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Towards a Convivial Built Environment: Developing an Open Construction Systems Framework

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Christina Priavolou

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CHRISTINA PRIAVOLOU

Contents

List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I   Pantazis, A., & **Priavolou, C.** (2017). 3D printing as a means of learning and communication: The 3Ducation project revisited. *Telematics and Informatics*, *34*(8), 1465–1476. **ETIS 1.1**.

II   **Priavolou, C.** (2018). The emergence of open construction systems: A sustainable paradigm in the construction sector? *Journal of Futures Studies*, *23*(2), 67–84. **ETIS 1.1**.

III **Priavolou, C.**, & Niaros, V. (2019). Assessing the openness and conviviality of open source technology: The case of the WikiHouse. *Sustainability*, *11*(17), 4746. **ETIS 1.1.**

IV **Priavolou, C.** (2020). To BIM or not to BIM? Lessons learned from a Greek vernacular museum building. *AIMS Environmental Science*, *7*(2), 192–207. **ETIS 1.1**.

Author's Contribution to the Publications

The author's contribution to the papers in this thesis is:

I   The author dealt with the investigation of the learning and communication potential of 3D printing through a participatory action research project. The author contributed to the following processes: designing the study, structuring the questionnaire, performing the analysis, and composing the manuscript.

II The author explored the challenges and opportunities of Open Construction Systems (OCS) with regard to technological, institutional, and social perspectives. The findings are intended to trigger discussions around sustainability in buildings and delineate the concept of OCS as a promising solution to sustainable building construction.

III The author performed in-situ investigations, including data gathering, field observations, and participation in the construction of a WikiHouse. The authors analyse the relationship between the concepts of openness and conviviality with the "Design Global, Manufacture Local" model. The author's contribution lies in conducting the field work, as well as in writing the manuscript.

IV The author implemented Building Information Modelling (BIM) technology for the architectural design and the energy analysis of a vernacular museum building. The aim was to critically assess the potential of BIM technology to grasp and analyse building information.

Abbreviations

BIM	Building Information Modelling
CNC	Computer Numerically Controlled
DGML	Design Global, Manufacture Local
ICT	Information Communication Technologies
LCA	Life Cycle Assessment
MCT	Matrix of Convivial Technology
OBS	Open Building Systems
OCS	Open Construction Systems
3D	3 dimensional
2D	2 dimensional

Explanations of abbreviations used in the thesis.

Introduction

I have spent most of my life in a mountainous region in north-western Greece. I strongly recall narrations by individuals who were striving to build their own houses with scarce resources being helped by family members and fellow residents, as my grandparents were. Observation and improvisation were key features that fostered these groups to build resilient structures.

During my university studies as a civil engineer, I realised how unsustainable current building production methods are. This view intensified when I started practising my occupation. At that time, I was sceptical about the notion of large companies' activities dominating construction activities, leaving little room for the involvement of end users in the construction process. Further, having used design software consistently throughout my Bachelor studies, I grasped the importance of technological design tools in monitoring and enhancing building performance.

I thus turned my attention to sustainable construction methods. In this direction, after completing my Masters degree in environmental studies, I decided to explore open-source software and experiment with open hardware. Through my interaction with like-minded individuals, I came across a novel model of collaborative production that utilises two key elements: technological tools and vernacular knowledge[1]. Such a convergence is made possible through the Design Global, Manufacture Local (DGML) model.

The theoretical position of this thesis lies at the intersection of social science and engineering. Its impetus has arisen from the need for sustainable construction practices emerging from the housing crisis (Timmer et al., 2019). The focus is placed on investigating the manifestation of the DGML model in the construction sector. In this regard, I use the term "open construction systems" (OCS) to describe a set of connected things and devices that operate together in designing globally and manufacturing locally buildings. These things and devices include the equipment, information resources, legal frameworks, and community practices required to enable the production of buildings based on the DGML model. Hence, apart from the building itself, emphasis is placed on the ecosystem around the building structure.

Although the DGML model presents an inherent capability to foster sustainability, limited scientific research has been conducted to assess its sustainability potential (Kohtala, 2015; Kostakis et al., 2016). The main objective of this thesis is to provide a preliminary evidence-informed understanding of the conviviality[2] dynamics of OCS. The links between conviviality and sustainability are discussed, as well as the need to leap into conviviality in order to enable self-managed communities to materialise their vision of producing built-environment structures in an autonomous and human-centred way.

The ultimate research question addressed in this thesis is: How could OCS provide a convivial alternative to the conventional construction approach? Some secondary research questions follow:

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[1] Knowledge that comes from shared understandings of natural occurrences happening in local settings.

[2] An intrinsic ethical value that correlates with "individual freedom realised in personal interdependence" (Illich, 1973, 24).

- What conviviality traits can be traced in OCS?
- What is the learning and communication potential of producing DGML artefacts for the built environment? (**I**)
- What are the emerging challenges and opportunities of OCS? (**II; III**)
- How convivial and open are OCS? (**III**)
- What are the strengths and weaknesses of using BIM technology for the design and analysis of vernacular structures[3]? (**IV**).

The thesis builds on four original articles. The development of the concept of OCS is the main theoretical contribution of this thesis, as well as the exploration of its conviviality potential as exemplified in its current seed form (**II**). OCS were studied from multiple perspectives, ranging from their educational and openness dynamics (**I; III**) to their technological and institutional potential (**II; IV**), while both quantitative (**III**) and qualitative approaches (**II; III**) were employed. These studies indicate how OCS are being formed and what are their strengths and challenges towards fostering conviviality in the construction process through distributed modes of transdisciplinary co-production.

The results of my research were approbated via scientific publications, conference presentations, workshop presentations, and PhD seminars. The publications I contributed to are related to Information and Communication Technologies (ICT), sustainability, environmental science, and future studies. All of them were peer-reviewed articles published in international journals.

The remaining part of the thesis is structured as follows. I discuss sustainability-related issues in the construction sector, stressing the need for alternative construction practices and introducing conviviality as the basis for meaningful transdisciplinary practices in the construction sector. I elaborate on the Matrix of Convivial Technology as a normative schema used to assess social, environmental, and economic elements associated with the production of technologies. I then present vernacular structures as an enlightening source for convivial construction practices. Next, the methodological approach followed is analysed and the DGML model is explained with emphasis placed on OCS as a manifestation of the DGML model in the construction sector. Finally, I explain how three core elements observed in the development of OCS enhance the conviviality potential of OCS. The thesis culminates in a summary of the conclusions.

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[3] Structures that utilise local materials and knowledge, usually constructed without the supervision of professional architects.

1. Moving Towards a Convivial Built Environment

1.1. Sustainability in Conventional Construction Practices

So far in the public discourse, there is a wide range of sustainability conceptualisations. The concept of sustainability was first introduced in forest management in 1713 to indicate a harvesting practice that can be maintained for generations, considering the natural regeneration of forests (Kuhlman & Farrington, 2010). The concept was subsequently used to raise environmental awareness at a global level (Meadows, 1972). Sustainable development has been ambiguously defined as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987; Purvis et al., 2019). Today, a mixture of environmental, social, and economic elements coexist in the concept of sustainability (Carter & Rogers, 2008; Zabihi et al., 2012). These elements are known as the three pillars of sustainability (Purvis et al., 2019).

The importance of enhancing environmental sustainability in the construction sector is indicated by the high impact of this sector on the environment. The construction of building structures accounts for 39% of global carbon emissions (Abergel et al., 2017; Rode et al., 2011). Most of the emissions arise from operational processes, while around 11% of them come from the embodied energy in construction processes and materials. Further, huge amounts of natural resources are used in building constructions. Indicatively, 50% of global water resources is consumed by building construction while 60% of global materials resources are used for buildings and roads (Dixon Group, 2010). Considering the contribution of the construction sector to carbon emissions, the role of technological design tools is viewed as crucial to improve energy analysis processes and enhance critical design decisions (Cho et al., 2011).

Moreover, the latest eruption of the housing bubble in 2006 has revealed the need for affordable housing (Hansen, 2013; Holt, 2009). Among its socio-economic implications, the consequent scarcity of housing through increasing land and house prices is evident, leading to increased homelessness and low and middle-income individuals without adequate housing (Kothari, 2005; De la Paz & Juárez, 2012; Parvin, 2013). The economic efficiency of the construction sector within the conventional production model is hindered by low productivity rates, which in turn affect the prices of buildings (Abdel-Wahab & Vogl, 2011). Additionally, the quality of the built structures is usually disregarded in pursuit of maximising economic gains (Du Plessis, 2002).

Social sustainability is considered to be the most significant target of sustainable development in the construction sector (Yılmaz & Bakış, 2015). It focuses on securing the basic human right to adequate housing (Hui, 2002; Sachar, 1993). In the conventional production model, our increasing reliance on large construction companies to produce buildings has favoured the establishment of a producer-consumer relationship that restricts the engagement of individuals in the construction process, infringing on the human right to housing (Larson et al., 2004; Parvin, 2013). Further, high rates of gender discrimination and corruption, as well as labour-intensive and monotonous activities have been observed in contemporary construction practices (Du Plessis, 2002).

The abovementioned analysis indicates the detrimental effects of conventional construction practices on the three pillars of sustainability (i.e. environmental, economic, and social elements). Despite the identification of these issues, construction practices have barely changed during the last six decades (Marshall & Worthing, 2006; McKinsey

Global Institute, 2017; Eastman et al., 2011). Resistance to change existing practices, lack of government incentives, and high costs of adopting new technologies and methods are some of the reasons to blame for slow changes in construction practices. On the contrary, instead of seeking to address burning sustainability-related issues within the construction sector, architects direct attention to the wrong side.

More specifically, the international homogenisation of the built environment nowadays has mainly resulted from the diffusion of ideas and practices through the rise of large-scale urban development projects, cultural globalisation, market liberalisation, and migration (Guggenheim & Söderström, 2010). Such homogenisation is related to the provision of fully standardised built structures offered to end users without leaving any room for their participation in the construction process. To address that, architectural practices have been steered towards the production of highly recognisable built structures with the aim to create a distinctive and consistent brand image, even if this means imposing alien and non-customised buildings on individuals (Knox & Pain, 2010; Salingaros, 2006).

