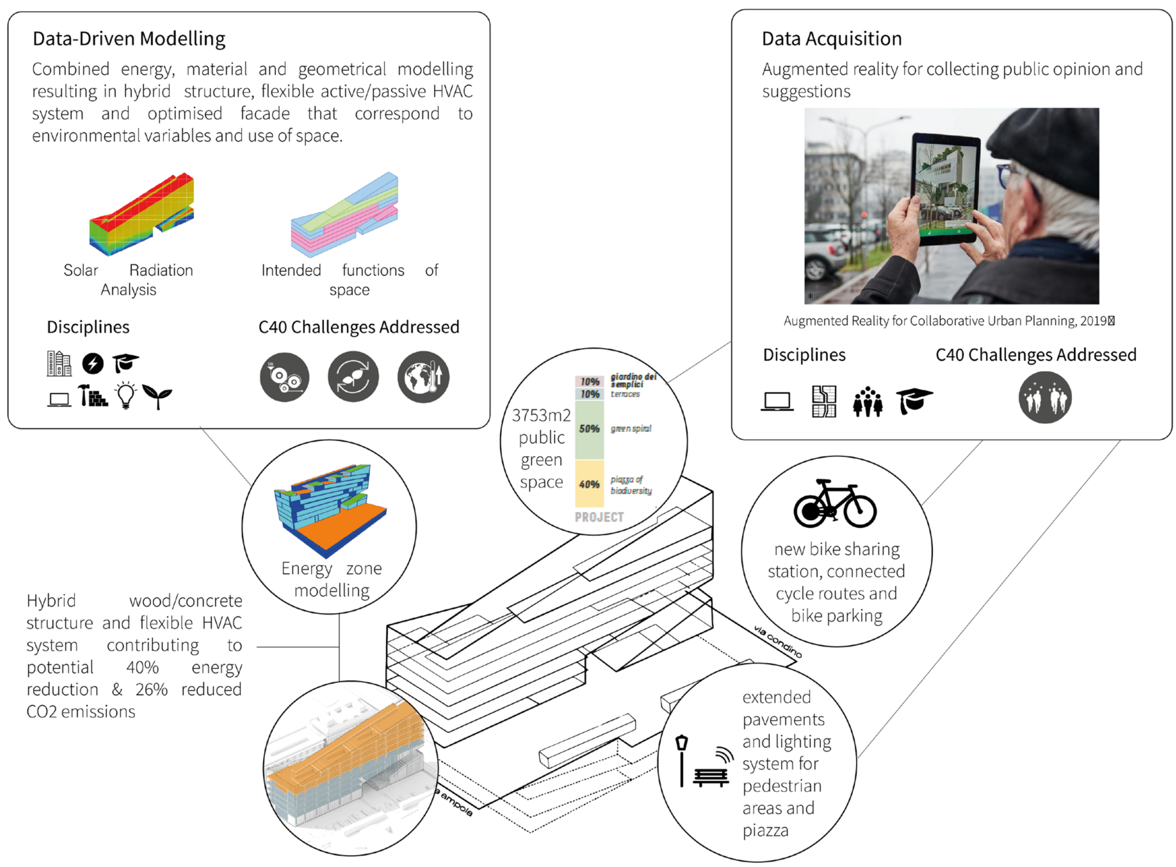


FIGURE 5 Data in the design process, based on Vitae Technical Report, Phase 1, 2019

Data Acquisition

During the design phase of Vitae, an augmented reality tool (Fig. 5) developed by a team of researchers, software developers, social and environmental psychologists and business strategists was used to stimulate communication between the public, designers and other stakeholders as well as to gather data on their views and suggestions to further inform the design (Augmented Reality for Collaborative Urban Planning, 2019). The software, capable of running on a tablet, computer or smartphone, allowed users to visualize the various design options on site, in real time; to rate different aspects of the project; and to submit their own suggestions and drawings. The interaction facilitated through the 'Experience Vitae' trial was an example of how data can encourage feedback between users and designers of the space, merging the two roles. The top priorities identified during the community consultation, which included accessible green space, integration with the surrounding neighbourhood, security and access, are strongly represented in Vitae's design. By opening the design process to the wider community, these tools provide a means to connect to the wider context of the site and encourage integration with the existing 'ecosystem/neighbourhood'.

Data-Driven Modelling

Digital models addressing multiple elements of the project including programme, facade, structure, vegetation planting scheme, and the heating, ventilation and air conditioning (HVAC) system allowed the project team to combine and test these elements in different design scenarios providing insights into the interactions between project elements that might otherwise be too complex to comprehend. The temporal dimension was also made more visible; so that changing demands based on future scenarios could be tested and considered in the design. Modelling allows designers to see and compare the effect of different project iterations on chosen metrics such as embodied energy, energy production and use, daylighting or greenhouse gas emissions. In Vitae, the team combined energy modelling with different programme scenarios to understand the varying energy needs of the flexible programmes within the building, resulting in a radiant HVAC ceiling system that allows for variable thermal zones corresponding to the particular use of a space at a given point in time. These flexible systems also allow for passive air conditioning when an active system is not needed. Another outcome was the proposed hybrid structure that corresponds to the intended programme, with concrete used for office spaces and wood for living spaces, resulting in reduced carbon footprint.

Vegetation as an ecological solution

Vegetation in Vitae contributes to many of the Reinventing Cities Challenges (Fig. 6) highlighting the interdisciplinarity of ecological solutions. The project aims to integrate vegetation into the project rather than considering it as an optional 'add on'. This is made possible through the collaboration with relevant experts including botanists and the agricultural associations that were involved in the design process (Fondazione Politecnico, 2020), as well as through modelling to provide detailed information on site conditions including climate, shading patterns, water availability and local vegetation. Importantly, sensors and connected networks will allow for automated and adaptive maintenance that monitors the health and physical needs of the natural elements and communicates with machines or humans depending on the need and resulting response. This is essential to the successful integration of vegetation within a large project like this as highlighted by the case study referenced in the definition of ecological solutions (Budds, 2020). By designing it into the project at an early stage, vegetation can provide multiple services to the project: contributing to the management of predicted future heat stress and flood risk, which were identified as important adaptation issues to address for the site (C40 Cities, 2021b); providing green space, the majority of which is publicly accessible, thereby addressing one of the main concerns identified during public consultation; an urban vineyard, hydroponic greenhouses and traditional vegetable gardens, which will allow Vitae to serve as a test bed for urban agriculture research as well as to provide produce for the planned on-site café that will in turn support the continued maintenance of the gardens. Through these functions, jobs are created, connections are made to the surrounding neighbourhood and knowledge about food production and the impacts of climate change on natural systems is disseminated.

The role of Biophilia

Both technical/scientific knowledge and an ecological perspective are needed to turn the information that data can provide into solutions. Vitae encourages not just technological solutions but also a more subliminal recognition of the connection between humans and their natural environment. This recognition is important in addressing environmental degradation as it emphasizes the real and sometimes unmeasurable value of our natural environment, even within the city. An example is the improved tolerance we have for high temperatures in urban spaces when vegetation is present – the increased 'naturalness' can significantly improve both user's physiological *and* psychological adaptation to high temperatures as well as reduce stress levels, illustrating the existing connection between humans and 'nature' (Nikolopoulou and Steemers, 2003; Shanahan et al., 2016). These more qualitative benefits are only recently being recognized as important aspects of reintroducing nature within the city and highlight the need for a deeper understanding of the 'natural' elements in our urban ecosystems. Vegetation and the associated interactions that Vitae provides, can allow us to (re)acquire information or 'data' on our relationship with the natural environment as well as natural processes and the services they provide. This can help improve our understanding of humans existing *within* the ecosystem and thus generate a more ecological perspective that can support more comprehensive solutions to environmental degradation. The knowledge gained from data acquisition, integration and sharing through our artificial devices is essential to addressing urban environmental degradation. So, too, is the knowledge gained from our own ability to sense the world around us. Vitae seeks to build on this 'natural' sensing and, together with the artificial sensing network that makes the implementation and maintenance of vegetation possible, to contribute to both the Reinventing Cities Challenges and a more ecological perspective.

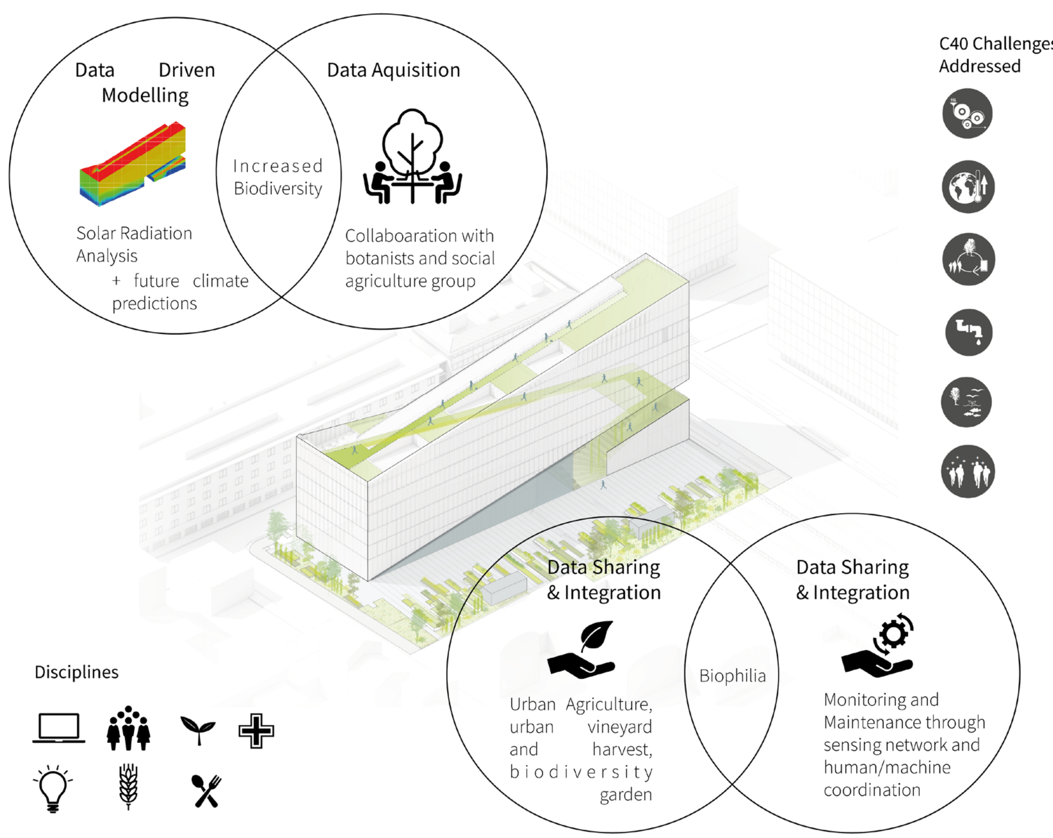


FIGURE 6 Vegetation in Vitae, based on Vitae Technical Report, Phase 1, 2019 (Vitae, 2019).

The value of data lies in how it is applied. We now have the possibility to collect and analyse vast amounts of data. However, to advance effective ecological solutions, the knowledge that data can provide must be understood and applied across the many disciplines, stakeholders and scales involved in urban environments. The C40 Cities case studies highlight the broad range of disciplines and scales encompassed by ecological solutions. Sensing projects, such as those mentioned above, make the complex web of connections in cities visible and pinpoint specific issues, driving a more ecological perspective in urban design and planning and supplying cities with the knowledge from which they can build solutions. Vitae is an example of this shift in perspective in action. It was conceptualized as a living organism within the wider ecosystem, utilizing both natural and artificial elements to integrate ecological solutions. This was the result of inputs from a diverse range of sources concerned with the urban environments, facilitated by the 'artificial' world of data. Ultimately data can drive a redefinition of the limited and problematic 'natural v. artificial' perspective that has contributed to our present crisis, leading to *ecological* solutions that match the complexity of the issues we face.

Acknowledgments

Sinéad Nicholson and Marika Tomasi are funded by the European Commission H2020-MSCA-ITN-2019 programme, European Industrial Doctorate (EID) 'Solutions for Outdoor Climate Adaptation' (SOLOCLIM) project, under grant agreement No. 861119.

References

Anjomshoaa, A., Duarte, F., Rennings, D., Matarazzo, T. J., deSouza, P., & Ratti, C. (2018). City Scanner: Building and Scheduling a Mobile Sensing Platform for Smart City Services. *IEEE Internet of Things Journal*, *5*(6), 4567–4579. https://doi.org/10.1109/JIOT.2018.2839058

Attstrom, K., Bailey, T., Gander, S., Hahn, F., Huxley, R., Leonardsen, J., Stener Pedersen, H., Porteron, S., & Sarfatti, C. (2020). *Urban Climate Action Impacts Framework* (p. 42). C40 Cities Climate Leadership Group & Ramboll. https://www.c40.org/research

Augmented Reality for Collaborative Urban Planning. (2019, December 16). *Experiencing VITAE – LABSIMURB*. http://www.labsimurb.polimi.it/research/ar4cup/experiencing_vitae/

Australian Bureau of Statistics. (2021, April 1). *Statistical Language—What are Data?* c=AU; o=Commonwealth of Australia; ou=Australian Bureau of Statistics. https://www.abs.gov.au/websitedbs/D3310114.nsf/Home/Statistical+Language+-+what+are+data

Benyus, J. (2015). The Generous City: The Generous City. *Architectural Design*, *85*(4), 120–121. https://doi.org/10.1002/ad.1939

Budds, D. (2020, September 18). *Skyscrapers Dripping in Gardens Look Great—Until the Mosquitoes Swarm*. Curbed. https://archive.curbed.com/2020/9/18/21445069/qiyi-city-forest-garden-mosquitoes-chengdu

C40 Cities. (2021a). *Winning Projects | Reinventing Cities | Reinventing Cities*. https://www.c40reinventingcities.org/en/professionals/winning-projects/

C40 Cities. (2021b, April 1). *C40 | Reinventing Cities*. https://www.c40reinventingcities.org/

C40 Good Practice Guides: Buenos Aires - Municipal Solid Waste Reduction Project. (2016, February). C40 Cities. https://www.c40.org/case-studies/c40-good-practice-guides-buenos-aires-municipal-solid-waste-reduction-project/

C40: Resilient Storm Water Management Leading to Climate Adaptation for Hong Kong, China. (2020, January 9). [Case Study: Hong Kong]. C40 Cities. https://www.c40.org/case_studies/resilient-water-systems-hong-kong

Coutts, A. M., White, E. C., Tapper, N. J., Beringer, J., & Livesley, S. J. (2016). Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. *Theoretical and Applied Climatology*, *124*(1–2), 55–68. https://doi.org/10.1007/s00704-015-1409-y

Fondazione Politecnico. (2020, April 3). Reinventing Cities Vitae: The City of Milan and the C40 together for a more sustainable city of the future. *Fondazione Politecnico*. https://www.fondazionepolitecnico.it/en/initiatives/visionary-cities/reinventing-cities-vitae/

Heymans, A., Breadsell, J., Morrison, G., Byrne, J., & Eon, C. (2019). Ecological Urban Planning and Design: A Systematic Literature Review. *Sustainability*, *11*(13), 3723. https://doi.org/10.3390/su11133723

Hirschlag, A. (2020, May 16). *How urban planners' preference for male trees has made your hay fever worse*. The Guardian. http://www.theguardian.com/environment/2020/may/16/how-urban-planners-preference-for-male-trees-has-made-your-hay-fever-worse

Li, X., & Ratti, C. (2018). Mapping the spatial distribution of shade provision of street trees in Boston using Google Street View panoramas. *Urban Forestry & Urban Greening*, *31*, 109–119. https://doi.org/10.1016/j.ufug.2018.02.013

Li, X., Zhang, C., Li, W., Ricard, R., Meng, Q., & Zhang, W. (2015). Assessing street-level urban greenery using Google Street View and a modified green view index. *Urban Forestry & Urban Greening*, *14*(3), 675–685. https://doi.org/10.1016/j.ufug.2015.06.006

McHarg, I. L., & Steiner, F. R. (2006). *The Essential Ian McHarg: Writings on Design and Nature*. Island Press. https://books.google.it/books?id=KyK8BwAAQBAJ

MIT Senseable City Lab. (2016). Exploring the Green Canopy in cities around the world. Treepedia. Retrieved 9 May 2021, from http://senseable.mit.edu/treepedia

MIT Senseable City Lab (2018). City Scanner. Retrieved 15 September 2021, from https://senseable.mit.edu/cityscanner/

MIT Senseable City Lab (2021, April 1). *Solar Cities*. https://senseable.mit.edu/solar-cities/

Mora, S., Anjomshoaa, A., Benson, T., Duarte, F., & Ratti, C. (2019). Towards Large-scale Drive-by Sensing with Multi-purpose City Scanner Nodes. *2019 IEEE 5th World Forum on Internet of Things (WF-IoT)*, 743–748. https://doi.org/10.1109/WF-IoT.2019.8767186

Morton, T. (2018). *Dark ecology: For a logic of future coexistence*.

Nikolopoulou, M., & Steemers, K. (2003). Thermal comfort and psychological adaptation as a guide for designing urban spaces. *Energy and Buildings*, 7.

O'Connor, M. I., Pennell, M. W., Altermatt, F., Matthews, B., Melián, C. J., & Gonzalez, A. (2019). Principles of Ecology Revisited: Integrating Information and Ecological Theories for a More Unified Science. *Frontiers in Ecology and Evolution*, *7*. https://doi.org/10.3389/fevo.2019.00219

Odum, E. P., & Barrett, G. W. (2005). *Fundamentals of ecology*. Thomson Brooks/Cole; /z-wcorg/.