The need to implement sustainable practices in building construction has only recently attracted attention (Heywood, 2019; Wong & Fan, 2013). For instance, such practices have been exemplified by the combined use of local resources, traditional architectural techniques, and local manufacturing technologies (e.g., CNC milling machines), which have been applied to produce digitally fabricated houses[4] through citizen participation in the construction process. Although sustainable practices usually present shared values, such as the focus on resource efficiency, social cohesion, and the adoption of cost-effective methods that meet human needs (Lee, 2008), there is not yet an established regulatory framework for sustainable construction. According to recent literature, a shared vision on sustainable construction can be achieved through collaborative efforts by supply chain stakeholders across the stages of construction (Solaimani & Sedighi, 2019). In this context, the concept of conviviality is introduced in this thesis to serve as the basis for meaningful sustainability practices in the construction sector.

1.2. Conviviality as an Enabler for Sustainability

1.2.1. The Concept of Conviviality and Links to Sustainability
Echoing Illich (1973, 24), conviviality can be described as an intrinsic ethical value that correlates with "individual freedom realised in personal interdependence". Conviviality calls for individual autonomy so that communities can create artefacts to satisfy customised needs by utilising collective human intelligence (Illich & Verne, 1976). It inaugurates a system that departs from that of conventional industrial production by focusing on social good and mutual giving.

"Survival, justice and self-defined work" are basic ideals of conviviality (Illich, 1973, 26), which initially appeared in order to summarise key values included within sustainable development (Krüger, 2019). The social pillar of sustainability relates to human wellbeing and includes a large list of issues associated with education, social inclusion, health, safety, housing, employment and more (Dempsey et al., 2011). Conviviality highlights the importance of dealing with these issues with a focus on human interdependence and friendship, which is intrinsically connected to happiness and

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[4]https://www.designboom.com/architecture/vuild-completes-first-digitally-fabricated-house-mountainous-village-japan-05-12-2020/

human fulfilment (McEvoy, 2003). According to recent literature (Carrigan et al., 2020), boosting conviviality and reciprocity in society can lead to a more sustainable sharing economy with pronounced environmental, economic, and social benefits (Gaziulusoy et al., 2013).

Instead of focusing on challenging current consumer practices, the emphasis of conviviality is on questioning the logic of consuming by endorsing the idea of "live with less", as advocated by the degrowth movement (Schneider et al., 2010; Kallis, 2011). The idea is to prioritise the assimilation of conviviality features in daily life instead of merely enhancing efficiency and optimising performance to achieve sustainability (Meng et al., 2018). Besides, the use of energy-efficient systems does not necessarily mean that less consumption takes place if consumption patterns remain unchanged (Dahmus & Gutowski, 2011).

Conviviality can be observed in plenty of temporal and spatial contexts, where groups of individuals intentionally organise themselves democratically and envision a common future with an eye to common humanity and the environment (Adloff, 2014). During this process, individuals share their contributions, exchange ideas, and engage in amicable communications with the aim to mitigate inequalities for the sake of common sociality. Further, conviviality offers insights in terms of personal identification, fostering the self-development of individuals (Alwall, 2012) and the utilisation of individual capabilities to form autonomous communities.

Putting the concept of conviviality into practice, convivial technologies are designed in such a way that users can learn about the technology, tinker with it, and modify it according to their needs, without the necessity of relying on specialists (Deriu, 2015). Thus, convivial technologies present increased levels of conviviality during their entire lifecycle, i.e., the design, manufacturing, use, and maintenance phase (MacKenzie & Wajcman, 1985; Giotitsas, 2019). The bicycle can be considered highly convivial since it is a technology relatively easy to comprehend, repair, adjust, and modify according to the user's preferences (Bradley, 2018). Individuals can transport themselves autonomously and economically, while spare parts can be reused in the production of new bikes. Although it is generally easier to tinker with and grasp low-tech artefacts like bicycles, more sophisticated technologies, such as buildings, may also be convivial (Bradley, 2018; Mies et al., 2018).

Convivial technologies are decentralised, reversible, and democratically controllable (Muraca & Neuber, 2017). Decentralisation takes place through the implementation of small-scale production units that create distributed supply chains by using local resources (Kohtala, 2015; Johansson et al., 2005). Reversibility is enhanced when the "black box" behind the development process of products opens up to the public, enabling the inclusion of users in all construction stages of artefacts (Lizarralde & Tyl, 2017). For instance, the integration of open-source practices into technological development can enhance the reversibility of produced technologies, since the transparency of information is facilitated. By keeping technologies under democratic control, people can produce technologies on demand to cover their own needs instead of being manipulated by technocratic elites. Granting equal access to the means of production enables the general public to self-learn in a joyful and collaborative manner (Illich, 1973).

To enhance the decentralised production, reversibility, and democratic control of convivial technologies, the empowerment of local actors is vital. Given the difficulty of grasping and tinkering with complex technologies like buildings, people with technical and specialised skills might be needed to participate in the development process of

technologies to ensure the increased quality of the produced technologies. Following the conviviality paradigm, the knowledge used by experts should be simplified and shared with other individuals to boost the socially responsible production of technologies. The focus should be on reinforcing individual skills and encouraging social inclusion and accountability with the aim of fostering the collective actions of self-managed communities (Strauss & Fuad-Luke, 2008). Finally, to avoid safety compromises, the degree to which the users of a DGML product feel in control of the technology and knowledge necessary for its use and manipulation needs to be studied thoroughly.

1.2.2. The Matrix of Convivial Technology

The variety of social, economic, and environmental contexts allows for a wide spectrum of sustainability conceptualisations based on local specificities and individual viewpoints (Sala et al., 2013). Consequently, the analysis of sustainability becomes complicated, necessitating transdisciplinarity and systems thinking (Brown et al., 2010). In that sense, the concept of conviviality is essential in order to broaden our understanding of the complexity entailed in systems and social relations (Rzepnikowska, 2020).

Contemporary tools for assessing the lifecycle sustainability impact of products, such as environmental Life Cycle Assessment (LCA) and Life Cycle Sustainability Assessment methods, tend to focus on a specific pillar of sustainability (i.e. environmental, social, economic). Thus, scant room is left for the investigation of interrelations among the pillars, or contextual components, such as political or spatial factors, that may be affected by the development of technological artefacts (Wulf et al., 2019; Sala, 2020).

Especially in building construction, sustainability assessments through LCA methods are hampered by the complexity of buildings and lack of data and expertise in the field (Gervásio et al., 2014; Khasreen et al., 2009). To this end, the need to implement interdisciplinary approaches when assessing sustainability has been highlighted (Sala et al., 2013; **II**). Such approaches should utilise scientific and non-scientific data to facilitate knowledge exchange and bridge the gap among diverse stakeholders (Sala et al., 2013; Wiek and Binder, 2005). The ultimate goal is to create strong links with the social context and enable citizens' participation in relevant processes.

The Matrix of Convivial Technology (MCT) is an empirical tool developed to provide an accessible and comprehensive means of measuring the degree of creativity, autonomy, and decentralisation in community-based production practices (Vetter, 2018; **III**). The significance of this matrix is associated with current concerns for sustainability, which necessitate the evaluation of the social, economic, and ecological impact of technologies during their lifecycle. Elements connected to the impact of technology on human relations (relatedness), the adaptability of technology to local contexts (adaptability), accessibility to technological means (access), the bio-interaction of technology with the environment (bio-interaction), and the appropriateness of socio-ecological benefits of technology in relation to its socio-ecological impact (appropriateness) are the basic levels of conviviality examined in this matrix.

Dimensions / Levels	Materials	Production	Use	Infrastructure
Relatedness	Organization distributed Need-driven Bottom-up control Local traditions	Creative Input Need-driven Bottom-up Control Local traditions	Supports trust/community Allows creativity Creates beauty Self-determination	Sustains trust/community Connects eco-processes Bottom-up control Simplifies care
Access	Open Low cost Supports skill building Comprehensible	Open Producer-owned Supports skill building Local knowledge	Open Usable by anyone Local knowledge Transforms constraints	Usable by anyone Low cost Comprehensible Transforms constraints
Adaptability	Everyday tools Small scale Everywhere possible Standardized materials	Everyday tools Small scale Permanently changeable Modular	Repairable by skill Independent use possible Permanently changeable Encourages diversity	Repairable by skill Locally operable Permanently changeable Encourages diversity
Bio-Interaction	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent	Improving soil/water Supports clean air Biodegradable Nonviolent
Appropriateness	Renewable Locally available Re-useable Durable	Frugal material use Standardized tools Joyful worktime Byproducts are used	Sustains sufficiency Re-used Joyful time Durable	Frugal material use Sustains sufficiency Joyful time Local settings

Figure 1: Dimensions and levels of the MCT. Adapted by:
https://www.andrereichel.de/2019/05/20/artificial-intelligence-convivial-technology/.

The MCT incorporates social, environmental, and economic elements, allowing for a comprehensive assessment of various factors. For instance, the bio-interaction and appropriateness levels include environmental elements and interrelations among humans and the environment (e.g., biodegradability and improvement of soil/water); economic factors can be found in the access and adaptability levels (e.g., cost of materials and economic scale); while the relatedness level mainly focuses on social aspects (e.g., trust and creativity).

The MCT can provide a useful tool for designers and engineers to integrate conviviality practices into the design process of technological artefacts. It empowers the general public to participate in technological development processes and adapt the matrix properly so that certain conviviality elements can be examined on a case-by-case basis (Popplow & Dobler, 2015). The result may be a reduction of corresponding ecological footprints, increased engagement of users in relevant processes, and more accessible production practices.

1.3. Vernacular Structures as a Learning Source for Convivial Construction Practices

The reconciliation of environmental, social, and economic demands in the construction process is essential for sustainable construction. As a first step, an in-depth consideration of all the building elements is required. More specifically, each building element (e.g., beam, window, floor) needs to be considered along with its function within the natural environment. Buildings should thus be designed to symbiotically connect and respond to the local, regional, and global environmental context (Frazer, 1995).