OECD. (2020). *Environment at a glance 2020.* https://doi.org/10.1787/4ea7d35f-en

OECD. (2020). *The Circular Economy in Cities and Regions*. https://www.oecd-ilibrary.org/content/publication/10ac6ae4-en

Ratti, C., & Belleri, D. (2020). Towards a cyber ecology. Agathon: International Journal of Architecture, Art and Design, 08, 8–19. (C40 Group, n.d., p. 40)

Ritchie, H. (2018, September 27). *How urban is the world?* Our World in Data. https://ourworldindata.org/how-urban-is-the-world

Shanahan, D. F., Bush, R., Gaston, K. J., Lin, B. B., Dean, J., Barber, E., & Fuller, R. A. (2016). Health Benefits from Nature Experiences Depend on Dose. *Scientific Reports*, *6*(1), 28551. https://doi.org/10.1038/srep28551

Sierra-Heredia, C., North, M., Brook, J., Daly, C., Ellis, A. K., Henderson, D., Henderson, S. B., Lavigne, É., & Takaro, T. K. (2018). Aeroallergens in Canada: Distribution, Public Health Impacts, and Opportunities for Prevention. *International Journal of Environmental Research and Public Health*, *15*(8). https://doi.org/10.3390/ijerph15081577

Vitae. (2019). C40 Group. https://www.c40reinventingcities.org/data/sites_134e6/fiche/39/projects_memo_-_vitae_-_milan-_serio_f9b88.pdf

Wilson, E.O. (1984). Biophilia, Harvard University Press

Data-driven design for Architecture and Environment Integration

Convergence of data-integrated workflows for understanding and designing environments

Defne Sunguroğlu Hensel [1], **Jakub Tyc** [2], **& Michael Hensel** [2]

[1] *Technical University Munich, Munich (Germany)*
[2] *TU Wien, Vienna (Austria)*

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

DOI

https://doi.org/10.47982/spool.2022.1.02

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).

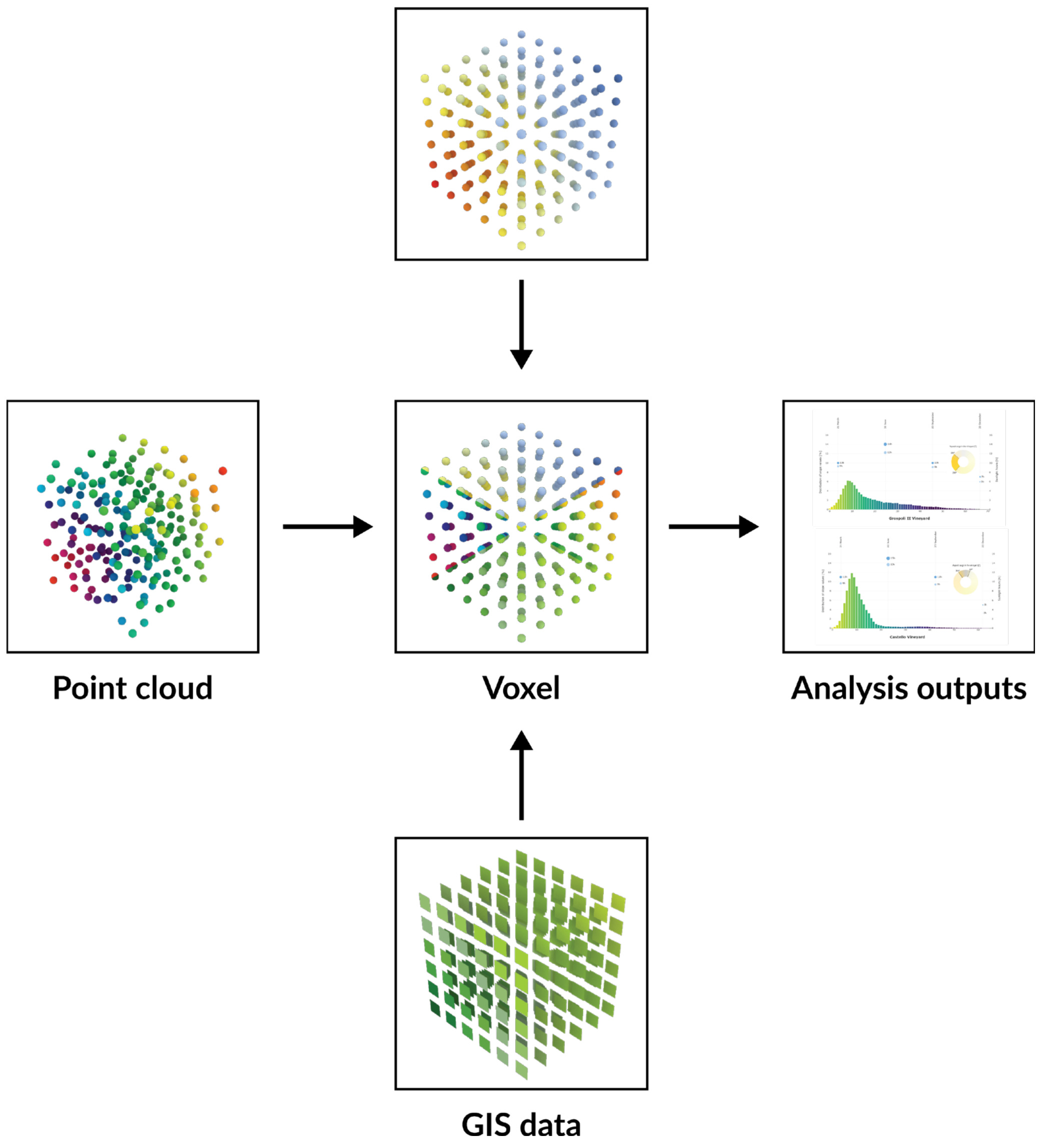


FIGURE 1 This diagram shows the main steps in the creation of a composite voxel model. Photogrammetric point clouds are voxelized and fused with datasets derived from GIS and diverse simulation tools. Data points of the voxel model can be both interactively queried by the users and accessed by ML algorithms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

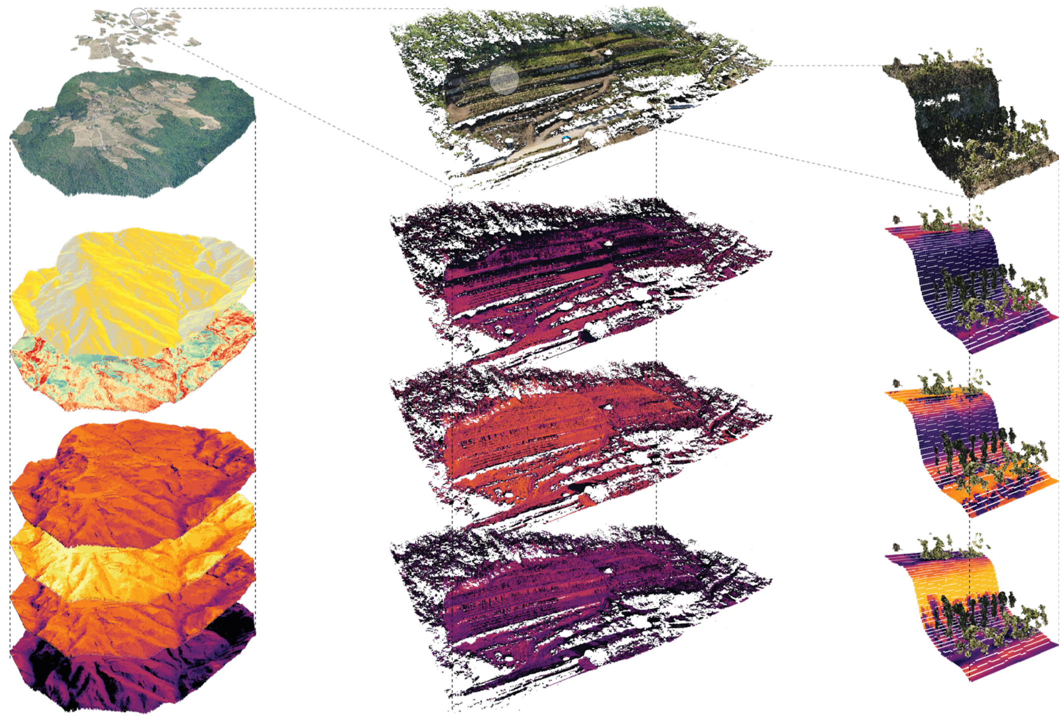
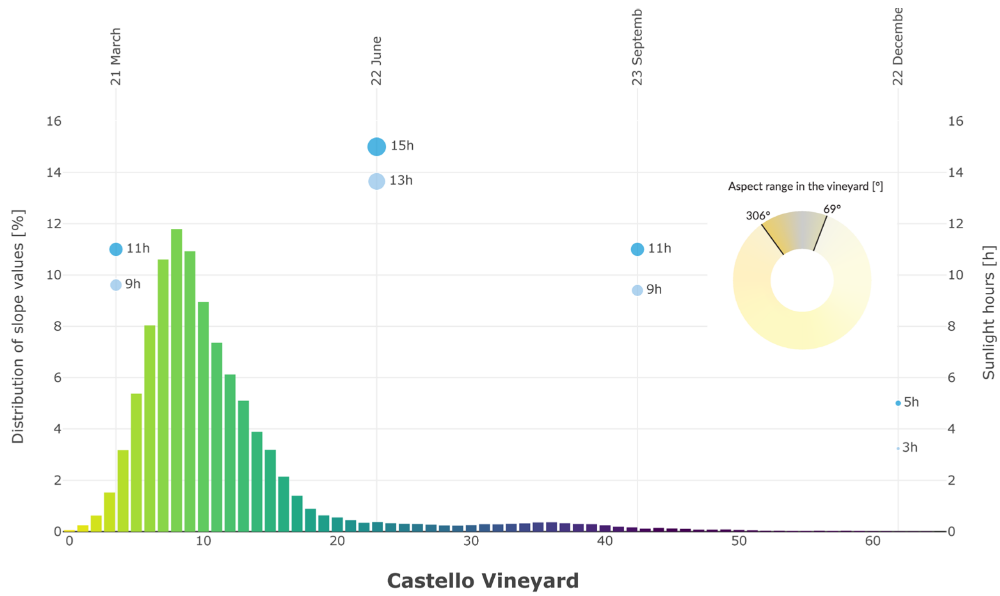


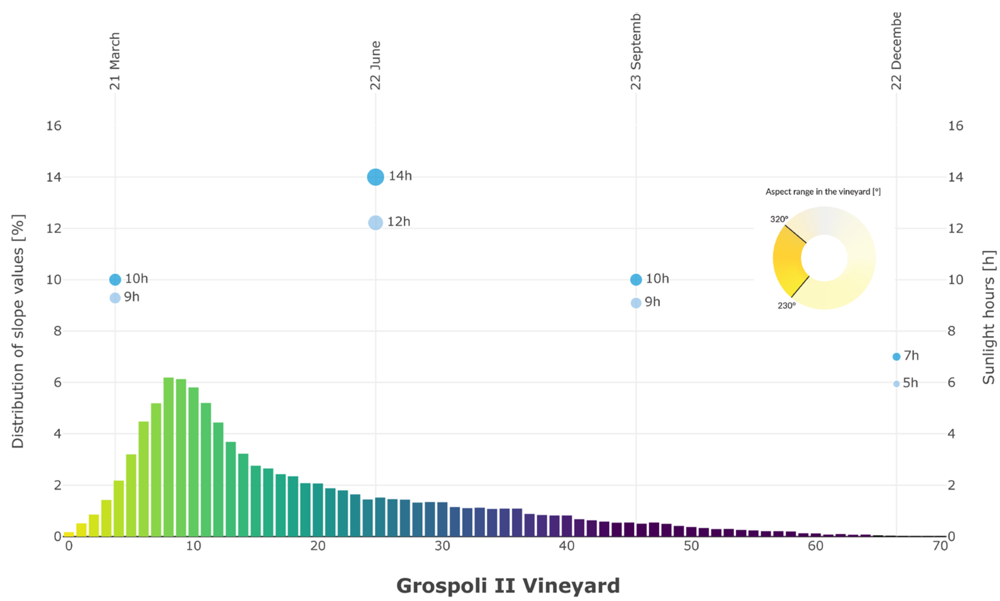
FIGURE 2 Integration of territorial, site and feature scale data in a composite voxel model. Geometric and multispectral data acquired with UAV photogrammetry and airborne LiDAR is augmented with outcomes of computational analysis and simulations at different scales.

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.



a



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).

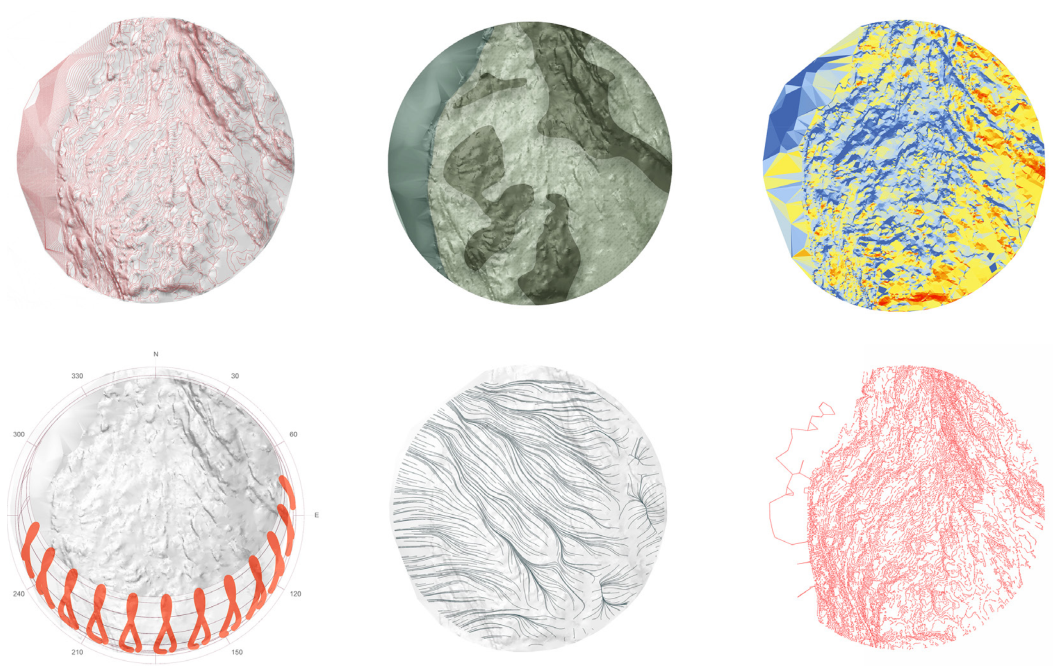


FIGURE 4 Analysis of terrain morphology, slope, vegetation distribution, sun path and water run-off, and closest points. Copyright: OCEAN Architecture | Environment, 2018.

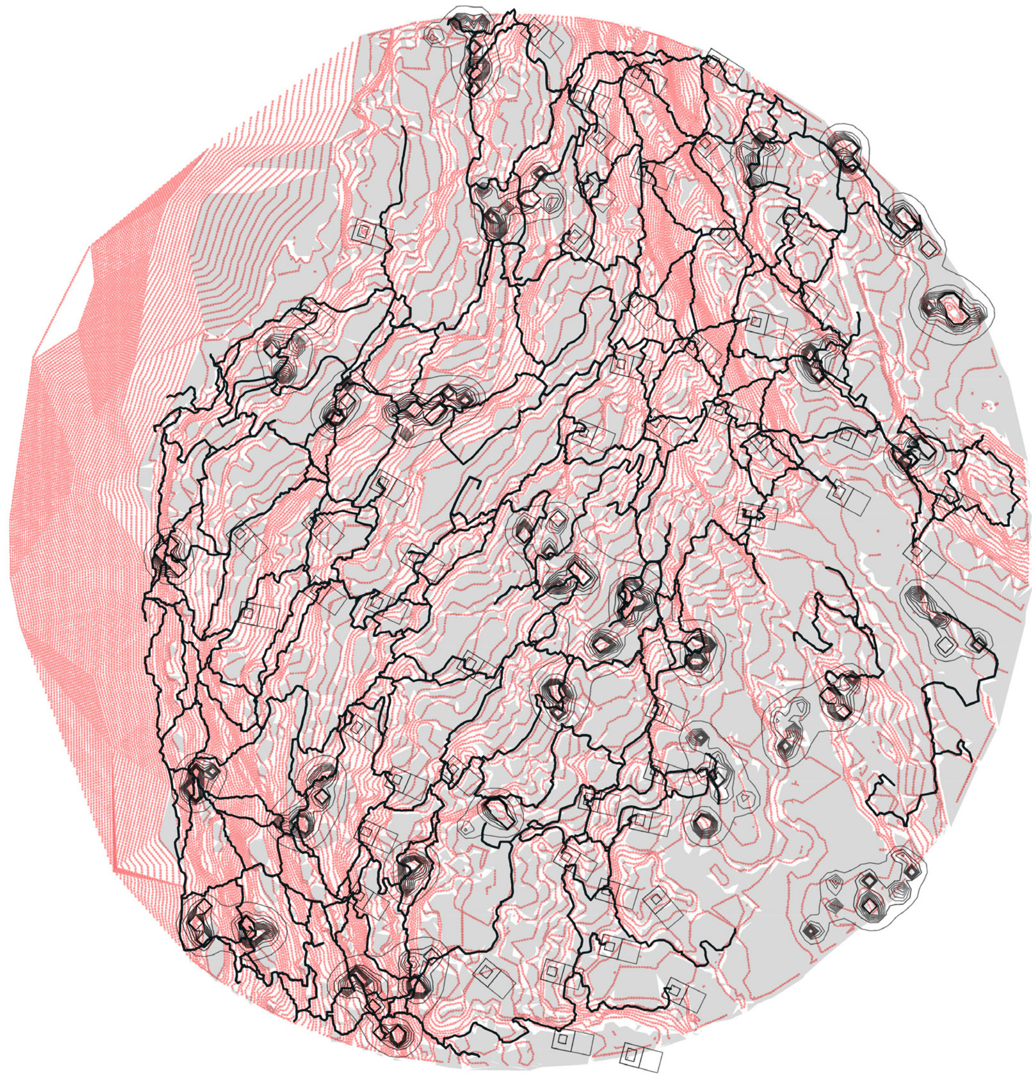


FIGURE 5 Terrain-specific circulation and dwelling typology distribution plan. Copyright: OCEAN Architecture | Environment, 2018.

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).

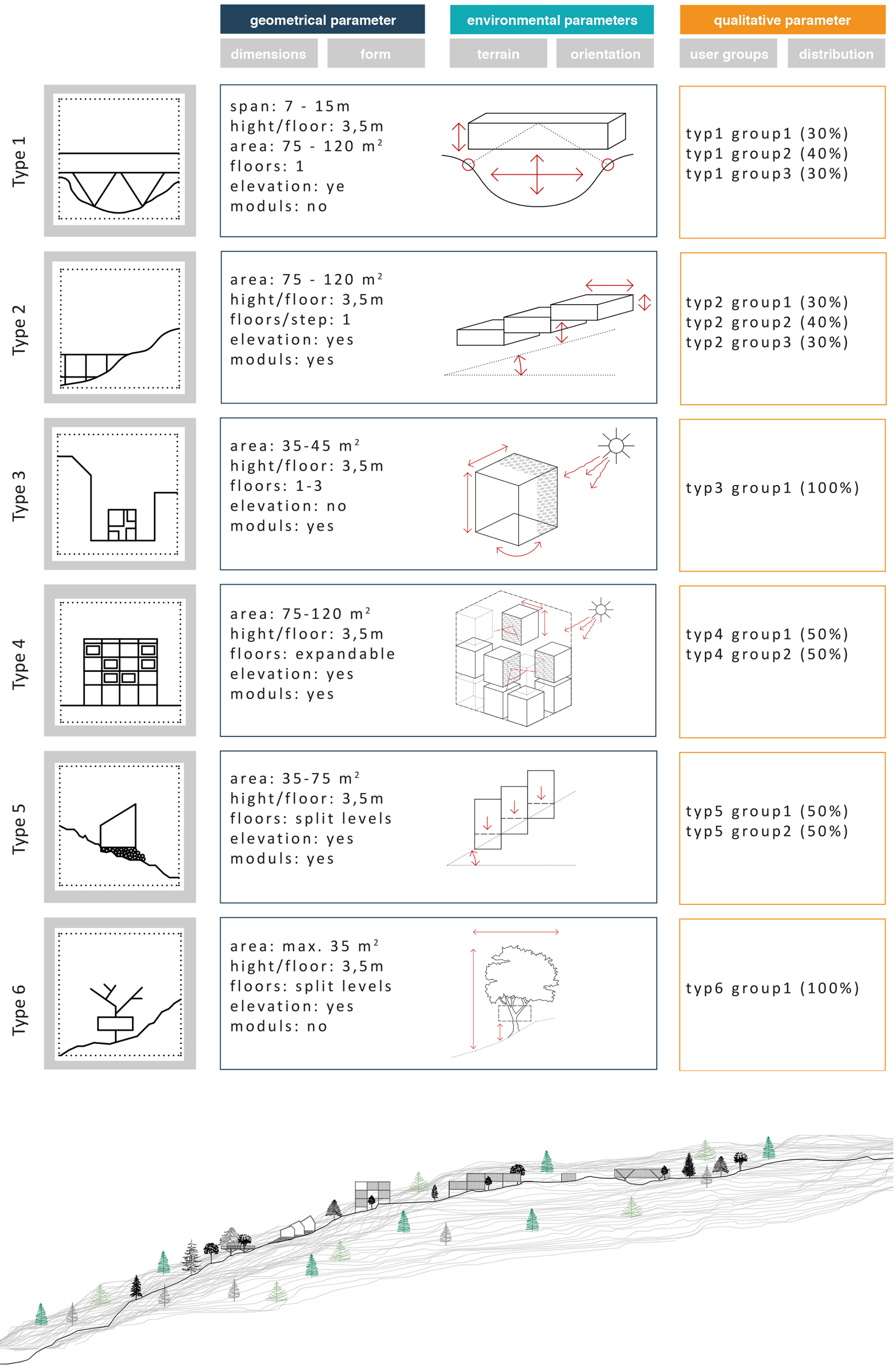


FIGURE 6 A newrevised illustration is provided. Caption: Top: Table of terrain specific architectures. Bottom: sample section through the site with allocated terrain specific architectures. Embedded Architectures Studio: Tina Selami and Fabian Pitscheider, 2019.

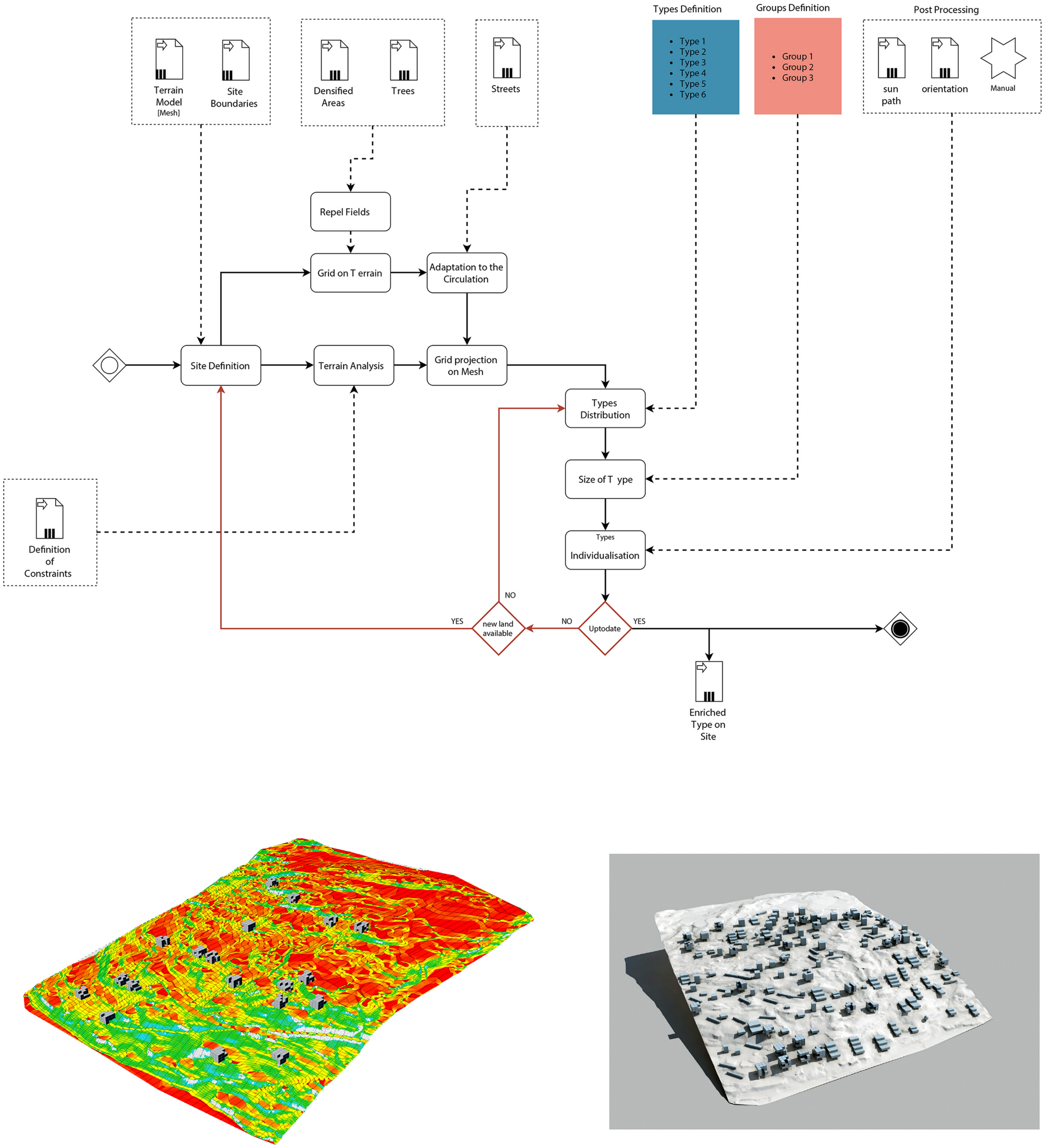


FIGURE 7 Top: computational workflow for developing terrain-specific circulation and dwelling type distribution. Bottom left: distribution of dwelling type 4 relative to the specified terrain features. Bottom right: one possible configuration of all dwelling types relative to their specified terrain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

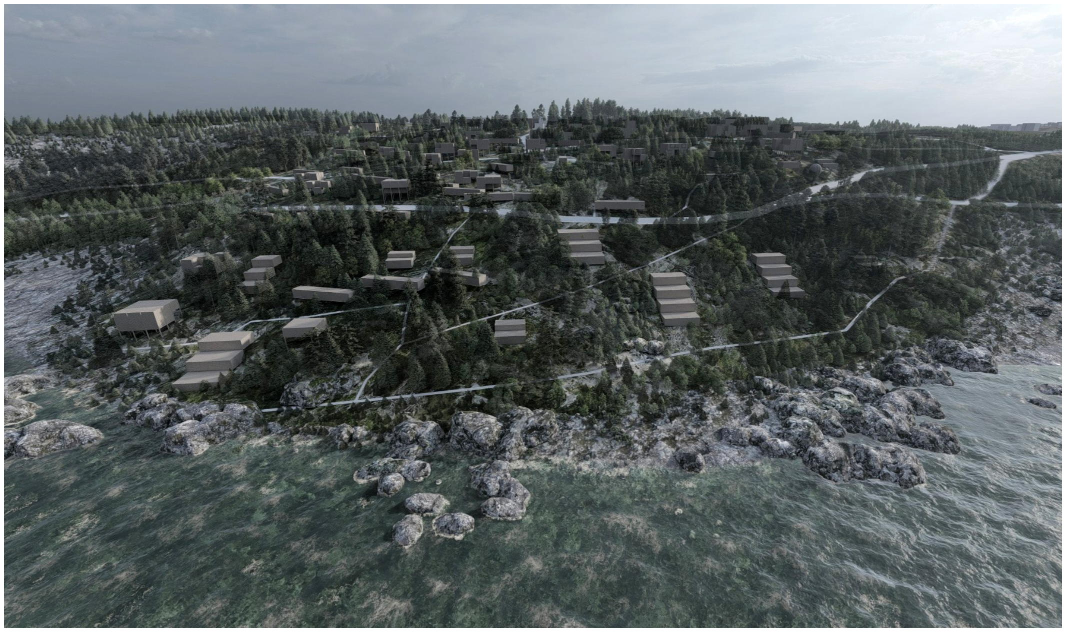


FIGURE 8 Top: rendered view of one possible configuration of all dwelling types relative to their specified terrain features. Embedded Architectures Studio: Tina Selami and Fabian Pitscheider, 2019.

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).

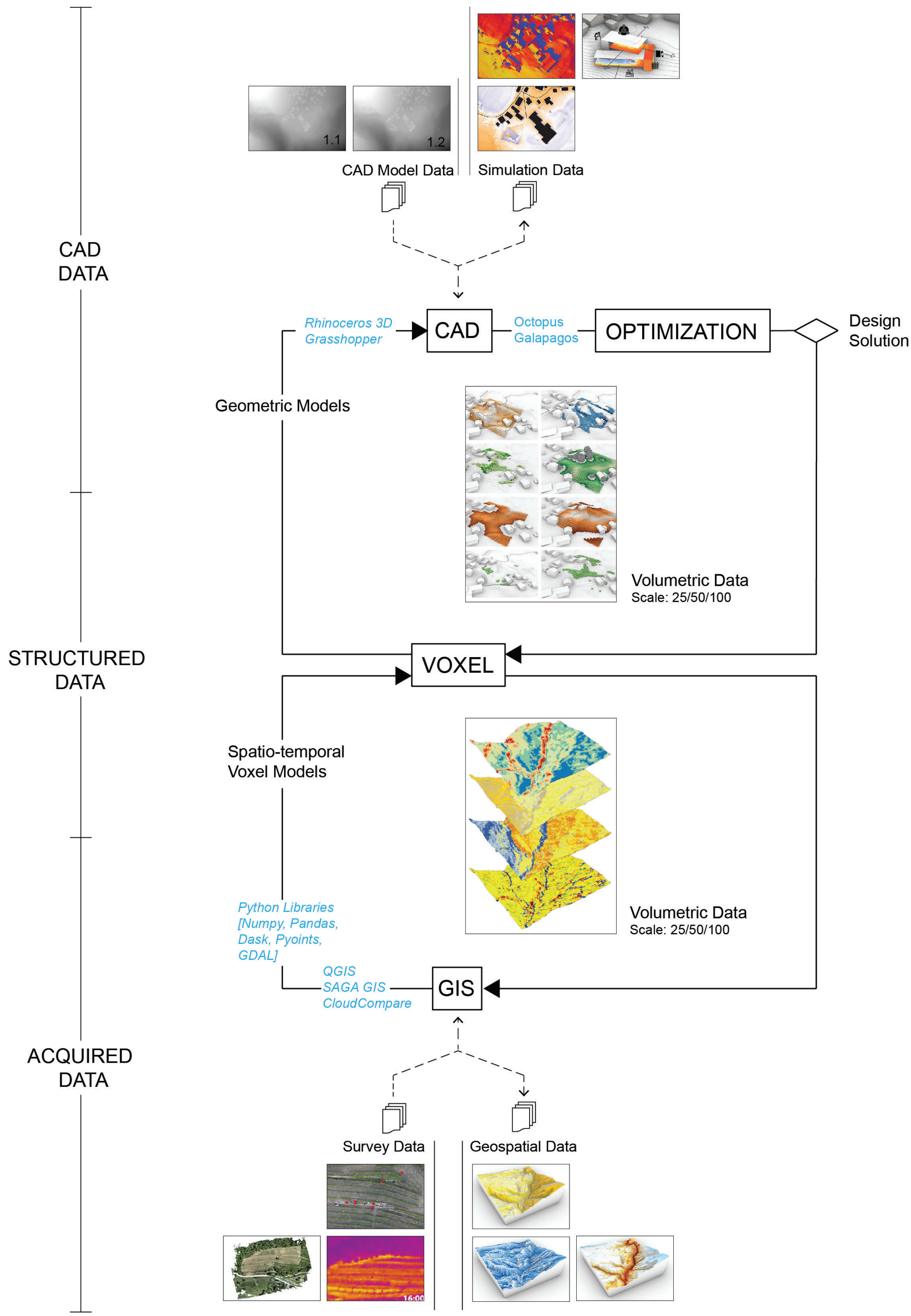


FIGURE 9 Data-integrated workflow that combines acquired data and GIS data in a voxel model linked with a CAD model that incorporates various simulation and optimization processes.

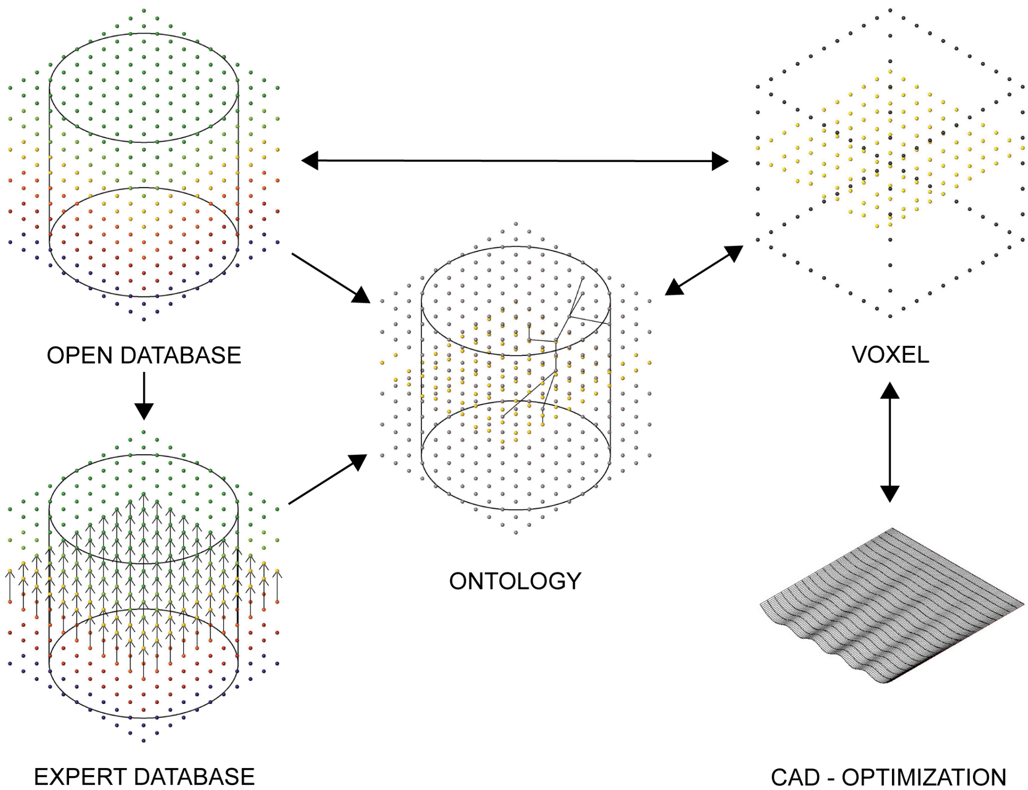


FIGURE 10 This diagram shows the key components of the design decision support system and how they are linked for data processing. Target sets from open spatial data integrated, managed and extracted from, e.g. GIS tools, feed into a relational expert database, built to expand and inform the ontology, 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.