Vernacular structures exemplify how the reconciliation of natural elements and building components is possible. These structures are made of construction materials, such as stone, wood, mud, and straw, that come from the near environment and undergo minimal processing. When it comes to buildings, natural resources (such as the soil, sun,

vegetation, and wind) are used to fulfil to some extent the energy demands for cooling, heating, and lighting. Thus, harmonious interactions between the building, climate, and natural environment can be fostered, following the principles of bioclimatic design (Nguyen et al., 2019). Bioclimatic principles facilitate energy savings, economic efficiency, environmental gains, and the improvement of indoor living conditions.

The development of vernacular practices is region-specific since these practices are defined by local elements like customs, religions, climate, and topography (Salman, 2018). However, despite local variations, vernacular practices share common principles (Walid & Omar, 2014). For instance, one could mention the utilisation of natural specificities (such as raw materials and energy sources) and the accrued knowledge of communities. This knowledge is empirically gained from observations of the natural environment, helping communities to build structures intuitively and locally (González, 2015; Gruen, 2017).

Considering the empirical acquisition of knowledge, the construction of vernacular structures does not necessitate the skills of professional architects and engineers. These structures are built by individuals or communities that experiment with construction materials and techniques in local contexts (Oliver, 1997). Interpretations of the vernacular knowledge accumulated through such experimentations have contributed to advancements of the contemporary engineered knowledge around sustainable construction practices.

Contemporary community-based construction activities often rely on vernacular principles in terms of using local material resources, prioritising environmental sustainability, and embracing community-based construction practices. For example, Earthship structures[5] are "off-the-grid-ready" houses that regulate indoor conditions via natural cross-ventilation, produce energy through solar panels and wind turbines, and harvest rain, condensation, and snow from the roofs. Hence, they reduce their reliance on public utilities and fossil fuels, boosting their conviviality dynamics.

Human coexistence and interdependence are key pillars upon which conviviality lies. Shared and habitualised practices and moralities play a significant role for enhancing conviviality (Adloff, 2014). In that sense, conviviality cannot be neglected when it comes to the vernacular commons (Putra, 2015). The construction of vernacular structures relies on intrinsically convivial construction principles, considering the use of local resources to meet economic and natural limitations, as well as collaborative construction processes that promote the establishment of reciprocal relationships and solidarity. This raises challenging questions that have acted as a trigger for my PhD research: How could vernacular structures evolve in tandem with current technological regimes to provide local responses to the global need for sustainability? How could OCS provide a solution towards that direction?

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[5] https://en.wikipedia.org/wiki/Earthship

2. Methodological Approach

In the absence of thoroughly investigated convivial approaches to building construction, this thesis uses a mixed methodological approach to investigate various aspects of OCS as a promising path towards convivial construction practices. Both quantitative and qualitative research methods are used (Fernández-Muñiz et al., 2009; 2012). Qualitative methods include semi-structured questionnaires (**II**, **III**), interviews (**III**, **IV**), tools such as the MCT (**III**), and in-situ observations of relevant practices (**I**, **III**, **IV**). Quantitative methods include structured questionnaires (**I**), software applications (**IV**), and tools such as the openOmeter (**III**). Finally, the gathering of empirical data was required to draw trustworthy qualitative and quantitative conclusions, while participatory approaches were implemented to allow for contributions to the understanding of relevant issues within the contextual setting (Reilly, 2010).

The thesis focuses on the European region, mainly due to time restrictions, financial limitations and ongoing activities on open-source housing taking place in the European context at the time of my research. Given that each project is defined by political, economic, and social specificities, the cases of this thesis were selected to provide an in-depth examination of the issues under study. However, investigating similar initiatives in different socio-economic contexts, such as in non-western countries, could provide further insights into the phenomena studied. For instance, additional conviviality features codified in OCS could be identified to enrich the findings of this thesis.

First, I experimented with the manufacturing of open hardware projects in the built environment. The emphasis was placed on the learning process followed to develop a 3D printed bridge model with a group of students (**I**). The aim was to understand how DGML projects are developed and communicated, as well as to consolidate the way 3D printing technology is perceived. Thus, a participatory action research project was implemented to illuminate the learning and communication potential of producing a DGML artefact for the built environment, i.e. a bridge model. This research highlighted the potential of 3D printing technology to motivate learning and electrify meaningful communication among people with and without visual impairments. Through this educational project, the conviviality potential of 3D printing technology surfaced.
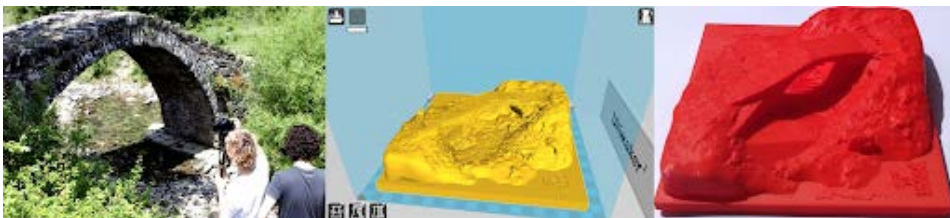
Figure 2: Snapshots from Article I

After gaining this knowledge, I attempted to outline the concept of OCS as a manifestation of the DGML model in buildings (**II**). In this context, Article **II** is a desk-research paper that offers a synthetic overview of OCS. In particular, I explored challenges and opportunities entailed in the development of OCS through the multi-layered study of three selected cases of OCS. It was concluded that the implementation of OCS calls for changes in current practices, the scale of conventional processes, and the role of various stakeholders involved in the construction process.
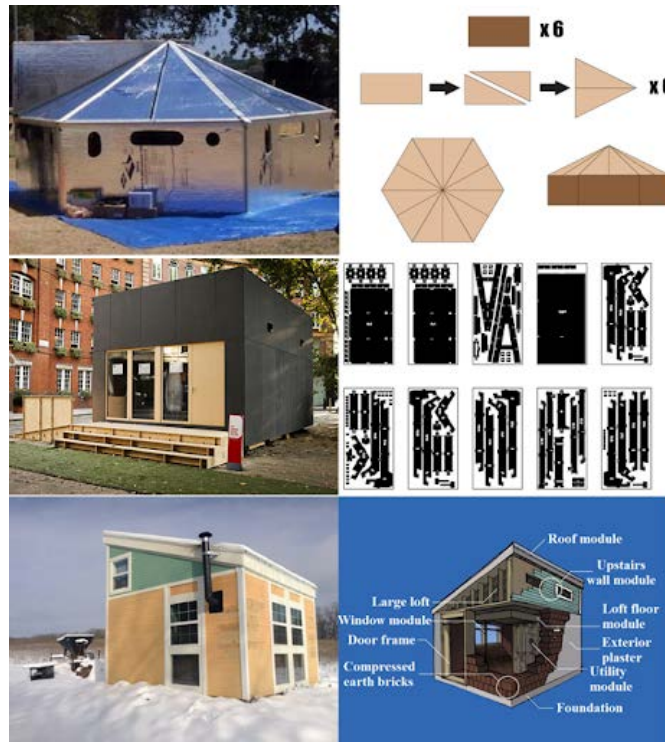
Figure 3: *Snapshots from Article II*

To put theory into practice, I performed field work and in-situ observations to analyse a prominent case of OCS, i.e., the WikiHouse ecosystem. By incorporating the critical theory of technology through the concepts of conviviality and openness, my goal was to assess relevant aspects of the WikiHouse (**III**). Based on Article **III**, it is argued that the conviviality and openness entailed in OCS are complex and context-specific factors. More specifically, there is a spectrum of degrees of conviviality and openness entailed in the development of technological artefacts and, thus, characterising an artefact as convivial or open cannot be a binary decision. Further, assessing the conviviality potential of complex artefacts ends up being subjective, since, for example, the level of the participants' expertise and skills is crucial (**III**).

Figure 4: *Snapshots from Article III*

The design stage of buildings should be carefully considered, given its dynamics to improve building performance (Cho et al., 2011). In Article **IV**, field work and software applications were used for the architectural design and energy analysis of a vernacular building structure. Given that the technical capabilities of BIM as an engineering analysis tool have been extensively discussed in the literature (Aouad et al., 2012; Diaz, 2016), the aim of this article was to expand the focus of Building Information Modelling (BIM) applications by exploring the social dynamics of BIM and its potential contribution to vernacular design towards sustainability. Accurate energy analysis and safety were the most important advantages realised through BIM. Contrastingly, the inability to capture tacit knowledge embodied in vernacular structures and the lack of adaptability towards contextual specificities were the main weaknesses of BIM technology (**IV**).

Figure 5: Snapshots from Article IV

All publications are based on different bodies of theoretical and analytical frameworks, from political ecology and engineering studies to critical technology theory and social science. Theoretical diversity, combined with qualitative and quantitative data from case studies, has allowed for the integration of a broad spectrum of perspectives that delineate the contours of an alternative production model in the construction sector. In this way, the thesis strives to provide a framework that enables engineers and social scientists to visualise a common path towards human welfare.

3. Open Construction Systems as a Convivial Paradigm in the Built Environment

Considering that social sustainability has been pursued as the most crucial aspect in sustainable construction (Kothari, 2005; Parvin, 2013), the necessity to foster conviviality in built-environment activities is more relevant than ever. Despite regional variations, issues discussed previously, including environmental concerns, social exclusion, and labour-intensive activities, are common to all contexts. Therefore, the delivery of affordable and convivial built structures remains on the research and development agenda.

The development of a convivial paradigm in the construction sector should incorporate vernacular principles (e.g., the use of construction materials of the immediate environment) but also adhere to the contemporary context. To this end, the Internet can provide an effective and inexpensive means for the sharing of construction-related data, such as building regulations and information on construction techniques and materials.

In a convivial setting, the improvement of the living conditions and the quality of life of individuals should be prioritised by boosting the overall sustainability of humanity. However, pursuing a path to conviviality is not easy. There is an evident need to transform existing production and consumption models, as highlighted by the degrowth movement (Schneider et al., 2010; Kallis, 2011).