Acknowledgements

In the context of the understanding environments research and specifically the Lamole project we wish to thank Paolo Socci, proprietor of Fattoria di Lamole, and our collaborators at the Geomatics for Environment and Conservation of Cultural Heritage Laboratory at the University of Florence, especially Prof. Dr. Grazia Tucci, Dr. Erica Isabella Parisi, Dr. Valentina Bonora, Associate Prof. Dr. Andrea Masiero, and Assistant Prof. Dr. Francesco Mugnai. Furthermore, we wish to thank our collaborators in the Research Centre for Architecture and Tectonics at the Oslo School of Architecture and Design, Associate Prof. Søren Sørensen, Assistant Professors Sofia Cunha and Jakim Wiig Hoen, and Dr. Sareh Saeidi, and senior lecturers Sigrun Swoboda, Arnold Faller and Andreas Jonas in the Research Department for Digital Architecture and Planning at Vienna University of Technology. Furthermore, in relation to the work in OCEAN we wish to acknowledge Matteo Lomaglio. Regarding the master-level studio at Vienna University of Technology, we wish to acknowledge our students Tina Selami and Fabian Pitscheider.

References

Batty, M. (2013) Big data, smart cities and city planning. *Dialogues in Human Geography*, *3*(3), 274-279. https://doi.org/10.1177/2043820613513390

Batty, M. (2016) Big data and the City. *Built Environment*, *42*(3), 321-337. https://doi.org/10.2148/benv.42.3.321

Bier, H., & Knight, T. (eds.) (2014) *Dynamics of Data-driven Design – Footprint*, *15*. https://doi.org/10.7480/footprint.8.2

Castrignanò, A., Buttafuoco, G., Khosla, R., Mouazen, A.M., Moshou, D., & Naud, O. (Eds.) (2020). *Agricultural Internet of Things and Decision Support for Precision Smart Farming*. London, UK: Academic Press – Elsevier.

Deutsch, R. (2012). *Data-driven Design and Construction: 25 Strategies for Capturing, Analysing and Applying Building Data*. London, UK: Wiley.

Fraga, H., García de Cortez Atauri, I., Malheiro, A.C., & Santos, J.A. (2016) Modelling climate change impacts on viticultural yield, phenology and stress conditions in Europe. *Global Change Biology*, *22*(11), 3774-3788. https://doi.org/10.1111/gcb.13382

Friedman, D.S. (2016) Researching: Kieran Timberlake's design ethic. In M. Hensel & F. Nilsson (Eds.) *The Changing Shape of Practice: Integrating research and design in architecture* (pp. 48-60). Oxon, UK: Routledge.

Hensel, M., Santucci, D., Sunguroğlu Hensel, D., & Auer, T. (2020) The Lampedusa Studio: A multi-method pedagogy for tackling compound sustainability problems in architecture, landscape architecture and urban design education. *Sustainability*, *12*(11), 4369. https://doi.org/10.3390/su12114369

Hensel, M., & Sunguroğlu Hensel, D. (2020a) Embedded Architectures – An Overarching Approach to Compound Sustainability Problems including Urban Climate Mitigation. In A. Battisti & D. Santucci (Eds.), *Urban Climate Mitigation for Activating Public Space* (pp. 55-63). Munich, Germany: Technical University Munich.

Hensel, M., & Sunguroğlu Hensel, D. (2020b) Performances of Architectures and Environments – A Framework',. In M. Kanaani (Ed.), *The Routledge Companion to Performativity in Design and Architecture: Using Time to Craft an Enduring, Resilient and Relevant Architecture* (pp. 1-17) London, UK: Routledge.

Hensel, M., Sunguroğlu Hensel, D., & Sevaldson, B. (2019) Editorial – Linking Design-thinking and Systems-thinking in Architecture and Urban Design. *FORMAkademisk, 12*(2), 1-5. https://doi.org/10.7577/formakademisk.3406

Hensel, M., Sunguroğlu Hensel, D., & Sørensen, S.S. (2018) Embedded Architectures: Inquiries into Architectures, Diffuse Heritage and Natural Environments in Search for better informed Design Approaches to Sustainability. *Time + Architecture*, *161*(3), 42-45.

Hensel, M., & Sørensen, S. (2019) Performance-oriented Architecture and Urban Design - Relating Information-based Design and Systems-thinking in Architecture. *FORMAkademisk*, *12*(2), 1-17. https://doi.org/10.7577/formakademisk.2963

Hensel, M., & Sørensen, S. (2014). Intersecting Knowledge Fields and Integrating Data-Driven Computational Design en Route to Performance-oriented and Intensely Local Architectures. *Footprint*, *15*, 59-74. https://doi.org/10.7480/footprint.8.2.812

Høyedata Retrieved from https://hoydedata.no/LaserInnsyn/

Kitchin, R. (2018) Data-driven Urbanism. In R. Kitchin, R., T.P. Lauriault & G. McArdle (Eds.). *Data and the City* (pp. 44-56) London, UK: Routledge.

Martens, P. (2006) Sustainability: science or fiction? *Sustainability: Science, Practice and Policy*, *2*(1), 36-41. https://doi.org/10.1080/15487733.2006.11907976

Perini, A., & Susi, A. (2004). Developing a decision support system for integrated production in agriculture. *Environmental Modelling & Software*, *19*(9), 821-829. https://doi.org/10.1016/j.envsoft.2003.03.001

Rose, D.C., Sutherland, W.J., Parker, C., Lobley, M., Winter, M., Morris, C., Twining, S., Ffoulkes, C., Amano, T., & Dicks, L.V. (2016) Decision support tools for agriculture: Towards effective design and delivery. *Agricultural Systems*, *149*, 165-174. https://doi.org/10.1016/j.agsy.2016.09.009

Solecki, W., Seto, K.C., & Marcotullio, P.J. (2013). It's time for Urbanization Science. *Environment: Science and Policy for Sustainable Development*, *55*(1), 12-17. https://doi.org/10.1080/00139157.2013.748387

Sunguroğlu Hensel D. (2020) Ecological Prototypes – Initiating Design Innovation in Green Construction. *Sustainability*, *12*(14), 5865. https://doi.org/10.3390/su12145865

Trusilova, K., & Churkina, G. (2008). The response of the terrestrial biosphere to urbanization: land cover conversion, climate, and urban pollution. *Biogeoscience*, *5*(6), 1505-1515. https://doi.org/10.5194/bg-5-1505-2008

Turner, B.L., II, Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T. & Meyer, W.B. eds. (1990). *The Earth as Transformed by Human Action*. Cambridge, UK: Cambridge University Press.

Turner, B.L., II, & Meyer, W.B. (1991). land use and land cover in global environmental change: consideration for study. *International Social Science Journal*, *43*(130), 669-679.

Underdal, A. (2010) Complexity and challenges of long-term environmental governance. *Global Environmental Change*, *20*(3), 386-393. https://www.sciencedirect.com/science/article/pii/S0959378010000117

UN Big Data for Sustainable Development Retrieved from https://www.un.org/en/global-issues/big-data-for-sustainable-development

Zhai, Z., Martínez, J.F., Beltran, V., & Martínez, N.L. (2020). Decision support systems for agriculture 4.0: Survey and challenges. *Computers and Electronics in Agriculture*, *170*, 105256. https://doi.org/10.1016/j.compag.2020.105256

Data-driven Urban Design

Conceptual and Methodological Interpretations of Negroponte's 'Architecture Machine'

Jeroen van Ameijde

The Chinese University of Hong Kong (Hong Kong)

Abstract

Nicholas Negroponte and MIT's Architecture Machine Group speculated in the 1970s about computational processes that were open to participation, incorporating end-user preferences and democratizing urban design. Today's 'smart city' technologies, using the monitoring of people's movement and activity patterns to offer more effective and responsive services, might seem like contemporary interpretations of Negroponte's vision, yet many of the collectors of user information are disconnected from urban policy making. This article presents a series of theoretical and procedural experiments conducted through academic research and teaching, developing user-driven generative design processes in the spirit of 'The Architecture Machine'. It explores how new computational tools for site analysis and monitoring can enable data-driven urban place studies, and how these can be connected to generative strategies for public spaces and environments at various scales. By breaking down these processes into separate components of gathering, analysing, translating and implementing data, and conceptualizing them in relation to urban theory, it is shown how data-driven urban design processes can be conceived as an open-ended toolkit to achieve various types of user-driven outcomes. It is argued that architects and urban designers are uniquely situated to reflect on the benefits and value systems that control data-driven processes, and should deploy these to deliver more resilient, liveable and participatory urban spaces.

Keywords

Urban Analytics, Data-driven Design, Participatory Design, Urban Placemaking, Public Space Design

DOI

https://doi.org/10.47982/spool.2022.1.03

Introduction

The increasing integration of information and communication technologies into buildings and urban spaces allows for cities to become 'a reflexive test-bed and workshop for connected habitation in enmeshed digital and physical space' (Ratti and Claudel, 2016, p.23). Data-driven systems can establish feedback loops between city users and their environment, enabling data-driven design decisions actualized through traditional forms of construction, or through electronic systems for control and communication.

The emerging field of urban analytics offers methodologies for data-driven types of urban studies, allowing new insights to be informed by detailed datasets of human activities and everyday interactions. This could help bridge the gap between the social sciences and urban planning practice (Dyer et al., 2017), as urban studies employ human-centric scientific research methods, while urban planning 'best practice' methods may prioritize commercial rather than community interests (Nisha and Nelson, 2012). Rather than being based on assumptions, urban design practice can now foreground human-centric and evidence-based methods for the design and management of cities.

The wide range of emerging 'smart city' technologies might seem to enable citizen empowerment and societal progress, as cities promote the synergy between 'smart cities' and 'smart people' (Hong Kong Government 'Smart City Blueprint', 2017). However, in many instances, these systems are operated by private organizations that monopolize data for commercially strategic reasons. Many urban scholars argue that smart city technologies will have a profound effect on the freedoms, inclusivity and sense of participation experienced in future public spaces, and Lefebvre's notion of 'the right to the city' (1968) is threatened by 'ecosystems of technology' that 'derive maximum resource efficiency by working coherently and systematically' (Adam Greenfeld, quoted in Ratti and Claudel, 2016, p.31).

Data-driven urban design processes may already be shaping current and future cities in different ways, often outside current modes of urban design practice. There is an urgent need for architects and planners to adopt a leading role in the exploration and discussion of new urban processes and systems, as a lack of engagement may leave them powerless in tomorrow's technology-driven society.
This article presents a series of research projects and experiments, aimed at providing insights and discussion around designers' potential to engage with data-driven methods for urban analytics and generative design. It will discuss in detail how these processes can be broken down into separate components of gathering, analysing, translating and implementing data. As each of these operations can be conceptualized in relation to the politics of urban space, we aim to illustrate how designers can deploy a new toolkit for the creation of human-centric urban design.

The Architecture Machine

The idea of integrating physical and digital layers in the built environment has been conceptualized since the early 1960s by pioneers such as Christopher Alexander, Cedric Price and William Mitchell. Gordon Pasks' 1969 article 'The Architectural Relevance of Cybernetics' described architecture as 'a mechanism of information exchange' and called for architects to adopt the role of 'system designers' (Steenson, 2017, p.17). In books published in 1970 and 1975, Nicholas Negroponte and MIT's Architecture Machine Group speculated about man–machine processes to translate client requirements into architectural designs solutions without the interference of the architect's self-interest:

In most cases the architect is an unnecessary and cumbersome (and even detrimental) middleman between individual, constantly changing needs and the continuous incorporation of these needs into the built environment. The architect's primary functions, I propose, will be served well and served best by computers. (Negroponte, 1975, p. 1)

The best-known project produced by the Architecture Machine Group was an art installation titled 'SEEK', on show during the 'Software' exhibition in New York in 1970 (Fig. 1). The installation consisted of a large plexiglass enclosure containing a three-dimensional landscape of small cubes, and a number of small, mouse-like animals (gerbils) whose movements disrupted the cubes. A computational feedback loop consisting of a camera and a robotic arm was calibrated to analyse and amplify changes made by the gerbils. The ideal 'final' configuration of the cubes would emerge over time, out of the interaction between the inhabitants and their architectural environment.

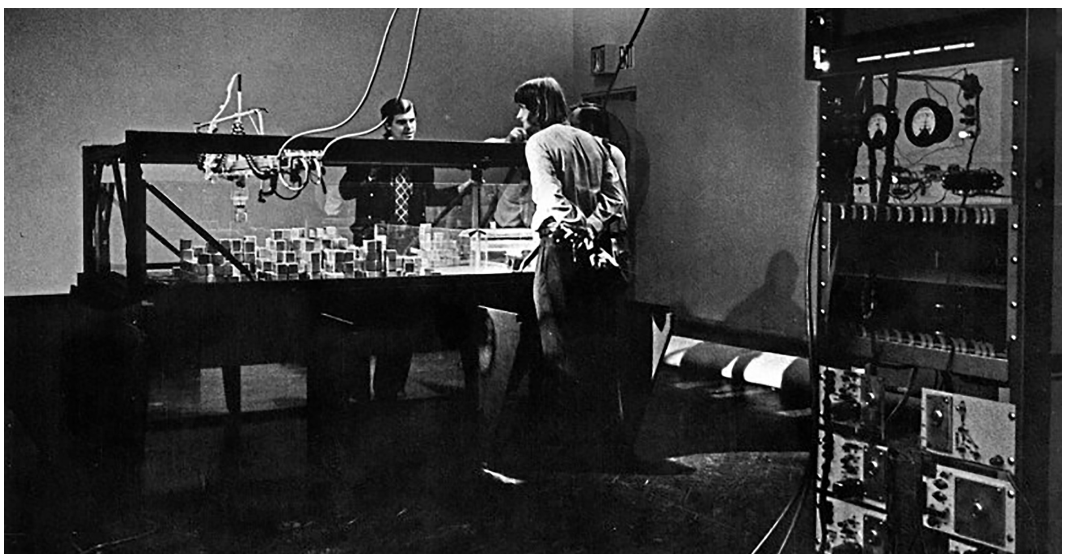


FIGURE 1 *'SEEK' installation by Nicholas Negroponte and the Architecture Machine Group, 1970. (Photograph by Harry Skunk and Jànos Kender J., image courtesy of Paul Getty Trust.)*

While the 'SEEK' project was criticized for 'inappropriate abstraction of real-world constraints and too great a scope of the design problem at hand' (Steenson, 2017, p.184), Negroponte's experiments made a provocative and influential contribution to the discourse around participatory urban design. It demonstrated the ambition to 'bring urban design back to the ordinary man' (Rowe, 1972, p.12), allowing citizens to be involved in the complex negotiations around urban problems through the mediation of a fair and transparent system containing computational rules.

Negroponte's collaborators Gordon Pask and Yona Friedman helped to define the 'SEEK' experiment as a cybernetic system, consisting of the separate processes of scanning and processing environmental data, and of responding and implementation with environmental remediation (Fig. 2a). While this feedback loop should function autonomously without the interference of designers, there was a crucial human role in defining the interpretation and reaction policies that should drive the environment's evolution. Figure 2b interprets this dynamic according to Friedman's principle of a 'non-paternalist' hierarchy: denying the designer a close association with the computer system to avoid interference based on preference, but instead having the computer be part of the environment. The designer's role is to conceive, test and develop the machine protocols and machine-environment interaction, evaluating their capacity to produce satisfying outcomes.

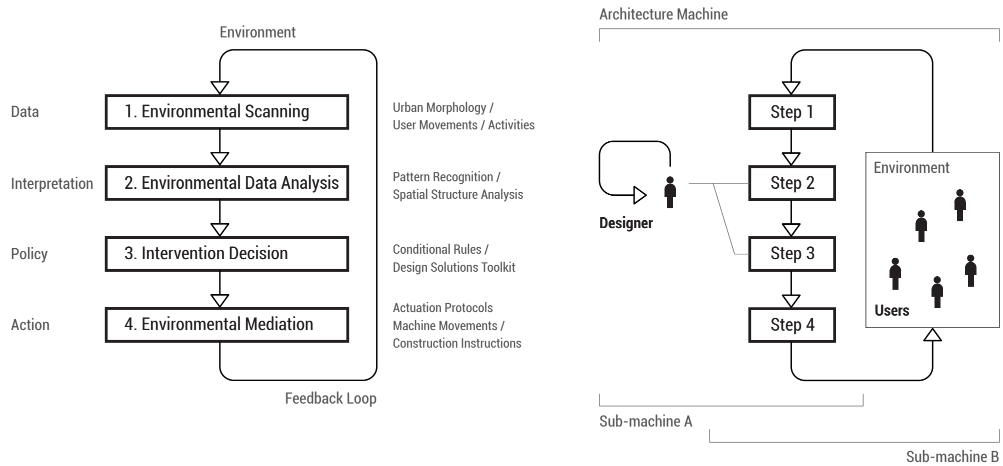


FIGURE 2 System diagrams of the 'SEEK' experiment, describing the relationships between environment, computer and designers of the system (Source: author, based on Friedman).

When evaluating these early conceptions of interactivity and participation explored by Negroponte and his contemporaries, it is easy to draw parallels with today's technological cities as described by Ratti and Claudel. As primitive computing systems and clumsy robotics are replaced by powerful miniaturized and distributed devices, there are clear opportunities to redefine the role and responsibilities of the urban designer. Negroponte's experiments aimed to provoke a debate about the ethics of creating controlled social environments, a topic that deserves urgent scrutiny in relation to the research around smart cities and urban analytics. Similar to the growing concerns about the negative effects of social media and the dilemmas in policing their complex systems of governance, it is crucial to reflect on the increasing influence that ubiquitous computing systems will have on the qualities of our urban spaces. While Negroponte and his contemporaries saw the consistent logic of computing operations as a tool to upgrade and democratize design processes previously limited by a single human designer, the current 'second digital turn' (Carpo, 2017) in society shows how computational systems can easily generate too much complexity, bias or undesirable results if they are not guided by human-defined limitations or ethical guidelines. While Ratti and Claudel are reservedly positive about Big Tech companies offering free services in exchange for the commodification of user data, their preferred models of augmented urban life are based on open data and platforms that enable grassroot initiatives and non-profit models of 'urban co-creation' (Ratti and Claudel, 2017, p.146). The objective of this article is to explore the tools, processes and socio-political implications relating to data-driven strategies for public space management. As we translate the various components of the 'SEEK' project to a range of contemporary tools from the fields of urban studies and generative design, we introduce open-ended technologies for human-centric and community-oriented design.

Methodologies for Integrating Urban Analytics and Data-driven Design

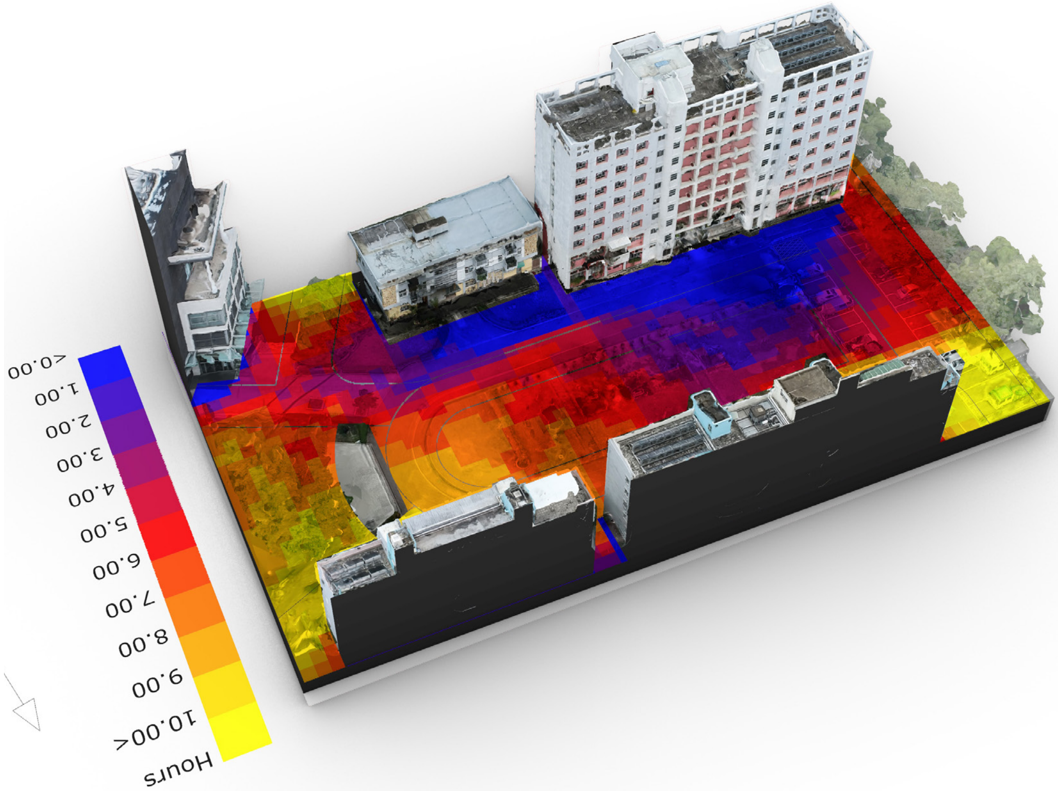
Component 1: Environment Scanning

The first component of a multi-stage workflow around data-driven urban site analysis and design should be a scanning methodology capable of harvesting detailed spatial data on the morphology of an urban site. In our experiments, we employ unmanned aerial vehicle (UAV) based site scanning techniques using aerial photography and photogrammetry software. A 3D model of buildings or spaces is generated by processing images captured with the UAV-mounted camera and on foot (Fig. 3).

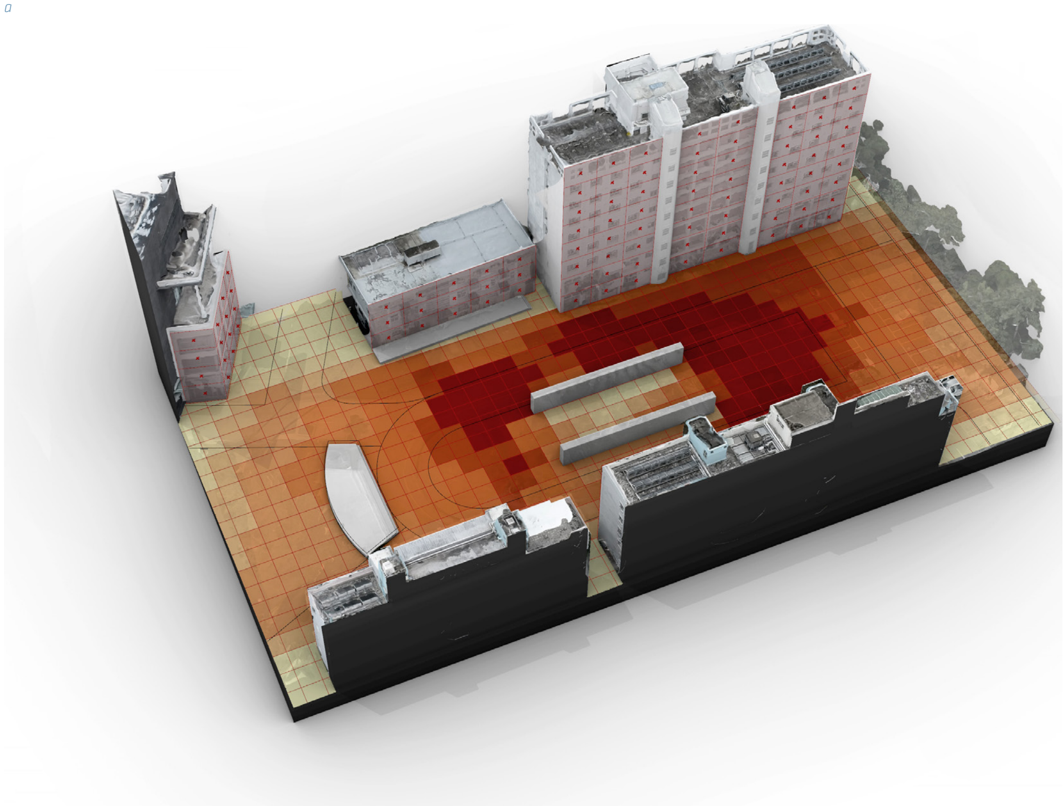

FIGURE 3 Point cloud model constructed with RealityCapture photogrammetry software, based on terrestrial photo datasets

Component 2: Environment Analysis

The 3D site models allow data compilation and analysis using a wide range of plug-ins and compatible software. In our workflow, we employ Visibility Graph Analysis (VGA) and Stamps' isovist, enclosure and permeability theory (2005) to evaluate the urban morphology, and the environmental and psychological comfort aspects of public open spaces. Our workflow has adapted the isovist analysis algorithms developed by Turner (2001, 2007) and Abdulmawla et al. (2017), as well as climate comfort analysis tools developed by Roudsari (2012). Figures 4a and b demonstrate the analysis of sunlight hours and visibility parameters across an underused public open space within the campus of The Chinese University of Hong Kong, which was scanned using drone and terrestrial photogrammetry.



a



b

FIGURE 4 Environmental analyses based on urban morphology, including sunlight hours (left) and surveillance mapping based on sight lines from surrounding windows to the public space (right).

Component 3: People tracking

Jane Jacobs (1961) famously demonstrated the value of social mechanisms within neighbourhoods, analysing the daily patterns of movements, activities and interactions that create resilient urban communities. Our workflow employs qualitative and quantitative documentation of activities in public spaces, following the methodology for the ethnographic study of space outlined by Low (2000; 2016; 2019). As part of our ongoing research, the use of digital cameras and image recognition software is being developed based on previously established methods for the analysis of people's movements and activities (Hanzl and Ledwon, 2017). We employ disguised naturalistic observation methods outlined by Cuttler (2019) who notes that 'ethically, this method is considered to be acceptable if the participants remain anonymous and the behaviour occurs in a public setting where people would not normally have an expectation of privacy' (Jhangiani et al., 2019, p. 170).

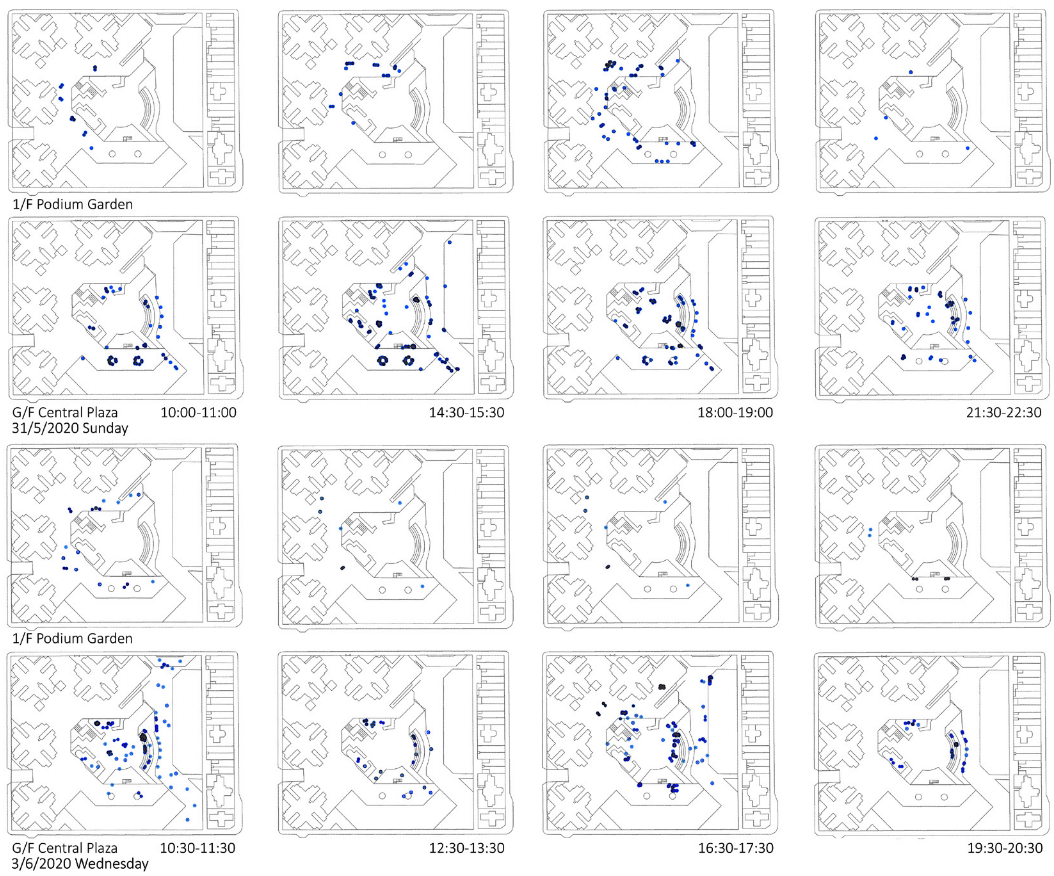


FIGURE 5 Documentation of people locations across various time intervals in the Prosperous Garden housing estate in the Yau Ma Tei district, Hong Kong.

After documenting data across specific periods of time, the movement and activity locations can be translated into time-based spatial data in the form of geolocation coordinate points. Figure 5 shows an example of a limited data set in this form, produced during a short ethnographic study of social activities in one of Hong Kong's public housing estates. For this case study, user data was collected across four one-hour intervals on a typical weekday (31 May) and Sunday (3 June) in 2020. Just under 600 datapoints were collected by a team of four observers. Referred to as 'snapshot' observations, these field studies have limitations compared to a structure study across longer time frames but can provide valuable initial insights into the general social dynamics of a study site.

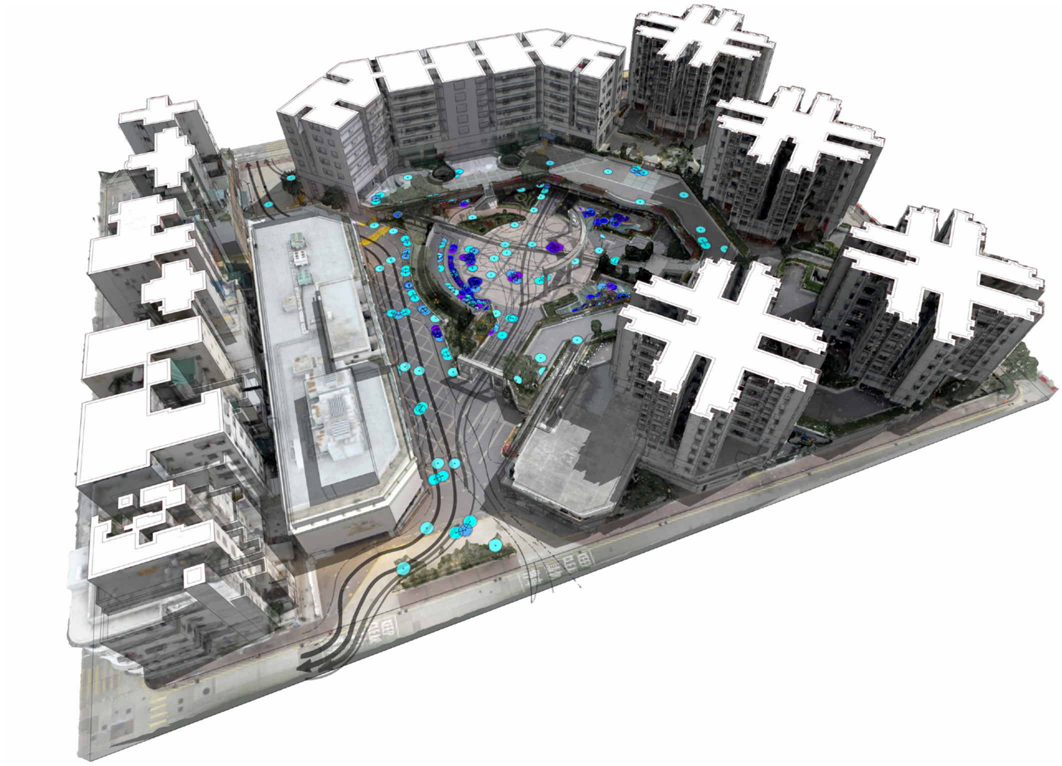


FIGURE 6 Analysis of people locations and closeness, based on a weekday snapshot (16:30-17:30) observation at the Prosperous Garden housing estate.

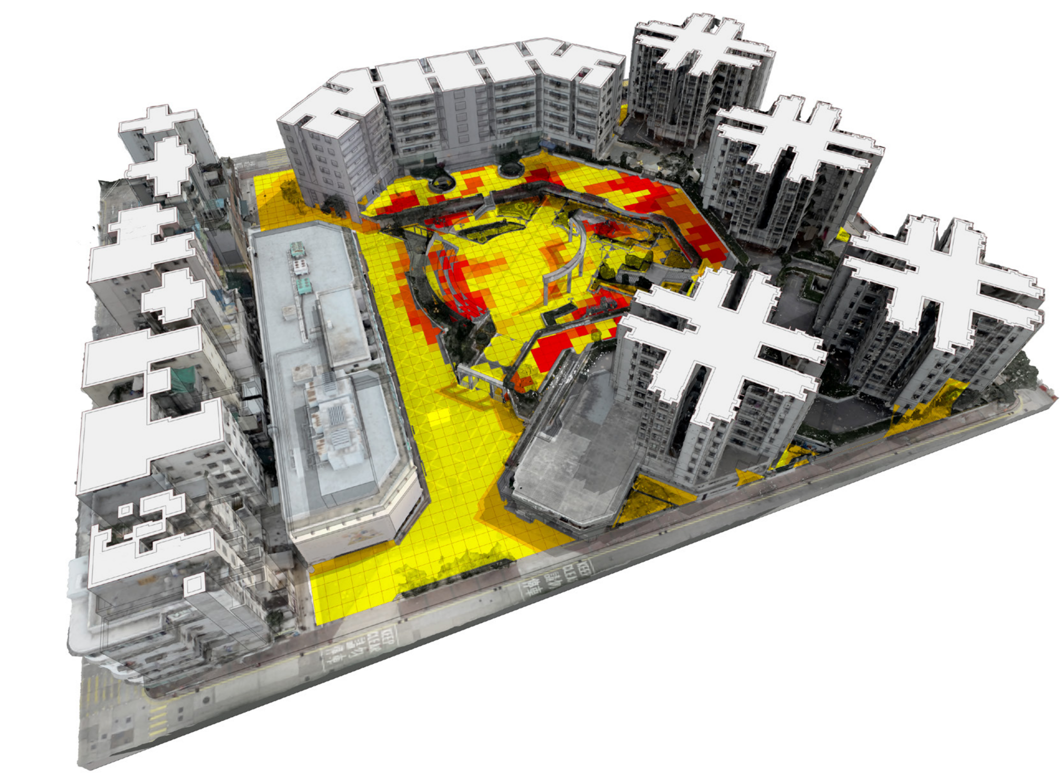


FIGURE 7 Space-centric analysis of people locations and closeness, based on a compilation of all weekday snapshot observations documented in Figure 5.