In this chapter, I explore an emerging production model in the construction sector through the concept of OCS as a possible convivial paradigm in the construction sector. Given the difficulty of exploring the whole spectrum of construction projects in the built environment, the focus is placed on building construction. Nevertheless, the analysis can be expanded to include more construction projects (such as bridge construction), considering the positive dynamics of applying the DGML model in the built environment (**I**).

3.1. Designing Globally: Open Design and Parametric Design Tools

Information and Communication Technologies (ICT) have facilitated the development of digital platforms that favour online information sharing. Given the potential of these platforms to enhance collaboration and knowledge transfer at low costs, ICT have been portrayed as a booster of democratisation (Benkler, 2006; Castells, 2000; Von Hippel, 2005). Digital resources (such as knowledge, software, and designs) can be distributed through ICT (e.g., the Internet) and shared as a "digital commons" (Hess & Ostrom, 2007).

By publicly sharing information regarding the development process of technologies, a growing pool of digital resources emerges. Such resources include online manuals and designs that can be tested, modified, and reviewed globally. Communities around the globe use digital commons to provide customised technological solutions locally. By adding their feedback, such communities enrich and improve the digital commons (van Abel et al., 2011). For example, the Open Source Wood initiative[6] is an open-source web portal that aspires to support global innovation in timber construction.

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[6] https://opensourcewood.com/Pages/default.aspx

Further, global inventories are developed that include simplified design rules, online tutorials, and illustrations around built-environment activities. Such an initiative was undertaken by the World Housing Encyclopedia[7], an online platform that contains extensive reports on the architectural features, structural systems, building materials, and socioeconomic indicators of several housing types around the globe. In the same vein, international platforms such as the International Council of Monuments and Sites Committee[8] and the International Association of Earthquake Engineering[9] provide access to information around the construction sector.

In architecture, integrated design approaches that consider the stakeholders involved in the construction process have been implemented during the last three decades (Parvin, 2013). Parametric design tools such as Building Information Modelling (BIM) have been used for that purpose. BIM design models can be shared to foster collaboration and communication among the engineering community but also between professionals and non-experts. BIM models consist of a set of interchangeable building components, which can undergo various analyses to ensure the durability of buildings.

Limitations of BIM technology include the resistance of construction stakeholders to change conventional practices, and interoperability issues that hinder broad collaboration (Wong & Zhou, 2015; Miettinen & Paavola, 2014). Despite such limitations, BIM allows for advanced building simulations, including structural tests, energy analyses, and geospatial calculations, which could lead to environmental and economic gains in building performance (**IV**; Krygiel & Nies, 2008; Ciribini et al., 2016). Hence, it is generally accepted in the literature that BIM holds the potential for enhancing sustainability in building design (Wong & Fan, 2013; Wong & Zhou, 2015; Oti & Tizani, 2015).

3.2. Manufacturing Locally: Local Manufacturing Technologies

Local manufacturing technologies enable the production of objects locally, thus facilitating distributed production networks (Perez & Santos, 2017). These technologies are exemplified by 3D printers, CNC routers, and laser cutters. They are fed with 3D models and designs, which are directly translated into tangible objects. The distribution of local manufacturing technologies boosts creativity and experimentation and paves the way for transforming the manufacturing process of physical products via the development of open-source hardware (OSH) solutions (Kostakis et al., 2016).

The Arduino microcontroller board[10] and Open Bionic Systems[11] illustrate open-source hardware (OSH) products. A broad spectrum of openness levels arises in regard to the production of physical artefacts. The degree of openness has been associated with features such as the transparency, accessibility, and replicability of relevant information, as well as the commercial usability and intellectual property rights of a work (Balka et al., 2013; Di Benedetto, 2010; Bonvoisin, 2016). Specified protocols, such as the Creative Commons licence[12], are used to foster the distribution of digital commons by ensuring the openness of the entire process.

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[7] http://www.world-housing.net/

[8] https://www.icomos.org/en/about-icomos/committees/

[9] http://www.iaee.or.jp/

[10] https://www.arduino.cc/en/guide/introduction

[11] https://openbionics.org/

[12] https://creativecommons.org/licenses/?lang=el

Makerspaces set the stage for materialising OSH products locally through machinery sharing and knowledge exchange (Anderson, 2012; Troxler, 2011). They constitute community-run co-working places, like hackerspaces, micro-factories, fablabs, and media labs, which adopt participatory decision-making approaches to manage shared resources (Gandini, 2015). Makerspaces are equipped with local manufacturing technologies and simple tools offered to the public for use and experimentation.

Makerspaces secure access to production means, bringing inclusiveness, collaboration, and human creativity to the fore. In the construction sector, 3D printed architectural models are created to grasp the volume of buildings (**I**; Bonwetsch, 2006), while local manufacturing technologies are used to produce building components and houses[13]. Although there are differences between the global North and South, makerspaces are generally a global phenomenon (Niaros et al., 2017; The Maker Map, 2018). The expansion of makerspaces and local manufacturing technologies could possibly generate societal transformations by providing the infrastructure needed for manufacturing technological solutions locally (Cutcher-Gershenfeld et al., 2017; Garmulewicz et al., 2018).

3.3. The Emergence of the "Design Global, Manufacture Local" Model

Makerspaces comprise globally distributed but networked communities of practice. Digital commons are used to produce customised solutions locally, bearing surrounding biophysical conditions in mind (Kostakis et. al, 2016). Such a convergence of global digital commons with local manufacturing technologies has been outlined through the DGML model.

The DGML model seems to differ substantially from the conventional market-driven production model. It promotes distributed production within the dominant capitalist system enabled via networked makerspaces (Kostakis et al., 2016; Kohtala, 2015). The collective intelligence and cooperation embedded in the development of DGML solutions strengthen the potential of relevant initiatives to thrive and foster innovation (Benkler et al., 2015). Relevant information behind the development process of technological solutions is shared as a digital commons, which can then undergo asynchronous modifications by contributors.

Modularity is a typical element embedded in the design of DGML products. This refers to the property of structures to be easily decomposed and recombined in smaller parts/modules (Kostakis, 2019). During the production of modular products, people can work asynchronously on different modules, while certain modules can be replaced or reused in other constructions. In that sense, the disassembly ability, recyclability, and reparability of DGML modules are facilitated (Bonvoisin, 2016).

The DGML model appears to entail inherent sustainability characteristics (Kostakis et al., 2016). Social sustainability is promoted through the inclusiveness aspect pervading the whole process, as well as the mutualisation of resources in makerspaces. The economic sustainability of DGML products relates to the removal of profit-oriented incentives and the purposive design of DGML products to last (Guiltinan, 2009). In addition, on-demand production promotes environmental sustainability, since the need for long-distance transport of heavy machinery is minimised (Kohtala & Hyysalo, 2015). However, claims about the sustainability potential of DGML products currently

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[13] https://www.iconbuild.com/

rest on thin empirical foundations, necessitating further scientific research (Kostakis et al., 2016).

Finally, research has illustrated some interrelated practices observed in the development of DGML products that could be associated with conviviality (Kostakis et. al, 2016). These practices include the incentives of communities to design for sustainability, on-demand production of technological solutions and the sharing of infrastructures that takes place when communities use local manufacturing technologies in conjunction with digital commons. Also, the main motives for communities engaged in the development of DGML products stem from their need for communication, learning and enrichment (Benkler, 2006), presenting connections with values embedded in the concept of conviviality.

3.4. Open Construction Systems

The conceptual framework of the DGML model was employed to outline how collective initiatives take place in the construction sector, albeit in a seed form. I use the term OCS to delineate a set of connected things and devices that operate together in producing buildings by designing globally and manufacturing locally (**II**). This set may include

  i.   equipment (such as design tools and local manufacturing technologies),
  ii.   information resources (such as those included in the digital and vernacular commons)
  iii. community practices (such as those implemented in makerspaces or by open-source communities), and
  iv.   legal components needed to produce DGML buildings (such as public copyright licences and building regulations).

Open building systems (OBS) are the starting point of OCS. The term OBS was introduced to describe modular building components able to form a variety of building types (Kamar et al., 2009; Siw, 2013). OBS are based on structured components that allow for interchangeability and thus present a certain degree of customisation and flexibility (European Commission, 2009). The Hexayurt[14], the Open Source Ecology Microhouse[15], and the WikiHouse[16] exemplify emerging forms of OBS, as descriptively presented in Article **II**.
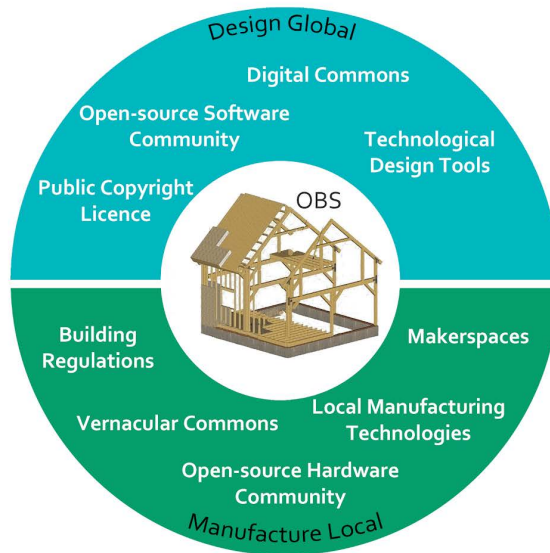
As a broader term compared to "building", "construction" emphasises the process of erecting structures, encompassing activities like drafting, computation, and the analysis of building information. In that sense, the concept of OCS builds on OBS, expanding the focus of attention from the building structure to the ecosystem around it. Such an ecosystem is required to foster the lifecycle management of OBS. The conceptual framework of OCS is presented below (Figure 6).

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[14] http://hexayurt.com/
[15] https://www.opensourceecology.org/portfolio/microhouse/
[16] https://www.wikihouse.cc/

Figure 6: Conceptual framework of OCS

OCS prefigure niche practices that take place on the margins of the dominant paradigm through community-based processes. They question the conventional construction model by inaugurating a new organisational and production framework that moves away from market-regulated structures. Beyond such shared focus of OCS, a combination of cultural, economic, social, and techno-political elements shapes the goals, interests, actions, and structure of OCS locally (**II**). By identifying various ideological frames of OCS, a common set of values, goals, and principles for the communities involved in such activities can be developed.