Component 4: People location analysis

To translate the basic data of movement and activity locations into meaningful insights about the intensities of use of public spaces, basic statistical analysis can be performed through computational processing. In addition to location data, we can analyse the degree of *closeness* – the physical distance between people and the in-between space that facilitates co-presence and regulates interpersonal relationships (Madanipour, 2003, p. 206). We can evaluate various distances based on *proxemic interactions theory*, and the discrete proxemic zones defined by the anthropologist Edward T. Hall: *intimate* (0 - 0.5 m), *personal* (0.5 – 1 m), *social* (1 – 4 m) and *public* (> 4 m) (Hall, 1966; 1968). Our algorithm uses lighter colours to indicate private individuals or couples, and increasingly darker colours to indicate social groups of three or more people (Figure 6).

In a final step of data translation, the statistical occurrence of user presence and co-presence is defined as a feature of the various locations within the case study space. The mapping process follows a basic logic of defining a spatial grid of cells (Fig. 7). For this analysis, multiple datasets relating to various time intervals can be combined, to produce insights into the general statistical patterns of space occupancy as they occur over longer periods of time.

As this article focuses on a conceptual and procedural overview of the separate components of a data-driven urban design process, the detailed findings of the particular case study research shown here will be discussed in different article. Instead, it is important to reflect on the critical overview and integration of the different stages of such a process, and how decisions around data-interpretation can be guided by socially-oriented policies.

Component 5: Data-driven design policies

In the previous sections of this article, we have outlined separate but interrelated steps for the scanning and processing of environmental data, including urban morphology and people location analysis. Following our interpretation of the Architecture Machine concept, the data-driven nature of the public space analysis now allows us to conceive a design intervention in the same space, as part of a cybernetic system aimed at empowering its inhabitants. Negroponte's vision to 'eliminate the middleman' between the individual's needs and the incorporation of those needs into the built environment, seems to align itself with the concept of 'the right to the city' introduced by Henri Lefebvre (1968). This concept argues for 'the right to belong to, and the right to co-produce the urban spaces' (Aalbers & Gibb, 2014, p. 208). To achieve this goal, we should set up policies for public space design and management that aim to fulfil as many user requests as possible, with a minimal amount of coordination and regulation to resolve conflicting demands of different groups of end users. This is in contrast to current public space planning policies in many cities, which often focus only on facilitating activities and behaviours of a certain desirable range.

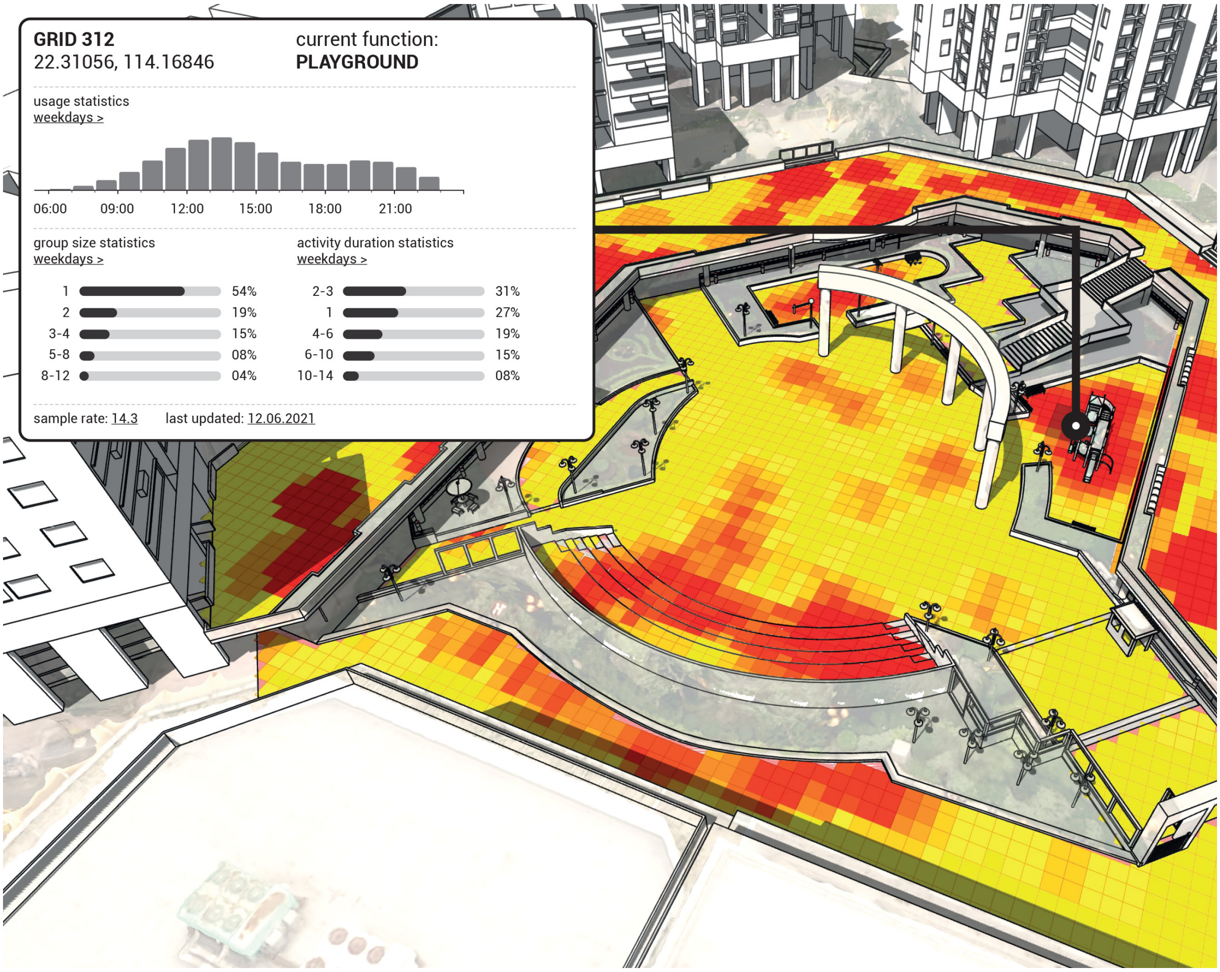


FIGURE 8 *User data evaluation on specific public space locations or elements, such as the visit intensity statistics, including group sizes and duration of the visit in minutes.*

Component 6: Data-driven design systems

In our case study experiment at the Prosperous Garden Estate, we speculate about a design strategy which matches supply to demand, providing public space facilities to the real-world usages as monitored. A permanent site monitoring system would be installed using CCTV camera feeds, and employing anonymized data collection as a formalized commitment to performance evaluation (Fig. 8). Facilities that prove to be less used could have their quantity or location priority reduced, and for elements that are often used to full capacity, additional elements would be installed. Changes would also be based on correlation analysis, analysing combinations of facility types and urban morphology characteristics that may produce more frequent user engagement. Instead of the notion of the 'masterplan' as an overarching, top-down framework of design decisions determined by planners, the project employs a catalogue of urban design elements, able to be installed on site in a range of configurations (Fig. 9). Decisions on the implementation of changes on the site would be made autonomously by a system that continuously monitors human activities and interactions, guided by a set of policies that facilitate democratized and participatory modes of design, to produce a community-driven and supportive urban environment.

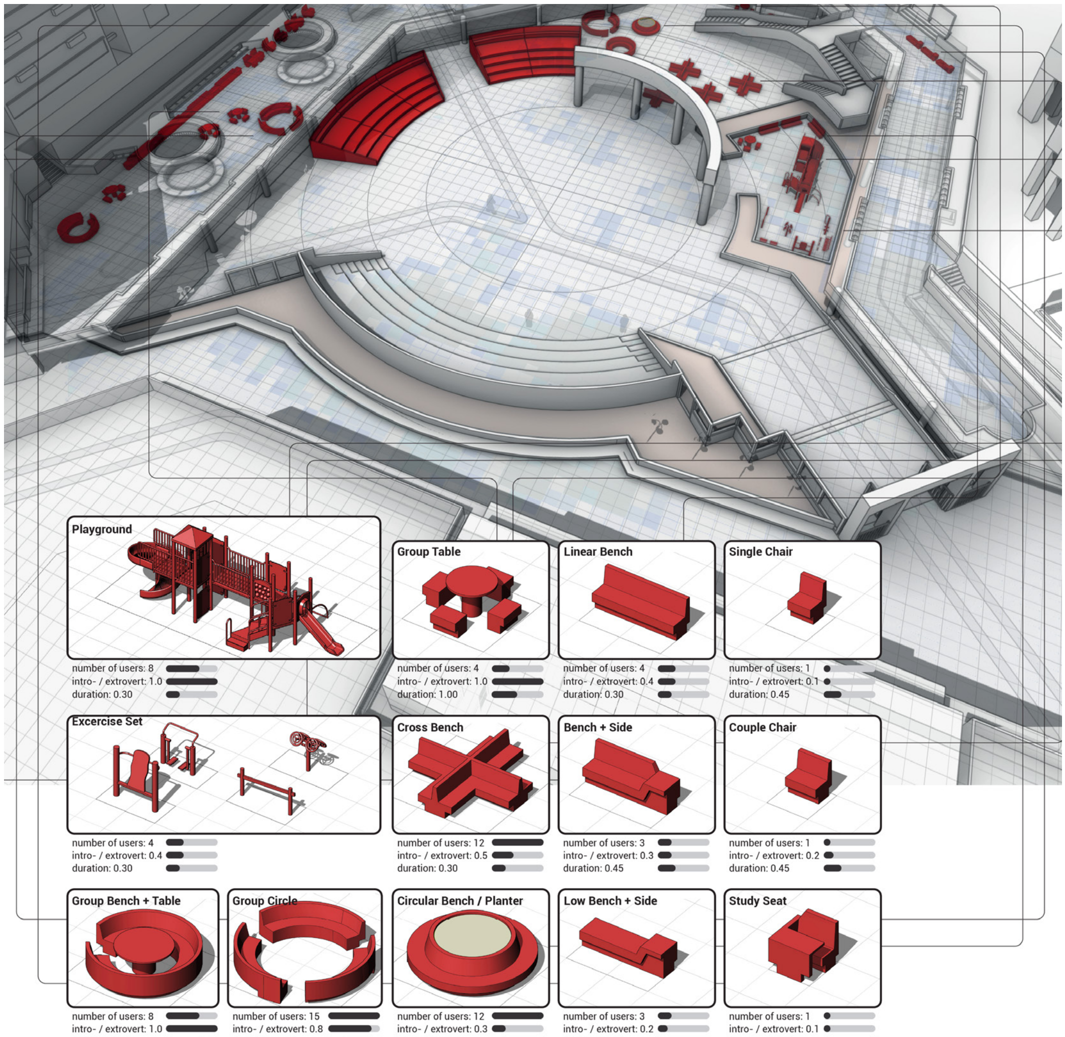


FIGURE 9 *Potential data-driven urban design implementation at Prosperous Garden Estate, where the placement of furniture is evaluated in real time based on the evaluation of people's activities.*

Discussion and Conclusions

In this article, we have traced some of the ambitions of the early explorers of cybernetic systems in architecture and urbanism, and attempted to reposition these in the context of the emerging opportunities offered by public space design in the age of ubiquitous computing. The visionary scenarios of Negroponte, Pask and Friedman highlighted the limitations of human designers, and proposed that machine systems of control would be better suited to translate the complex requirements of end users into appropriate design solutions. As identified by Negroponte and emphasized in this article, autonomous systems could produce desirable or highly undesirable outcomes, and 'architecture machines' would have to be sensitive and open to human criteria and interventions. The key issue is to focus on the overarching objectives governing these systems, to verify whether data-driven systems produce meaningful management scenarios that implement positive social policies in relation to human-centric urban theories, such as the notion of 'the right to the city' and that of 'spatial justice'. The real-world implications of these theoretical concepts involve social, political and economic rights, and a production of urban spaces that contributes to enabling people rather than excluding or exploiting them.

In our own data-driven design experiments and speculations, we aim to develop an open-ended approach to data gathering and analysis that is able to learn about the requirements of diverse public space users, without making specific presumptions or prescriptions. We speculate about how the central component of Negroponte's 'Architecture Machine', the feedback loop, could translate into cybernetic systems that continuously evaluate and improve the infrastructure for social activities in public urban spaces, to improve recreation, socializing, community formation and participation. While the monitoring of daily activities should adhere to research ethics and privacy protection protocols, the contemporary state of technologies now allows exciting new types of analysis of the behavioural, cultural and sociological aspects of interactions between people in urban spaces. We are only at the beginning of a paradigm shift, in which new types of computational systems and emerging modes of practice allow us to start testing real-world scenarios of intelligent adaptive environments.

References

Aalbers, M. B., & Gibb, K. (2014). Housing and the right to the city: Introduction to the special issue. *International Journal of Housing Policy*, 14(3), 207-213.

Carpo, M. (2017). *The second digital turn: design beyond intelligence*. MIT press.

Dyer, M., Corsini, F., & Certomà, C. (2017). Making urban design a public participatory goal: toward evidence-based urbanism. *Proceedings of the Institution of Civil Engineers-Urban Design and Planning*, 170(4), 173-186.

Gehl, J., & Svarre, B. (2013). *How To Study Public Life*. Washington, DC: Island Press/Center for Resource Economics.

Hall, E.T., (1966). *The Hidden Dimension*, 1st ed. Doubleday, Garden City, NY.

Hall, E.T., (1968). Proxemics. *Current Anthropology* 9, 83–108. DOI: 10.1086/200975. 35

Hanzl, M. & Ledwon, S. (2017). Analyses of human behaviour in public spaces. In: *Proceedings of Joint Conference ISOCARP-OAPA - 53rd ISOCARP Congress, Smart Communities,* Editors: Hongyang Wang & Slawomir Ledwon, Portland, Oregon, USA, October 24-27, 2017.

Hong Kong. Innovation Technology Bureau. Office of the Government Chief Information Officer, issuing body. (2017). *Hong Kong smart city blueprint*.

Jacobs, J. (1961). *The Death and Life of Great American Cities*. New York: Vintage Books.

Jhangiani, R. S., Chiang, I. C. A., Cuttler, C., & Leighton, D. C. (2019). *Research methods in psychology*. Kwantlen Polytechnic University.

Lefebvre, H. (1968). *Le droit a la ville*. Paris: Anthropos.

Low, S. (2000). *On the plaza: The politics of public space and culture.* Austin, TX: University of Texas Press.

Low, S. (2016). *Spatializing Culture: The Ethnography of Space and Place.* London, England; New York, New York: Routledge.

Low, S., Simpson, T. and Scheld, S. (2019). *Toolkit for the Ethnographic Study of Space (TESS)*, Public Space Research Group, Center for Human Environments, The Graduate Center, City University of New York.

Madanipour, A. (2003). Social exclusion and space. In R. LeGates, & F. Stout, *The city reader* (Third ed., pp. 181-189). London: Routledge.

Negroponte, N. (1969). Toward a Theory of Architecture, in *Journal of Architectural Education*, Blackwell Publishing on behalf of the Association of Collegiate Schools of Architecture, Inc., March 1969.

Negroponte, N. (1970). *The Architecture Machine*. Cambridge, Mass, MIT Press.

Negroponte, N. (1975). *Soft architecture machines.* Cambridge, Mass.: MIT Press.

Nisha, B., & Nelson, M. (2012). Making a case for evidence-informed decision making for participatory urban design. *URBAN DESIGN International, 17*, 336-348.

Pask, G. (1969). The architectural relevance of cybernetics. *Architectural Design*, 39(9), 494-496.

Ratti, C., & Claudel, M. (2016). *The city of tomorrow: Sensors, networks, hackers, and the future of urban life.* New Haven; London: Yale University Press.

Rowe, J. (1972). Life in a Computerised Environment, in *Electronics Australia*, September 1972.

Stamps, A. (2005). Isovists, enclosure, and permeability theory. *Environment and Planning B: Planning and Design.* 32. 735-762. 10.1068/b31138.

Steenson, M. (2017). *Architectural intelligence: How designers and architects created the digital landscape.* Cambridge, Massachusetts: The MIT Press.

Turner, A. (2007). UCL Depthmap 7: From isovist analysis to generic spatial network analysis. *New developments in space syntax software, Istanbul Technical University*, 43-51.

Turner, A., Doxa, M., O'sullivan, D., and Penn, A. (2001). From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and Planning B: Planning and design*, *28*(1), 103-121.

Whyte, W.H. (1980). *The Social Life of Small Urban Spaces.* Conservation Foundation, Washington, D.C.

Bio-Cyber-Physical 'Planetoids' for Repopulating Residual Spaces

Pierre Oskam [1,2,3], **Henriette Bier** [2,4], **& Hamed Alavi** [5]

[1] *University of Aveiro (Portugal)*
[2] *TU Delft (the Netherlands)*
[3] *University of Porto (Portugal)*
[4] *Politecnico Milano (Italy)*
[5] *University of Fribourg (Switzerland)*

Abstract

Minimal interventions that provide various microclimates can stimulate both biodiversity and social accessibility of leftover spaces. New habitats are often developed for different animal and plant species based on studies of the microclimates typical of such residual spaces. By introducing interventions of 0.5-1.0 m diameter 'planetoids' placed at various locations, existing and new life is supported. The 'planetoid' described in this paper is prototyped by means of Design-to-Robotic-Production and -Operation (D2RP&O). This implies that it is not only produced by robotic means, but that it contains sensor-actuator mechanisms that allow humans to interact with them by establishing a bio-cyber-physical feedback loop.

Keywords

Bio-cyber-Physical Systems, Computational Design, Robotic Production and Operation, Artificial Intelligence, Residual Space, Minimal Intervention

DOI

https://doi.org/10.47982/spool.2022.1.04

Context

In Europe, large swathes of built space have been abandoned. The abandonment is related to rapid programmatic changes due to deindustrialization, population ageing, migration, political and economic shifts, cultural reframing or ineffective planning (Accordino and Johnson, 2000; Haase, et al., 2016). As a consequence, a variety of spatial forms emerge, such as abandoned villages and industrial buildings, neglected agricultural land, polluted and exhausted mines, et cetera. The prevailing aggressive capitalist way of dealing with space leads to increased social polarization and a global decline in biodiversity which in turn fuels the increase in abandoned, unused places. A cost-efficient strategy is needed that can enrich those places for both human and non-human use.

The need to find low-cost solutions to improve the social and ecological value of residual places that do not involve large investments is addressed in this project by exploiting available on-site assets and digital technologies. Residual places may contain invisible but valuable assets such as unique animal and plant species (e.g. Laurie, 1979). Residual places provide opportunities for wildlife and spontaneous succession within the urban fabric (Kawata, 2014) by offering refuge for species displaced by intensive agriculture (Harrison & Davies, 2002; Kowarik, 2013; Schwarz, 1980). Residual places can introduce new opportunities for material and social interaction. The absence of rules brings about a sense of freedom, creating a place of possibility while hosting various forms of interaction, such as artistic creation, adventurous play, and exploration (Edensor, 2005). The 'emptiness' of those places offers an alternative to the often overcrowded, predictable spaces of the city, providing scope to question the over-regulated way that contemporary urban space is formed (Edensor, 2005). The challenge is to find solutions that improve the socio-ecological value of such places without requiring large investments.

FIGURE 1 *Minimal interventions in leftover spaces have the potential to stimulate biodiversity and social accessibility.*

Site Interventions

A possible strategy to enhance residual spaces is to apply 'minimal interventions' (Lassus, 1998) that could stimulate both biodiversity and social accessibility. Such 'minimal interventions' trigger transformation in the spatial experience. The interventions resemble miniature planets, as they are roughly spherical and have at least partially differentiated interiors (Schmidt et al., 2007). The 'planetoids' take the form of 0.5-1.0 m diameter artefacts (Fig. 1) large enough to relate to the architecture of the site and small enough to be easily handled by humans. Their porosity contributes to the development of ecosystems by hosting a wide number of species. They support the life that already exists at the location, but they also attract new life. They provide opportunities for unforeseen interactions and, therefore, for the ‘unintended’ to happen (Oskam and Mota, 2020).

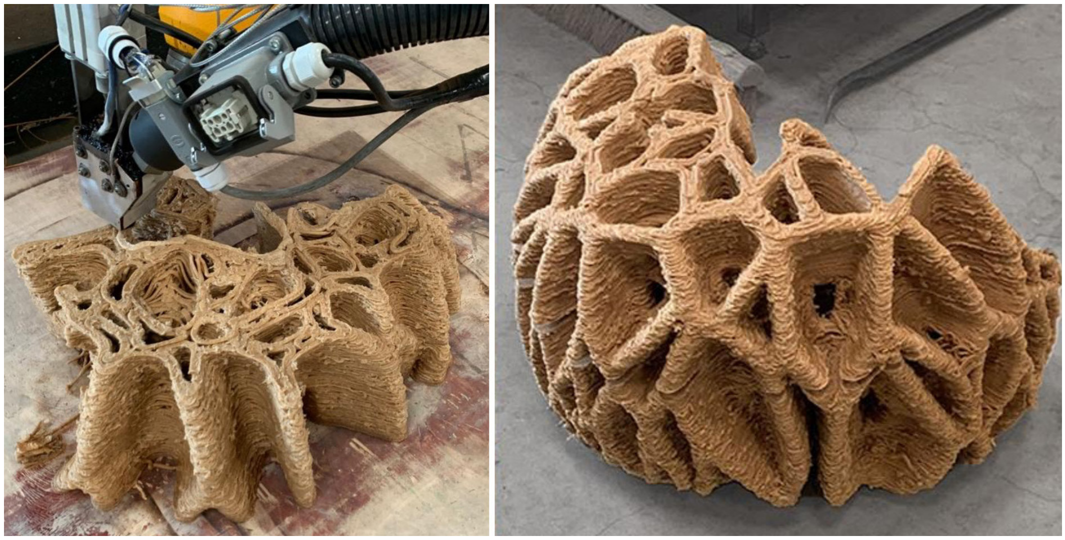


FIGURE 2 *D2RP process (left) and robotically 3D printed fragment of the ‘planetoid’ (right)*

Inside the ‘planetoids’, room is made for earth, plants and insects, small animals. The ‘planetoids’ interact with the conditions on site by serving as ‘sponges’ to preserve water, store heat from the sun, et cetera. The hull is made to a large degree from biodegradable materials. Their material properties represent various temporal realities: some may exist for weeks, months or years, others may last for several decades and may be overgrown by plants. Others may dry out or fall apart and become the genesis of new life in the soil. In order to interact with the process, the hulls contain sensors that show location, temperature, humidity, et cetera. Data is recorded and shared via the Internet, where changes detected in the ‘planetoids’ are visualized on a mobile application. The recorded data is made accessible to a wider audience via notifications, such as when the soil with plants needs to be watered by neighbours or passers-by. By watering them the humans interact with the ‘planetoids’ and this interaction is acknowledged by means of visual and/or audio feedback. This feedback loop between the ecological and socio-technical systems requires Design-to-Robotic-Production and -Operation (D2RP&O) approaches.

Design-to-Robotic-Production and -Operation

The D2RP&O processes (Bier et al., 2018) employed for prototyping the planetoid involve two aspects. While D2RP is implemented by means of parametric design and robotic production involving 3D printing with biopolymers using wood fibres[1] (Fig. 2), D2RO is introduced for integrating sensor-actuators in order to track the temperature and humidity of the microclimates within and around the ‘planetoids’. The overall shape is informed by the various functionalities of the ‘planetoid’, from hosting plants, insects and small animals to

1 Robotic Building website: http://www.roboticbuilding.eu/project/d2rp-for-product-from-landscape-microruin-lab/

harbouring sensor-actuators and interacting with humans. These functionalities require a material design that accommodates variable sizes, densities and structural performances. Hence, an adaptive Voronoi mesh approach is adopted (Fig. 3).

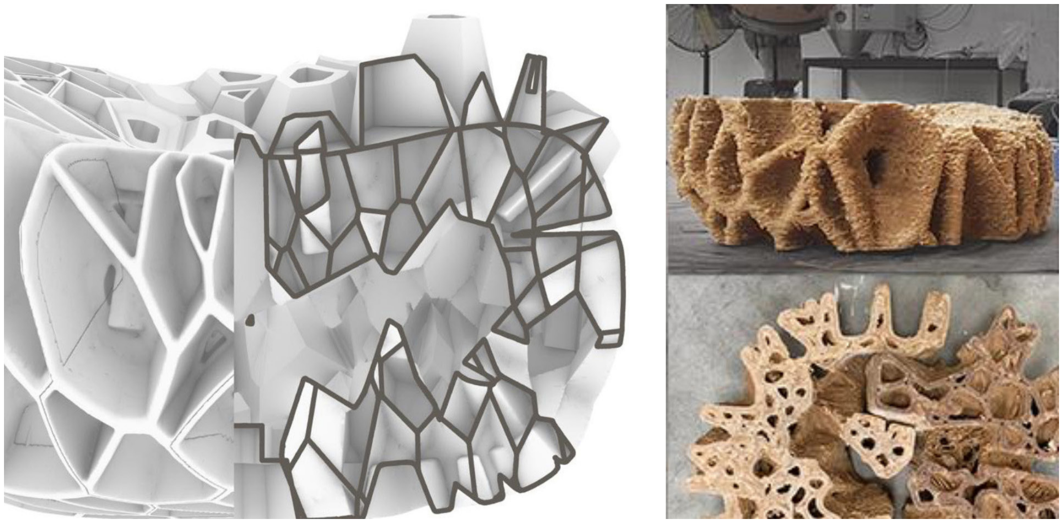


FIGURE 3 *The Voronoi structure facilitates the creation of convex and concave areas that offer opportunities for capturing or repelling sun and rain and fostering animal and plant species.*

While the D2RP part has already been completed (Figs. 1 and 2) the D2RO is still a work in progress. With the Voronoi (Fig. 3) creating the surface tectonics as well as the interior structure, which hosts the protected environment for animals and seed balls that develop into plants, the 'planetoid' creates opportunities for animal and plant species to dwell and grow. Depending on the location, the surface tectonics are designed to create 'craters' and 'volcanoes' that capture or repel sun and rain. Multiple plants grow from a single 'planetoid' and multiple sensor-actuators are integrated into the 'planetoid'. Data is streamed to an app, which notifies users/potential visitors in real time and 'invites' them to interact with the 'planetoids' and their microclimates by irrigating or weeding them, even relocating them. Additional sensor-actuators are envisioned to track human movement and playfully facilitate interaction.

Sensor-actuator system

The integrated sensor-actuator system consists of various components that require further definition:

A Sensing modules: each sensing module carries a unique identifier, defining its function as well as modes of functioning, including frequency of data collection and communication. Each 'planetoid' hosts several sensing modules, which can be added, maintained and modified individually. The sensors require a remarkably low amount of energy and can operate on a battery for several months.

B One gateway collects, via Bluetooth, the data transmitted by all the sensing modules in its physical proximity. It broadcasts the sensor data, along with the identifier of the sensing module, to the LTE urban antenna. The transmitted data also contains information about the cloud service associated with this set-up as well as the credentials to access the cloud database.

C LTE (Long-Term Evolution) networks that are available in most European cities via various commercial providers.

D Through the MQTT protocol the cloud database 'subscribes' to receive the data collected by sensing modules with certain identifiers. The data will be stored and made available for queries via any web-based application.

E Data made accessible to the users through either the QR code associated with the 'planetoid', or simply its placement. Gamified presentation of data is intended to be engaging and to lead to action.

In the future, the 'planetoid' will develop learning capacities in order to predict moments – depending on the patterns of human and non-human activities around the planetoids – when opportunities arise for interaction with the evolving nature (vegetation, insects, etc.) and humans. K-means and Hierarchical Clustering (HC) as established Artificial Intelligence (AI) methods will be applied to discern correlations between presence, movement, actions and weather variables, in order to be able to offer structured predictions of opportune interaction moments and to promote them through the app.

While interaction scenarios between 'planetoids' and humans have been sketchily outlined, an in-depth study of the implementation and scalability of the system requires further consideration. The goal is to engage users in interactive experiences that can realize some of the potentials of abandoned areas as public urban spaces. The system will be able to sense environmental parameters such as temperature, humidity and light, as well as information related to the presence and movements of humans, animals and insects around the 'planetoids'. The main actuation will be in the form of mobile application notifications informing the inhabitants about the emerging activities around the planetoids or the need for their action such as watering the plants. Additional actuation is envisioned in form of lights (Fig. 4) and sounds that could engage visitors in a playful manner.

Discussion

Socio-technical interventions made in natural environments in order to improve bio-diversity are not new. Various projects involving artificial reefs and 3D printed scaffolding for micro-organisms (Gautier-Debernardi et al., 2017) have shown that eco-friendly solutions can meet the needs for increasing bio-diversity in various natural environments. Such systems are employed in natural environments that lack biodiversity and seem incapable of recovering on their own.

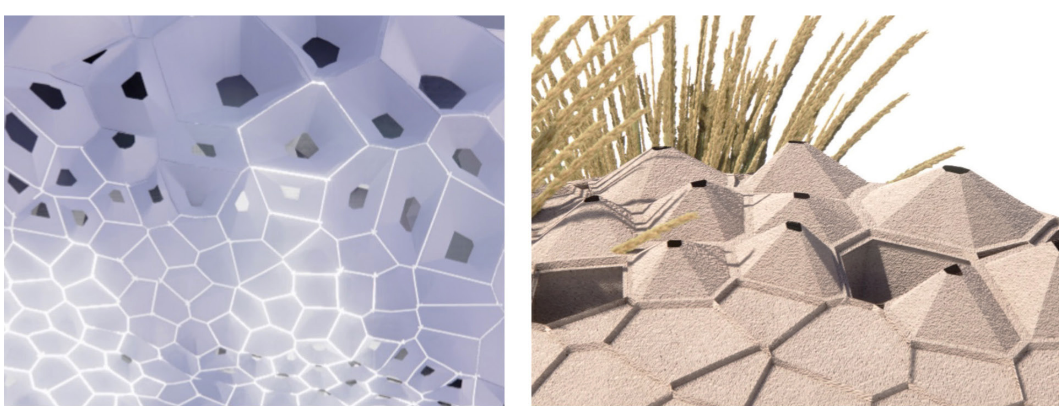


FIGURE 4 *Sensor-actuators (proximity sensor and light actuator) integrated in the Voronoi structure.*

The prototype described in this paper employs socio-technical systems not only to improve biodiversity but also to increase human–nature interaction as well as social acceptability and accessibility of leftover spaces. The expectation, based on studies of the micro-climates prevalent in the respective leftover space, is that the first prototyped 'planetoid' will establish new habitats for various animal and plant species. The development over time will be monitored and recorded on the 'bio-cyber-physical planetoid' app and results will be published in due course. The main hope is that by inviting potential visitors to irrigate the 'planetoids' or protect them from the sun, or playfully engage with them, a bio-cyber-physical feedback loop will be established, thus contributing to sustainable urbanism.

The novel opportunities offered by cybernetic social-ecological systems involve AI and rely on its ability to, in this case, identify correlations between the evolving nature, weather variables and the actions of humans in order to be able to offer structured prediction of opportune interaction moments and to promote them through open-access, web-based platforms and mobile applications. The established bio-cyber-physical feedback loop frames human and non-human agents as co-creators of processes and events in which agency is not attributed to one or the other but emerges in the interaction between them.

Acknowledgements

This project has been funded by the Dutch Research Council, the Creative Industries Fund NL and FCT Portugal (Fundação para a Ciência e Tecnologia) and has profited from the contribution of the 'Microruin Lab',[2] ID+ Research Institute for Design, Media and Culture. The D2RP&O process was developed in the Robotic Building lab by researchers and students participating in the 'Bio-cyber-physical Planetoids' and 'Cyber-physical Space' projects.[3] The robotic 3D printing employed the 3D Robot Printing system while the sensor-actuator system was provided by Starnberger Innovation and Technology.

2 Microruin Lab project: https://stimuleringsfonds.nl/nl/toekenningen/microruin_lab/

3 Cyber-physical Space wiki: http://cs.roboticbuilding.eu/index.php/Shared:FinalG1

References

Accordino, J., and Johnson, G. T. (2000). Addressing the Vacant and Abandoned Property Problem. *Journal of Urban Affairs*, *22*(3), 301–315. https://doi.org/10.1111/0735-2166.00058

Bier, H., Cheng, A. L., Mostafavi, S., Anton, A., and Bodea, S. (2018). Robotic Building as Integration of Design-to-Robotic-Production and -Operation. In H. Bier (Ed.), *Robotic Building* (pp. 97–120). Springer International Publishing. https://doi.org/10.1007/978-3-319-70866-9_5

Edensor, T. (2005). *Industrial Ruins: Space, Aesthetics, and Materiality*. Bloomsbury Academic.

Gautier-Debernardi, J., Francour, P., Riera, E. and Dini, E. (2017). The 3D-printed artificial reefs, a modern tool to restore habitats in marine protected areas. The Larvotto-Monaco context. *Proceedings of International Marine Protected Areas Congress Chile 2017*.

Haase, A., Bernt, M., Großmann, K., Mykhnenko, V., and Rink, D. (2016). Varieties of shrinkage in European cities. *European Urban and Regional Studies*. https://doi.org/10.1177/0969776413481985

Harrison, C., and Davies, G. (2002). Conserving biodiversity that matters: practitioners' perspectives on brownfield development and urban nature conservation in London. *Journal of Environmental Management*, *65*(1), 95–108.

Kawata, Y. (2014). Need for Sustainability and Coexistence with Wildlife in a Compact City. *International Journal of Environmental Science and Development*, *5*(4), 357.

Kowarik, I. (2013). Cities and Wilderness. *International Journal of Wilderness*, *19*(3).

Lassus, B. (1998). *The Landscape Approach*. University of Pennsylvania Press.

Laurie, I. C. (1979). *Nature in cities: the natural environment in the design and development of urban green space LK - https://tudelft.on.worldcat.org/oclc/3361580*. Wiley.

Oskam, P. Y., and Mota, J. A. (2020). Design in the Anthropocene: Intentions for the Unintentional. In *International Conference on Design and Digital Communication* (pp. 269–279). Springer.