Considering recent concerns for sustainability (Green Building Council, 2018; Whicher et al., 2018) and the need for a convivial paradigm in the construction sector, OCS present non-negligible tendencies to promote conviviality, given the fundamental principles upon which they are based. For instance, the use of distributed infrastructures (such as the Internet and local manufacturing technologies) aligned with the DGML model allows for autonomous production processes (Illich, 1973). It also enables the production of buildings in local makerspaces, reducing the demands for transporting machinery (Kohtala & Hyysalo, 2015). Further, open-source communities working on OCS mainly design towards customisation and not profit maximisation. Hence, it is possible for these communities to design for sustainability (Kohtala, 2015). Finally, the mutualisation of resources (both digital ones, i.e. software, designs, information, know-how, etc., and physical ones, i.e. machinery, makerspaces, etc.) promotes collaboration and bonding among the community.

The limitations of the approach indicated through OCS stem from ambiguity in the set of elements that define OCS. For instance, the concept of community is subject to many interpretations. In the current digitally connected world, there are digital communities without territorial reference that can be potentially global. Further, resources like rivers

need to be managed by numerous communities whose actions and practices are confined by different central political powers and production networks. Hence, the question of who comprises a community can be tricky.

Based on the commons definition (Bollier, 2014), communities are composed by individuals who manage a resource by conforming to certain protocols, values, and norms set by communities themselves. In that sense, a community called upon to contribute to the management of a given resource is composed of any individuals who take full responsibility on an equal footing for the decision-making and protection surrounding this resource. Thus, for instance, a makerspace community sets the rules for the operation and administration of the equipment and activities present in a specific makerspace. Similarly, an open-source software community consists of a group of individuals who work together to develop, test, modify, and maintain an open-source software product following certain rules.

Further, considering local specificities around the globe, the set of tangible and intangible resources, tools, and actors included in the definition of OCS may present huge differences from place to place. However, the aim of the definition is to provide a first step towards establishing a theoretical framework for OCS to enable dialogues between principally social and mainly engineering agendas. The implementation of OCS depends on the discretion of local actors, who need to understand the importance of such an approach for humanity in its entirety.

4. Three Interlocked Elements for Conviviality in the Built Environment

In this section, I elaborate on three interrelated features that enable the conviviality potential of OCS. I also propose improvements that could tackle issues associated with these elements towards conviviality. These features include modularity, sharing, and adaptability. Modularity enables the decomposition and recombination of building modules, leading to the simplification of structures (Kostakis, 2019). In this sense, it arguably acts as a facilitator for social inclusiveness in the construction process. Sharing allows for the mutual benefit of individuals from the same resources in tandem and enables the production of collective value, as well as shared values and purpose (Bollier & Helfrich, 2019). Adaptability is catalysed through the engagement of the user in construction processes, and is enabled via modularity and sharing (Elgammal et al., 2017).

To narrow down the scope and reduce the ambiguity entailed in the concept of conviviality (Caire, 2010), the MCT is used as a normative schema to provide further insights on how OCS could enhance conviviality. To this end, three interlocked elements for conviviality observed in the development of OCS are discussed in relation to the five levels of the MCT. Referring to the levels of conviviality as analysed in the MCT, modularity potentially facilitates accessibility to technology (access), sharing strengthens socio-ecological relations (relatedness, bio-interaction, and appropriateness), and adaptability facilitates the consideration of local contexts.

The following analysis offers a synthetic overview of the findings of all four articles included in this thesis. The manifestation of these three interlocked features was roughly described within three case studies of OBS examined in Article **II** and is now presented in a more coherent way. Given the novelty and seed form of OCS, certain features related to the maintenance and disposition of OBS are based on perceptions of my own (as stated in Article **II**) and of the participants in the construction process of a WikiHouse (**III**). The next figure (Figure 7) depicts the main conviviality features observed in OCS.
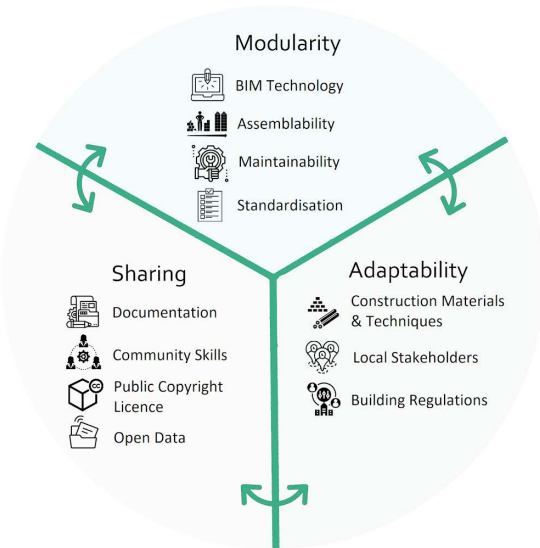
Figure 7: Conviviality features of OCS

4.1. Modularity

The concept of modularity provides a useful means to deal with complex systems (Baldwin & Clark, 2000). Echoing Gershenson et al. (2003), the adoption of modularity enhances the simplification of the design process and the ability to customise solutions. Given the high complexity and interdependence among various stakeholders involved in building construction, the role of modularity in handling the complexity of building systems is important. Thus, by increasing the modularity of building systems, certain processes can be structured and design decisions can be decoupled (Viana et al., 2017).

Modularity is embedded both in the design tools used and in the design of OBS. Digitalisation enables the integration of the design with the construction of buildings, boosting the accuracy, quality, and lifecycle management of buildings. Parametric design tools, such as BIM technology, enable the decomposability of building structures into distinct but interrelated modular components. These components can function independently but are still interconnected and integrated into the architectural BIM model. Additional BIM models (such as structural and mechanical ones) are linked to the architectural-central model to enhance computational analyses of the building structure. Based on existing literature, BIM could provide a new paradigm for communication that fosters social engagement and collaboration in the construction process (Gu et al., 2014).

Although in principle parametric tools allow for infinite modifications in the form and shape of components, fixed rules apply so that BIM can grasp internal relationships between the building components. These rules hinder the creation of complex building elements through BIM (Yamazaki, 1990; Yamazaki et al., 2014). In addition, recent research has demonstrated that the use of BIM technology imposes restrictions on the accurate design of certain elements of vernacular structures (**IV**). Such restrictions are associated with the use of standardised building components, which can be modified independently and combined in various ways to form structures and superstructures (Open Structures, 2018).

In that sense, standardisation embedded in the design through BIM technology creates a challenge and an opportunity at the same time. The challenge is related to the need for explicitly defined rules so that BIM technology understands relevant functions. The existence of such rules may obstruct the imprint of distinctive building components (**III**). The opportunity correlates with the capability to structure data, codify and share parameterised objects, which facilitates the replicability of building solutions. Such a potential empowers BIM technology to provide a precise interface with an integrated set of applications for well-defined building types (**III**).

The design-embedded modularity in OBS facilitates the construction, maintenance, and disposal of OBS. For example, the WikiHouse includes the structural framework (the chassis), the electrical equipment, the foundation, the mechanical equipment, the roof, and solar utilities. All these subsystems can be constructed independently, while certain tasks can be outsourced to expedite but also simplify the entire process (Kostakis, 2019).

During the assembly of OCS, participants can be grouped by ability and interests: some may work on insulation, others on the chassis system, while still others may undertake the mechanical, electricity, and plumbing installations (**II**). In that sense, modularity leads to a division of human labour that reduces the complexity of the construction process, making it more accessible and inclusive.

Increased modularity during building design offers the flexibility to piece together, modify, rearrange, and substitute optional modules during the use stage to best suit the needs of users. During the maintenance process, modularity enables the

disassemblability of buildings into manageable modules that can be substituted or repaired independently. Thus, instead of demolishing the entire building, certain modules can be tested and maintained with the support of local experts (**III**).

4.2. Sharing

Sharing and collaboration are crucial for all stages of the construction process of OCS. Sharing takes place both in distributed makerspaces, where equipment and simple tools are used by local communities, and also online, given that digital resources (i.e. information, designs, etc.) are exchanged to facilitate the production of open-source building solutions. Collaborative processes are evident throughout the construction stage of OCS, where subgroups work asynchronously on the assembly process of different parts, developing friendship and joyful feelings (**III**). These subgroups work closely with the design team to exchange information, create feedback loops, and document the entire process (**I**).

In makerspaces, shared resources are managed by communities that set rules for using resources in a fair manner for all, with a view to maximising optimisation and minimising the processing of material. Recyclable, locally sourced, and reused materials are preferred as far as possible so as to mitigate environmental impacts, in consideration of the sustainability focus of these communities and vernacular principles. Special attention is paid to sustainably managing ecosystems from which raw materials are obtained. For instance, sustainable solutions for wood are produced through forest-based bio-economy.

The existence of detailed documentation guides and manuals is vital to ensure the replicability and openness of OCS (Bonvoisin, 2016). Architectural data, construction details, and chemical, environmental, economic, and biophysical information should be extensively documented to foster autonomy during the construction and maintenance phases of OBS. In the current development stage of OCS, fragmentation issues arise due to the lack of a comprehensive platform that includes all the up-to-date information around them. In the case of the WikiHouse, for instance, design files are shared on online platforms like GitHub. These design files are usually uncategorised and non-engineered. Yet to ensure the applicability and safety of OBS it is important to review the quality, clarity, and comprehensiveness of the published information.

Additionally, the plurality of expertise and skills among the participants in the construction process enhances the degree of autonomy that the local community feels during the construction and maintenance stages of OBS. The level of conviviality in the construction phase rises when a highly engaged community with a strong supporting network is involved. However, in the current stage of OCS, uncertainties concerning the ability of local communities to handle the entire lifecycle demands of buildings have been pointed out (**III**). For instance, concerns have been raised regarding the ability of users to maintain certain building infrastructures, such as plumbing and electricity modules. Further, although it is expected that OCS fulfil the basic needs of users to a satisfactory degree, there is uncertainty about the durability of the buildings (**III**). Consequently, technical interventions are required at certain stages, indicating that OCS are still far from being fully convivial (**III**).

The application of the MCT to a WikiHouse indicated that the conviviality assessment of the WikiHouse technology may be quite subjective (**III**). For instance, the conviviality perception of the output is influenced by the subjectivity of cost-related factors and the

simplicity of the tools and methods used. More specifically, these factors were interpreted with regard to personal insights and the participants' familiarity with the tools, respectively.

To facilitate local production processes, the physical infrastructure needed for the development of OCS should be provided. For example, real estate public infrastructures could be used as physical co-working spaces that facilitate skill-sharing and the development of open hardware projects. Also, distributed ad-hoc divisions could consult specialists regarding documentation and administrative procedures, such as building permits and funding applications. At the same time, executive committees formed at national levels could check validity and revise the uploaded information of the digital pool. Last but not least, given the scarce funding sources of open-source communities, the economic encouragement and institutionalisation of these communities is vital to boost their impacts.

When it comes to the sharing of digital resources, Creative Commons public copyright licences enable the free distribution of building solutions, facilitating the integration of the construction industry. Such a condition empowers engineering companies, educational institutions and public entities to participate in the research and development of OCS by providing technical support to local communities throughout the building supply chain. However, the participation of private companies in the construction process may obstruct the sharing of outputs (**III**).

Raising awareness about the importance of scaling up the impact of OCS for humanity is significant in fostering conviviality through the engagement of individuals in relevant processes. Some steps in this direction could be offered through the investment in open data and information, the promotion of open-source technologies by policymakers, and the integration of open-source structured protocols for data sharing and coordination among stakeholders: from local governments and professionals to international organisations. Such protocols could ensure the effective implementation of construction practices in each region and country, as well as establishing networks and partnerships at regional, national, and international levels. By accessing international codified datasets of vernacular knowledge and disseminating the construction practices of various districts, experimentations and combinations of best building practices could be fostered.

Attention should be paid to facilitating the accessibility of building information to people without technical knowledge. For instance, grasping the structural behaviour of buildings is fundamental for communities to achieve high autonomy levels. Given that a considerable portion of the engineered knowledge has emerged through interpretations of vernacular knowledge, robust engineering knowledge could be simplified and given back to the communities, as the conviviality concept dictates. Evidence could be supported by conducting experiments to study the efficiency of building performance, while model structures and building simulation methods could be used to reproduce the behaviour of buildings in diverse configurations and under changing external forces. Further, workshops, training programs, and lectures could be implemented to reinforce the engineering skills required for the development of OCS and spread their impact beyond the scope of the local initiatives.

4.3. Adaptability

The international homogenisation of structures in the built environment has indicated the need for buildings' adaptability to local contexts with an eye to biophysical conditions (Guggenheim & Söderström, 2010). The emphasis of OCS is placed on endorsing adaptability according to human needs rather than offering one-size-fits-all solutions.

During the introduction of OBS, monolithic and standardised materials are usually used as a starting point to facilitate experimentations around OBS. For instance, standardised sheets of plywood are the main materials used for the chassis system of the WikiHouse: these are usually obtained from Finnish wood industry producers. As the pool of digital commons for OCS grows, new materials and designs are being tested in local contexts with the aim to enhance the performance of buildings through the use of sustainable materials and techniques (**II**). The use of open data is crucial to democratise accessibility to information around robust construction materials, as well as material-related properties and performance data. In this direction, platforms like Materiom[17] are substantially useful to provide recipes for materials made from widely available natural and bio-based ingredients, including agricultural waste. In that sense, open-source databases could further decentralise the production of OCS by providing the means needed to self-produce construction materials.

Local stakeholders (i.e. architects, manufacturers, designers, structural engineers, etc.) can freely access and modify digital commons related to building information, and ensure the applicability of digital resources to local contexts. Distributed networks of local operators can provide technical support to end users, as well as be commissioned to manufacture buildings in local makerspaces on demand. Also, contribution guides can be used to serve the changing needs of a given project and to invite people with specific skills ad hoc to join the construction process at certain stages.

To increase the dynamics of local networks, it is important for standardised building elements to be modifiable. Based on the current state of OCS, time-consuming processes that relate to the editing of existing designs have been reported (**III**). Also, the inability of BIM technology to capture vernacular knowledge and thus to adapt to local specificities (e.g., local construction techniques, materials, and vegetation) has been pointed out (**IV**).

The creation of open databases that include environment-related elements could benefit BIM technology. Further, the addition of smart features and the combination of geospatial technologies with BIM technology could enable the detection of locally available construction materials and the evaluation of alternative design solutions on a context-specific basis. Also, the addition of smart features and the combination of geospatial technologies with BIM technology could enable the detection of locally available construction materials and the evaluation of alternative design solutions on a context-specific basis.

Regional variations related to building regulations, zoning codes, and inspections should also be considered. OBS bear an inherent potential for adaptability to local building regulations owing to their design-embedded modularity. Specifically, modularity fosters the substitution of materials and building components, as well as the modification of building components to fit predefined geometric constraints. Further, the development of open databases with regulation-related documents could enhance the reproducibility of OCS at local levels (Open Building Institute, 2018).

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[17] https://materiom.org/

In addition, the simplification of international technical guidelines (such as the International Building Code in the US and the Euro Code in the EU) could further facilitate the application of OCS in different locations.

Last but not least, the integration of available open-source databases and platforms associated with the construction of built structures should be prioritised in order to enhance local production. Classifications according to the type of construction project and the construction stage concerned should be made to facilitate accessibility to information. Also, through the use of geospatial technologies, certain types of OBS, materials, building regulations, and administrative processes could be demarcated based on local specificities.

5. Conclusions and Proposals for Future Research

This thesis provides a preliminary framework for a convivial paradigm in the construction sector. Its starting point is the housing crisis that the conventional construction model has failed to avert and the accompanying need for sustainable construction practices. The thesis delineates the contours of an emerging model based on the convergence of digital commons with local manufacturing technologies and indicates how new forms of value creation could be created by shifting towards conviviality to analyse transdisciplinary issues in building construction.

The main body of this thesis lies in the intersection of engineering and social sciences. The analytical framework is built on two main pillars: i. sustainable construction practices, which point out social, environmental, and economic issues associated with the current construction model, as well as sustainable practices observed in the construction of vernacular structures; and ii. the importance of conviviality for serving as the basis for meaningful sustainability conceptualisations and sustainable construction practices with an eye to human wellbeing. To further stress this importance, the Matrix of Convivial Technology (MCT) is presented as an inclusive tool used for analysing complex processes taking place during the lifecycle of socially constructed products.

Despite the plurality of existing perspectives towards sustainable construction, the challenge of sustainable construction has remained unanswered to date. In an attempt to provide preliminary answers, this thesis explores a specific option that brings sharing and solidarity into focus. The emphasis is placed on the emerging Design Global, Manufacture Local (DGML) production model, which embraces community-based innovations informed by the capacities of technological capabilities. The scale, values, and collaborative practices of the DGML model differentiate it from the conventional model of mass production.

In this context, the concept of OCS is introduced to explore the manifestation of the DGML model in the construction sector. OCS include physical resources, such as equipment and tools, and intangible elements, such as information resources, community practices, and legal elements, which operate together when producing DGML-based structures in the built environment. The establishment of a theoretical framework for OCS may enable dialogues between social and engineering agendas to trace opportunities for transdisciplinary cooperation and visualise common paths towards human welfare.

Through a multifaceted investigation of OCS, the main objective of this thesis is to illustrate three interlocked elements for conviviality identified in OCS: design-embedded modularity, sharing practices of digital and physical infrastructures, and adaptability to local contexts. These elements are connected to the conviviality levels of the MCT and provide preliminary evidence of the positive dynamics of OCS for conviviality. Through the analysis, it is concluded that OCS present non-negligible tendencies towards conviviality.

In addition, certain proposals that could boost the conviviality potential of OCS are formulated. Among these, advancements in Building Information Modelling technology enhancing its capability to capture contextual information, the implementation of open-source protocols for data sharing to enhance the documentation process of open hardware solutions, and the institutionalisation of open-source communities, as well as the integration of open-source platforms available to facilitate activities related to any construction stage, stand out.

Considering the involvement of diverse stakeholders, including professionals (i.e. engineers, architects, suppliers, construction workers, etc.) and governmental organisations (i.e. central government, local authorities, etc.), all of whom are in construction processes together, bearing multiple interests, the abovementioned issues cannot be addressed in the absence of transdisciplinary cooperation and institutional transformations. By stimulating policy-making efforts to build relevant institutions, OCS could pave the way for an inclusive and democratically controlled approach in the construction sector, as the concept of conviviality dictates. To enable the flourishing of OCS at regional, national, and global levels, awareness should be raised globally for promoting socio-environmental considerations in the construction sector.

A point of criticism one may level against this thesis is the lack of empirical data regarding the maintenance and disposal stages of OCS, which, as mentioned before, is due to the seed form of OCS. It is highly recommended that future research should focus on evidence-based assessments for these stages to provide sound data about the lifecycle performance of OBS. In addition, the investigation of variations in the development of OCS observed in different socio-economic contexts and the exploration of how DGML could work in the case of other built-environment structures, such as in bridge construction as tentatively explored in Article I, could enrich the findings of this thesis. Further, a comprehensive sustainability comparison with an industrially produced building with a similar OBS, as explained below, would be beneficial to test the sustainability potential of OCS.

Further, a compilation of targeted tools should be used to comprehensively assess the sustainability degree of different technologies. For example, applying the LCA methodology may be challenging for assessing complex technologies such as buildings, mainly due to high input requirements and a lack of capability to capture complex interrelations of our co-existence. On the other hand, the MCT cannot be easily adapted to thoroughly assess complex technologies, given the multi-layered interrelations of diverse factors that need to be considered. Hence, in the case of buildings, flexible but structured tools should be used, which i) assess both the building structure and the ecosystem around it and ii) aim to simplify the entire construction process (such as through the use of modular building elements), without compromising the simplicity in use of the tools. The development and institutionalisation of such tools or combinations of targeted tools could foster meaningful sustainability assessments of construction processes.