Schmidt, B.; Russell, C.T.; Bauer, J.M.; Li, J.; McFadden, L.A.; Mutchler, M.; et al. (2007). 'Hubble Space Telescope Observations of 2 Pallas'. Bulletin of the American Astronomical Society.

Schwarz, U. (1980). *Der Naturgarten: mehr Platz für einheimische Pflanzen und Tiere*. Krueger W.

Indoor Air Quality Forecast in Shared Spaces– Predictive Models and Adaptive Design Proposals

Hamed Alavi, Sailin Zhong, & Denis Lalanne

University of Fribourg, (Switzerland)

Abstract

The high concentration of air pollutants in indoor environments can have a remarkable adverse impact on health and well-being, cognitive performance and productivity. Indoor air pollutants are especially problematic in naturally ventilated shared spaces such as classrooms and meeting rooms, where human-generated pollutants can rise rapidly. When the inhabitants are exposed to indoor air pollution, recovering from its ramifications takes time and harms their well-being in the long run. In our approach, we seek to predict and prevent such hazardous situations instead of rectifying them after they happen. The prediction and prevention are accomplished through algorithms that can learn from the evolution of air pollutants and other variables to indicate whether or not a high level of pollution is forecast. We present two AI-enabled methods, one providing the forecast for the concentration level of carbon dioxide in the next 5 and 20 minutes with 86% and 92% accuracy. The second algorithm provides predictive indicators about how the CO_2 level will evolve during the upcoming session (meeting or a course) before the session starts. We will discuss design implications and present design proposals on how these methods can inform interactive solutions for preventing high concentrations of indoor air pollutants.

Keywords

Indoor Environmental Qualities, Quantified Buildings, Human-Building Interaction, Indoor Air Quality, Predictive Models

DOI

https://doi.org/10.47982/spool.2022.1.05

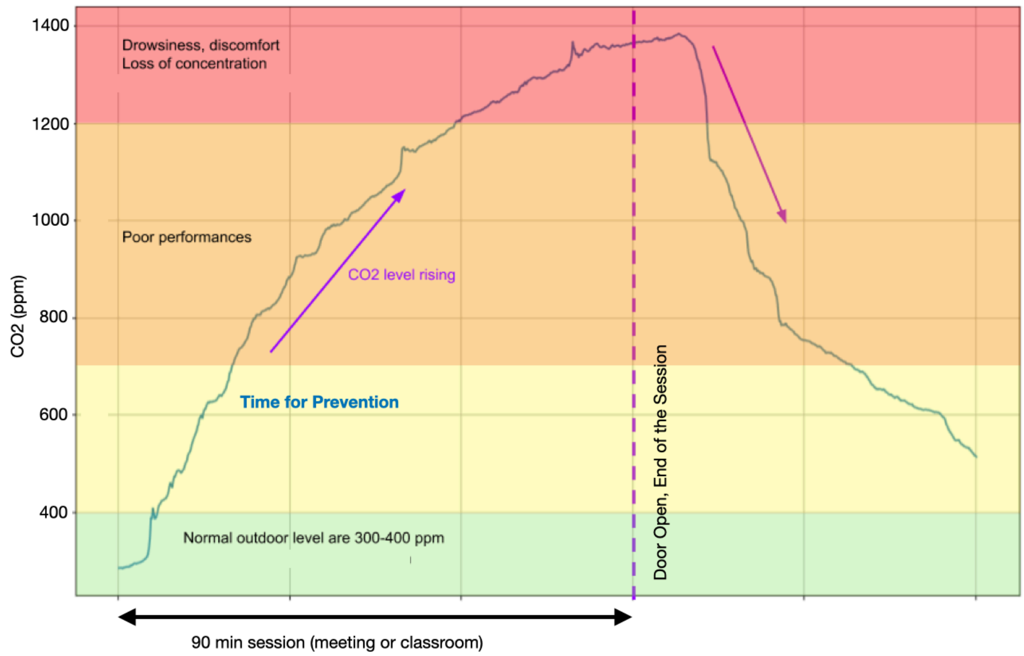


FIGURE 1 The high concentration level of CO_2 in meeting rooms is a common problem with health and productivity adverse consequences.

Introduction and Motivation

Evidence for direct links between exposure to high levels of carbon dioxide concentration and problems such as lethargy, headache, and cardiac arrhythmia, as well as difficulty in retaining attention, concentration, and cognitive performance, have been repeatedly presented in previous studies (e.g. Apte and Erdmann, 2002; Fisk, 2010; Erdmann et al. 2002; Griffiths and Eftekhari, 2008). These health impacts reoccur commonly in shared closed spaces such as open-plan office spaces, conference halls, and classrooms. For example, a recent study of more than 100 schools in Switzerland revealed that students suffer in more than two-thirds of the learning spaces from a high concentration of carbon dioxide (Swiss Federal Office of Public Health, 2016). Research in this area builds on the Indoor Environmental Qualities (IEQ) literature that developed standards and quality norms for an acceptable range of parameters and architectural design guidelines to ensure those norms (e.g. Frontczak and Wargocki, 2011, Burge, 2014, Redlich, 1997). However, it is only recently that studies of comfort in buildings consider the role of humans as active users of buildings.
The new research directions also seek to explore the opportunities that new methods of sensing, actuation techniques, and, more broadly, data science can bring to the problem of indoor air quality (Alavi et al. 2017, Hsu et al. 2018, Meurer et al. 2019). Our research pursues a similar human-centric perspective enabled by data-oriented methods. We examine a novel approach in which the objective is to predict and prevent situations of discomfort rather than rectifying them after they occur. Two reasons motivate this preventive approach: (1) recovering from discomfort exhausts time, and cognitive effort, (2) regular exposure to situations that are even mildly uncomfortable can harm health in the long term.
It is worth noting that carbon dioxide is a common indicator for assessing ventilation efficiency and consequently the overall indoor air quality; particularly, it is a surrogate for the indoor concentration of occupant-generated pollutants. That is why our research focuses on the prediction of CO_2 concentration levels.
In this chapter, we present two methods of forecasting the evolution of carbon dioxide in naturally ventilated indoor environments, evaluate their performance, and conclude with a discussion of how to integrate them in a design solution.

Real-Time Forecast

The primary source of carbon dioxide indoors is human respiration, and thus its concentration is directly related to the number of people in a room. Nevertheless, the level of CO_2 in the air is also affected by many other variables such as room size, ventilation rate, relative humidity, and outdoor air quality (e.g. Fang et al. 1998). Since measuring all of these parameters entails heavy instrumentation of the environment and its inhabitants, we aim to develop a prediction model that can function independently of their variations. More precisely, the goal is to develop and compare real-time prediction algorithms that can indicate whether or not the CO_2 level in a room will exceed a threshold solely based on previous measurements of carbon dioxide in the same office.

We can predict the level of carbon dioxide in office space by determining the likelihood L that after a time interval Delta T the concentration of carbon dioxide molecules in the air will exceed a value V. To do so, we examined Autoregressive (AR) and Autoregressive Integrated Moving Average (ARIMA) on CO_2 measurements collected in shared office spaces and meeting rooms. We can gather the data by sensing systems that we have developed in collaboration with an industrial partner (see Figure 2), logging the concentration of air pollutants every five seconds. In addition, we examined Long Short-Term Memory (LSTM) – a recurrent neural network architecture – in which the problem was formulated as multiple parallel input and multi-step output case. To evaluate and compare the performance of the models, we consider two parameters: (1) the accuracy of prediction verified by the actual values and (2) the time required for training the model.

FIGURE 2 Two sensing devices that we developed for recording the concentration of various indoor air pollutants. Connected to these devices, smartwatch and phone applications are provided to make available the live prediction of indoor air quality..

We computed the accuracy of a prediction based on the percentage of predicted values that fall within the confidence interval around the actual value with the confidence interval fixed to 30 ppm, based on the technical error range of the sensor. The model's overall accuracy is the average accuracy of all instances of prediction executed on one day of data (four devices, 12 times prediction per hour, 10 hours, and excluding the last 20 minutes). We used a sliding window to test the AR and ARIMA models: an observation buffer to build the model to predict the CO_2 concentration in the next Delta T minutes.

We tested combinations of observation buffer sizes of 10 and 20 minutes and Delta T of 5, 10, and 15 minutes. In all performed tests, the Autoregressive (AR) model outperformed the other methods, both in terms of accuracy and in training time. Using AR and a buffer size 20 minutes, we have achieved 97.66% accuracy of prediction for Delta T = 5 minutes and 87.51% for Delta T = 20 minutes.

Pre-session Prediction

This section explores the opportunities to predict the evolution of air quality much more in advance: before a meeting (or a classroom session) starts. Instead of predicting the value of CO_2 concentration level, the objective is to predict how the CO_2 level will evolve during the upcoming session based on parameters such as the size of the room, number of participants, outdoor weather, time of the day, and so forth. In the first step, applying hierarchical clustering on the data collected from more than 1000 meeting sessions in 26 meeting rooms , we distinguished seven patterns of evolution of CO_2. Each pattern is identified by the initial value and the coefficient of the rise during the first and second half of the session. The data used in this part were collected using CO_2 sensors developed by an industrial partner, installed on the meeting room desks, logging CO_2 values every 10 seconds during five months. More than 300 employees in a naturally ventilated building used the meeting rooms of various sizes during sessions of typically around one hour long.

In the second step, we search for a combination of external parameters that can suggest which of the seven patterns will occur in the upcoming session. This has been accomplished using Linear Discriminant Analysis (LDA) on a list of parameters including size of the room, number of occupants, indoor conditions (temperature, humidity, light, etc.), outdoor conditions (temperature, humidity, luminosity, wind speed, etc.), time of the day, as well as the concentration level of indoor air pollutants before the session.

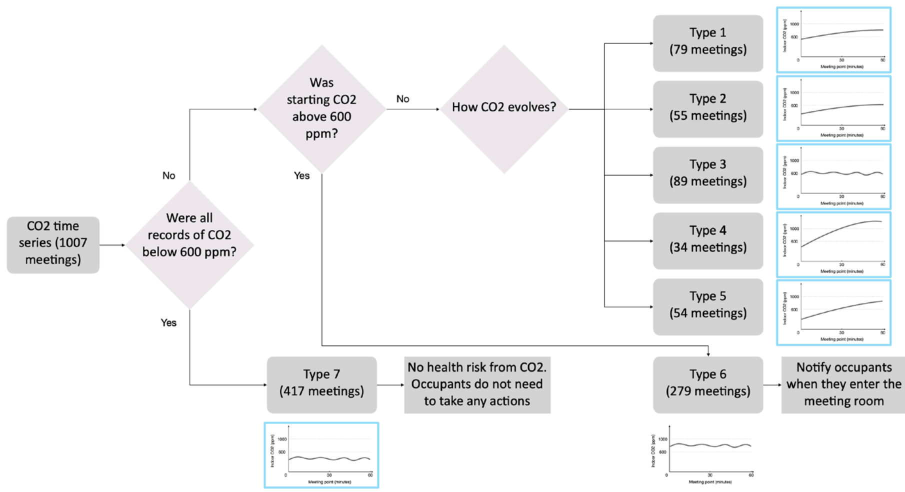
The results suggest certain indications – in the form of a combination of external parameters – that can specify which of the seven patterns of CO_2 evolution is most likely to occur in the upcoming session (Zhong et al. 2021). This can be particularly helpful in social situations when interrupting the session (meeting or lecture) to deal with environmental qualities that can harm productivity or may not be appropriate. In the next section, we describe how the coupling of the two predictive methods informs a design solution that can unobtrusively integrate into the social context of shared spaces.

From Prediction to Prevention: An Interactive Design Proposal

Once a high concentration of air pollutants is forecasted, it needs to be communicated with the users to take preventive action (e.g. opening a window). However, such notifications, particularly in cooperative work situations, can disrupt the workflow and eventually be counterproductive and substantially reduce the adoptability of the solution. Building on the two predictive algorithms presented in the last sections, the design solution that we develop seeks to find the right moment to notify the users to minimise the interruption cost and maximise the long-term impact. Figure 3 demonstrates how the interaction with the users is intelligently determined before and during a cooperative work or learning session. In a nutshell: depending on the likelihood that the level of CO_2 passes the healthy threshold during the upcoming session, the users would be made aware of the prediction and the solution that can prevent the hazardous situation (operating one of the room openings for how long). In cases where the pre-session prediction does not provide an adequately high level of certainty, the real-time prediction provides notifications through various modalities, including ambient interfaces. The decision on whether or not the users should be notified before the session is informed by:

A the predictive models that anticipate the risk of high levels of CO_2 pollution in the upcoming session (i.e. the pattern of evolution of CO_2), and
B the design of the notification system during the session, informed by the predictive models (AR) that with high accuracy estimated the level of CO_2 in the next 5 to 20 minutes.

1. Classifying the pattern of CO2 Evolution



2. Determining external indicators for each pattern

Feature	Test	p-value
indoor_co2	ANOVA	< 2.2E-16***
co2_last_5min_slope	ANOVA	0.04067*
occupancy_calendar	ANOVA	< 2.2E-16***
attendee_diff	ANOVA	3.185e-14 ***
snow_1h	ANOVA	0.03336 *
Gaz(i)	ANOVA	4.826e-06 ***
Light(i)	ANOVA	0.003428 **
room_size	ANOVA	.033e-05 ***
Hour of the day	ANOVA	0.01064 *
Day of the week	ANOVA	0.003742 **
floor	χ^2	0.001499 **
is_a_meeting_bf	χ^2	0.004498 **
Win facing	χ^2	0.0009995 ***

3. Interaction style based on social and physical context

FIGURE 3 When a high level of CO_2 is forecasted, the design solution determines whether or not to notify the users. The notification can occur before or during the session. That depends on the predicted evolution pattern of CO_2 among the seven patterns.

Conclusion

This contribution presents a preventive approach to the problem of poor indoor air quality in shared spaces. The broad objective is to predict the situations where the concentration of air pollutants, particularly carbon dioxide, may harm the well-being or cognitive performance of the occupants and inform them through interaction mechanisms that minimise the disruption caused by the awareness/notification system.
To that end, we have developed a predictive model that can, with very high accuracy, indicate whether or not the level of CO_2 would be higher than a certain threshold in 5 minutes. Furthermore, a second predictive model can specify before a collaborative session starts the pattern of evolution of CO2 during that session. Combining these two algorithms enabled a solution that can notify the users when action is needed while reducing the interruption costs.

Acknowledgements

The Swiss Agency for Innovation Promotion (Innosuisse) financed the research, conducted within the framework of the Smart Living Lab project in Fribourg, Switzerland.

References

Alavi, H. S., Verma, H., Papinutto, M., & Lalanne, D. (2017). Comfort: A Coordinate of User Experience in Interactive Built Environments. Human-Computer Interaction – INTERACT 2017, 247–257. https://doi.org/10.1007/978-3-319-67687-6_16

Apte, M. G., & Erdmann, C. A. (2002). Indoor carbon dioxide concentrations, VOCs, environmental sensitivity association with mucous membrane and lower respiratory sick building syndrome symptoms in the BASE study: analyses of the 100 building dataset. Lawrence Berkeley National Laboratory (LBNL) Report, 51570.

Burge, P. S. (2004). Sick building syndrome. Occupational and Environmental Medicine, 61(2), 185–190. https://doi.org/10.1136/oem.2003.008813

Erdmann, C. A., & Apte, M. G. (2004). Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset. Indoor Air, 14(s8), 127–134. https://doi.org/10.1111/j.1600-0668.2004.00298.x

Fang, L., Clausen, G., & Fanger, P. O. (1998). Impact of temperature and humidity on the perception of indoor air quality. Indoor air, 8(2), 80-90.

Fisk, W. J. (2010). CO_2 monitoring for demand controlled ventilation in commercial buildings. https://escholarship.org/uc/item/4bk4x479

Frontczak, M., & Wargocki, P. (2011). Literature survey on how different factors influence human comfort in indoor environments. Building and Environment, 46(4), 922–937. https://doi.org/10.1016/j.buildenv.2010.10.021

Griffiths, M., & Eftekhari, M. (2008). Control of CO_2 in a naturally ventilated classroom. Energy and Buildings, 40(4), 556–560. https://doi.org/10.1016/j.enbuild.2007.04.013

Hsu, Y. C., Cross, J., Dille, P., Tasota, M., Dias, B., Sargent, R., Huang, T. H. K., & Nourbakhsh, I. (2019). Smell Pittsburgh. Proceedings of the 24th International Conference on Intelligent User Interfaces. https://doi.org/10.1145/3301275.3302293

Meurer, R. S., Frohlich, A. A., & Hubner, J. F. (2018). Ambient Intelligence for the Internet of Things Through Context-Awareness. 2018 International Symposium on Rapid System Prototyping (RSP). https://doi.org/10.1109/rsp.2018.8631989

Redlich, C. A., Sparer, J., & Cullen, M. R. (1997). Sick-building syndrome. The Lancet, 349(9057), 1013–1016. https://doi.org/10.1016/s0140-6736(96)07220-0

Swiss Federal Office of Public Health. (2016, January 5). Insucient air quality in two- thirds of the classrooms in Switzerland. The Federal Council. https://www.admin.ch/gov/fr/accueil/ documentation/communiques.msg-id-74177.html.

Zhong, S., Lalanne, D., & Alavi, H. (2021). The Complexity of Indoor Air Quality Forecasting and the Simplicity of Interacting with It – A Case Study of 1007 Office Meetings. Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems. https://doi.org/10.1145/3411764.3445524

www.spool.ac

ISBN 978-94-6366-570-4