There is no single solution to the housing crisis. Lessons should be drawn from global experiences and effective strategies should be developed on local levels, bearing in mind regional social, economic, and political specificities. Vernacular knowledge can be a profound asset for defining principles for sustainable design at local contexts, while offering the opportunity for us to digest and assimilate conviviality values. Such values will enable us to build a common future with a particular focus on human interrelation and wellbeing. In this context, I introduce the concept of OCS as a promising pathway for fostering conviviality in the built environment. The question, however, of whether we want to follow a promising but arduous path towards convivial construction practices remains; and the answer is up to us.

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Christina Priavolou

Abstract

Towards a Convivial Built Environment: Developing an Open Construction Systems Framework

This thesis aspires to provide a preliminary framework for a convivial paradigm in the construction sector. So far, there is no established approach to sustainable construction in this sector. In this context, the concept of conviviality was introduced to serve as the basis for meaningful sustainability practices in the construction sector. The construction of vernacular structures has valuable lessons to teach us in terms of building structures in an autonomous and decentralised way, as the concept of conviviality dictates.

With the housing crisis forming the starting point of the research, the thesis aims to shed light on how a convivial alternative to the conventional construction approach can thrive. The implications of conventional construction practices on the three pillars of sustainability include high contribution levels to global carbon emissions, augmented rates of homelessness, and low user participation in the construction process.

Hence, the focus is placed on an emerging production model based on sharing and solidarity which could constitute a tentative alternative to conventional construction practices; namely the Design Global, Manufacture Local (DGML) model. Based on the DGML model, I introduce the concept of Open Construction Systems (OCS) as a possible pathway for fostering conviviality in building construction. This concept aims to expand the focus of attention from the building structure to the ecosystem around it by considering things (such as equipment, information resources, and legal components) and devices (like community practices) required to enable the lifecycle management of building structures.

The thesis uses a mixed methodological approach that consists of both quantitative and qualitative methods to allow for a multi-layered analysis of different aspects of OCS. The analysis ranges from educational and openness perspectives (I; III) to the technological and institutional potential of OCS (II; IV). The main objective of this thesis is to illustrate three interlocked elements that enhance the conviviality potential of OCS: design-embedded modularity, sharing practices of digital and physical infrastructures, and potential for adaptability to local contexts. These elements stem from the analysis of the Matrix of Convivial Technology, a normative schema used to provide a comprehensive means for assessing social, environmental, and economic elements associated with the production of technologies.

Further proposals for future research are necessary to boost the conviviality potential of OCS, especially regarding the improvement of Building Information Modelling technology to enhance contextual information analyses, the implementation of open-source protocols for data sharing to enable the documentation process of open hardware solutions, the institutionalisation of open-source communities by governmental organisations, and the need for integration of existing open-source platforms to facilitate accessibility to construction-related information.

In our path towards conviviality, lessons can be learnt from vernacular structures, which serve as successful exemplifications of how conviviality can thrive in the construction sector. The development of an OCS framework aspires to reinvigorate vernacular structures by mobilising individuals to find their role and participate actively in built-environment activities. Hopefully this thesis will trigger discussions among engineers and social scientists, and experimentations around OCS.

Resümee

Ehituses inimmõõtmelisusele üleminemine: avatud ehituse süsteemi raamistik

Selle lõputöö eesmärk on tutvustada lihtsat inimmõõtmelise tehnoloogia raamistikku ehitussektori jaoks. Antud sektoris pole siiani ühtegi kindlaks kujunenud jätkusuutlikku lähenemisviisi. Töös pakutakse üheks võimalikuks variandiks inimmõõtmelise tehnoloogia kontseptsiooni, mis võiks olla mõjusate jätkusuutlike tavade aluseks ehitussektoris. Inimmõõtmelise tehnoloogia printsiibil ehitatakse struktuure autonoomselt ja detsentraliseeritult, juhindudes muu hulgas ka väärtuslikke õppetunde pakkuvatest rahvuslikest ja pärandtavadest.

Uue kinnisvarakriisi tekkimist silmas pidades näitlikustab see lõputöö, kuidas edeneb ja õitseb tavapäraste ehitussektori tavade kõrval selle alternatiiv – inimmõõtmeline tehnoloogia. Traditsiooniliste ehitustavade negatiivsed mõjud jätkusuutlikkuse kolmele alustalale kujutavad endast suuri süsinikdioksiidi emissioone, suurenevat kodutusmäära ning liiga väikest kasutajapoolset osalust ehitusprotsessis.

Traditsiooniliste ehitustavade alternatiivina on hetkel katsetamisel mudel nimega disaini globaalselt ja tooda lokaalselt (Design Global, Manufacture Local ehk lühemalt DGML), kus on fookus jagamisel ja solidaarsusel. DGMLi mudelile tuginedes tutvustab autor avatud ehituse süsteemi (Open Construction Systems ehk lühemalt OCS), mis kasutab just inimmõõtmelise tehnoloogia põhimõtet. OCSi eesmärk on juhtida tähelepanu ainult ehiselt ka seda ümbritsevale ökosüsteemile, võttes arvesse ehitise elutsükli haldamiseks kasutatavaid vahendeid (nagu seadmed, teabeallikad ja õiguslikud aspektid) ja meetmeid (nagu kogukonnatavad).

Selles doktoritöös on kasutatud nii kvantitatiivseid kui ka kvalitatiivseid meetodeid, et OCSi erinevaid aspekte mitmel viisil analüüsida. See analüüs ulatub õppimise ja avatuse aspektidest (I, III) OCSi tehnoloogilise ja institutsioonilise potentsiaalini (II, IV). Töö põhieesmärk on tuua välja kolm omavahel põimunud aspekti, mis parendavad OCSi inimmõõtmelisuse potentsiaali: disaini modulaarsus, digitaalsete ja füüsiliste infrastruktuuride jagamistavad ning kohalike kontekstidega kohandumise potentsiaal. Need aspektid on valitud inimmõõtmelise tehnoloogia maatriksi analüüsi põhjal, mis on normatiivne raamistik, mis pakub paljuhõlmavat vahendit tehnoloogiate loomisega seotud sotsiaalsete, keskkonnaalaste ja majanduslike mõõtmete hindamiseks.

OCSi inimmõõtmelisuse potentsiaali suurendamiseks on vaja täiendavate uuringute ettepanekuid, eriti seoses ehitusteabe modelleerimise tehnoloogia parendamisega, et täiustada kontekstuaalse teabe analüüsimist, avatud lähtekoodiga protokollide kasutamisega andmejagamiseks, et võimaldada avatud lähtekoodiga riistvaralahenduste dokumenteerimist, avatud lähtekoodi kogukondade institutsionaliseerimisega valitsusasutuste poolt ja olemasolevate avatud lähtekoodi platvormide integreerimise vajadusega, et võimaldada ligipääsu ehitusteabele.

Inimmõõtmelisuse poole püüdlemisel võime õppida rahvuslikest ja pärandtavadest, mis ilmestavad seda, kuidas inimmõõtmelisus võib ehitusvallas edukalt toimida. OCSi raamistiku loomine võib aidata rahvuslikke ja pärandtavasid taaselustada, kutsudes inimesi üles elamiskeskkonna loomises oma rolli leidma ja selles aktiivselt osalema. Autor loodab, et see doktoritöö algatab inseneride ja ühiskonnateadlaste seas vastavateemalisi arutelusid ja OCSi alaseid katsetusi.
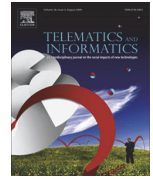
Appendix

Publication I
Pantazis, A., & **Priavolou, C.** (2017). 3D printing as a means of learning and communication: The 3Ducation project revisited. *Telematics and Informatics*, *34*(8), 1465–1476.

3D printing as a means of learning and communication: The 3Ducation project revisited

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ABSTRACT

This research project explores to what extent the utilization of open-source 3D printers and 3D design software could serve as means of learning and communication. The principles of non-formal education aligned with the concept of constructionism are used to create an experimental educational scenario focused on geocultural tourism for persons with visual impairments. This paper documents our experience and presents our findings from a 25-day long project, which took place in Zagori, northwestern Greece. 11 high school students from Portugal designed and manufactured natural and cultural heritage artifacts carrying messages in the Braille language. The objects were then handed to people with visual impairments with a twofold aim. First, to enable the communication among persons with and without visual impairments; and, second, to empower students to participate in training projects through open educational procedures. We conclude that open educational practices can boost students' active engagement in educational processes. Finally, 3D printing encourages a meaningful communication among people with and without visual impairments via the tangible exploration of geocultural components.

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1. Introduction

The development of learning theories and practices globally justify their characterization as objects of extensive research. Social and collective processes within teaching procedures are currently targeted to alienate the hierarchical constraints of knowledge production (Kemmis and McTaggart, 2005). Student-centered approaches, including the constructionist learning theory and open, non-formal educational practices, are used as means to facilitate student's active involvement in learning (Blikstein, 2013). Moreover, the integration of 3D printing technology in teaching inaugurates new ways of personal expression, fostering students' creativity and experimentation (Huang and Lin, 2016).

This paper focuses on the implementation of an educational scenario of non-formal education aligned with the concept of constructionism. It builds upon a critical making research project, which took place in two Greek high schools (Kostakis et al., 2015). The main goal of this paper was to explore how 3D printing can electrify various literacies and creative capacities of students.

In the context of our project held in Zagori, northwestern Greece, 11 Portuguese students manufactured 3D printed bridge and canyon artifacts of the local region handed to persons with visual impairments. This work attempts to explore to what extent open-source technologies and 3D printing could serve as a means of learning and communication among persons

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with and without visual impairments. The educational scenario was then presented to Greek educators with the aim to discuss our findings and trigger awareness of the application of open educational practices in teaching.

As far as the structure of this article is concerned, a short review of the corresponding theoretical background is presented. The methodological part follows with a description of our methodology and research questions. Then, we narrate and discuss our findings from both students' and educators' perspective. Finally, we summarize our conclusions and culminate with suggestions for future research.

2. Theoretical background

In the framework of developmental psychology, Rousseau's invention of childhood provided a breakthrough in the research field of education (Boone, 2017). Thenceforward, contemporary educational practices have been treated with skepticism, while the need for democratic education has been recognized (Soomro et al., 2010). Bearing in mind the fact that our networked world impinge on the way that societies are organized, educated and developed, alternative ways of transforming the educational landscape have been explored (Kemmis and McTaggart, 2005).

Towards this goal, international communities are moving towards non-formal education settings. The concept dates back several decades and differs from formal and informal learning. Formal learning focuses on hierarchical, teacher-centered approaches and promotes standardized, academic knowledge production (Ngaka et al., 2012). On the other hand, informal education refers to incidental accumulation of experience or skills deriving from daily life and interaction with the environment (Dib, 1988). Non-formal educational practices, located somewhere in the middle of the two above-mentioned concepts, are open, innovative and adaptable to the changing conditions and individual needs.

Aiming to drift apart from schooling as a prevailing way of learning, non-formal education attempts to make knowledge accessible to those who are not enrolled in schools (Yasunaga, 2014). The main purpose of non-formal practices is not certification but the acquisition of knowledge and skills through participation, observation and communication (Souto-Otero et al., 2013). The content of a non-formal educational procedure is basically practical, while its delivery modes remain flexibly structured. Non-formal educational programs are usually small-scale, short-term and entail specific purposes.

Despite the non-negligible potential of non-formal education, concerns about its effectiveness have been raised. The short duration of non-formal programs in combination with their preclusion of broader national education may create the impression that, unlike formal, non-formal education is insufficient (Yasunaga, 2014). However, having realized the importance of gaining knowledge outside institutions, the conjunction of the different educational types matters rather than their counterpositioning (Rogers, 2004, p. 234). Thus, non-formal education could be viewed as complementary, supplementary and/or alternative to formal education, which enhances social cohesion and individual capabilities (UNESCO Institute for Statistics, 2012).

In an effort to increase the possibilities for effective learning through experience, non-formal educational settings are correlated with the concept of constructionism. The development of the constructionist learning theory by Seymour Papert (1980, 1993) was an important movement towards the active involvement of students in education. In the vein of many prominent scholars in the educational philosophy (for example Maria Montessori, Lev Vygotsky, Paulo Freire or John Dewey), Jean Piaget developed the constructivist learning theory, which defines learning as "building knowledge structures". Constructionism extends the idea of constructivism by constructing and publicly share objects via conscious and felicitous actions (Papert and Harel, 1991, p.1).

Instead of making deposits of information into their minds, students interact with the environment and gain knowledge rooted in their experience (Ackermann, 2001). Students build objects rather than consume knowledge, being involved in hands-on explorations which boost their experience and inventiveness (Papert, 1993; Ackermann, 2001). An indirect impartation of knowledge occurs combined with collaborative and social activities that accompany the educational procedure. Considering the tight relationship between education and social values, a collective learning process could lead to a culture of sharing and open collaboration (Temple and Moran, 2011, p.195; MacDonald, 2012).

Beyond traditional educational approaches, where students could not see themselves as makers, constructionism provides the appropriate context for collaboration, communication and creative learning. Students engage vigorously in the discovery of solutions especially in meaningful problems, which enhance the educational outcomes (Cavallo, 2000). Within such an environment, teachers act as eager facilitators who consult students and race against the school bell with the aim to spur learners' self-motivation.

To achieve the full potential of constructionism the importance of students' participation emerge. Attracting students' interest plays a vital role in the rise of positive outcomes, taking into account students' inner incentives for learning beyond competition (Wadsworth, 1998). In an attempt to satisfy students' need for communication and collaboration, discussions around the utilization of technology in teaching arose.

In the framework of constructionism, Papert, as an enthusiastic proponent of technology, pioneered the penetration of digital tools in learning institutions (Blikstein, 2013). Since the 1980s, Papert spread the powerful ideas of the Logo programming language and made robotics accessible to children. Information and Communication Technologies (ICT) were acknowledged as tools able to construct personal experience, enable human interaction and manufacture powerful artifacts within self-driven educational settings (Schelly et al., 2015).

In the contemporary era of ubiquity of digital fabrication technologies, the implementation of relatively low-cost 3D printers into training courses has become a focus of research (Nemorin and Selwyn, 2016). A new way of individual expression which fosters students' creativity and experimentation surfaced (Huang and Lin, 2016). Objects can be designed through a computer-aided design software or even a scan of existing objects, using open-source digital tools and additive manufacturing technologies (Kostakis et al., 2015; Rayna et al., 2015).

Utilizing 3D printing in education posits students' ability to view things from various angles so as to perceive 3D modeling techniques. A systematic learning context to educate learners so as to become competent to create their own models is required (Huang and Lin, 2016). Through their participation, students acquire skills, increase their self-esteem and apply their knowledge to further improve the results. However, the risk of the "keychain syndrome" due to easy endeavors handled by students has been highlighted (Blikstein, 2013). To reap the benefits of using technology for educational reasons, students should be impelled to undertake complex projects, which help them enhance their creativity.

Delving into the ethics of the open-source/commons-oriented concept (Bauwens, 2005; Benkler, 2006) the association between open-source infrastructures and the commons-oriented concept is appreciable. Technologies with free and open-source hardware (e.g. Arduino micro-controller, 3D printers) or software (e.g. Moodle, free encyclopedia Wikipedia) can be easily examined and modified, catalyzing the openness of the educational process (Kostakis et al., 2015). Peer learning towards a shared purpose within educational institutions can be interrelated with societal development and co-creation of value. Therefore, students have the opportunity to acknowledge and further develop their inner positive motives and need for cooperation.

3. Research objectives and methods

First, this paper attempts to investigate the communicational potential of 3D printing among persons with and without visual impairments. People with visual impairments could experience geocultural tourism of the Zagori region via the exploration of 3D printed objects. Second, this paper aims to enable students to grasp the idea of 3D design and printing through open educational practices as part of a living experience (Papert, 1993; Dewey, 1997; Conole and Ehlers, 2010). To this end, we extend our educational scenario by engaging educators willing to test, criticize and implement similar methods in their teaching.

From the abovementioned objectives, sub-questions regarding the reform of contemporary educational environments emerge. Through alternative scenarios, the possibility of handling current problems observed in schools arises, including the lack of students' participation and critical thinking skills. Furthermore, educators could become more aware of the importance of collaboration and communication as meaningful values within an educational process. Thus, education could be approached from different perspectives with a view of ensuring the continued comprehensive development of learners.

According to Verschuren and Doorewaard (2005), our research framework is concretized through the following flowchart (Fig. 1). Similar to the work carried out by Kostakis et al. (2015), our project is a case study which involves high-school students. However, while in their case the students were allowed to manufacture 3D objects of their own choice, there was a definitive goal presented to the students in our project. The communicational potential of 3D printing among persons with and without visual impairments was investigated. Namely, 3D printed artifacts of natural and cultural heritage elements that compose the local identity of the Zagori region were manufactured by the students with the aim to, first, boost students' engagement in the educational procedure and, second, empower people with visual impairments to explore geocultural tourism via their interaction with the students.

Participatory Action Research (PAR) was utilized in our training scenario to facilitate students' active involvement in education through collaborative practices. This method was developed as a research endeavor focused on organizational conversion, co-learning and participation (Greenwood et al., 1993). It aims to emancipate people from the constraints of current
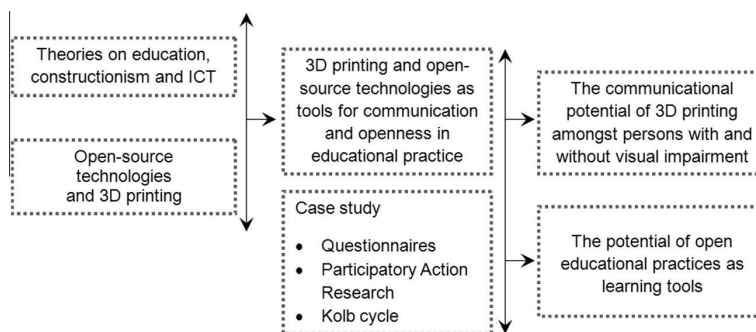
Fig. 1. Schematic representation of the research framework. The vertical arrows stand for the "confrontation" of particular issues, from which a conclusion (the horizontal ones) can be drawn.

hierarchies of knowledge production and disrupt inequitable social relations through mutual involvement and collaboration of the participants (Kemmis and McTaggart, 2005).

Transitioning from the linear model of conventional research into PAR, an iterative reflective cycle is created (Fig. 2). Action is taken, reviewed and results in new action throughout the learning process with the aim to improve the learning level. Students' knowledge is constructed via reflexive approaches, while the adaptability and flexibility of the educational reality is maintained (Salto-Youth, 2012). Despite its open nature, the learning process is unfolded with constant focus on the project's goals.

Designing a process which promotes imagination is regarded as the greatest challenge for participatory action researchers (Wadsworth, 1998). The latter assume a largely facilitating role and may turn to external sources for technical assistance. Bearing in mind that the lack of students' engagement limits the effectiveness of an educational practice, discussions about the mutual interaction of researchers and participants towards knowledge production have arisen. Within such a framework, PAR promotes collaborative partnerships and bonding relationships between teachers and students (Kim, 2016).

Echoing Dewey (1859-1952), students' participation in project-based courses is essential condition for their learning. Via learning-by-doing processes, students enhance their active experimentation and participation in an experiential way (Kolb and Kolb, 2005). Identifying the way of learning, students follow a sequence of stages in accordance with Kolb's learning theory, depicted below (Fig. 3). They experience an activity, consciously reflect back on their experience, try to conceptualize what they observed through a theory or a model and test their model/theory for an upcoming experience. Thus, learners grasp an experience and consciously transform it to learning through reflection, which spans theoretical conceptualization and practical experience (Kohonen, 2012).
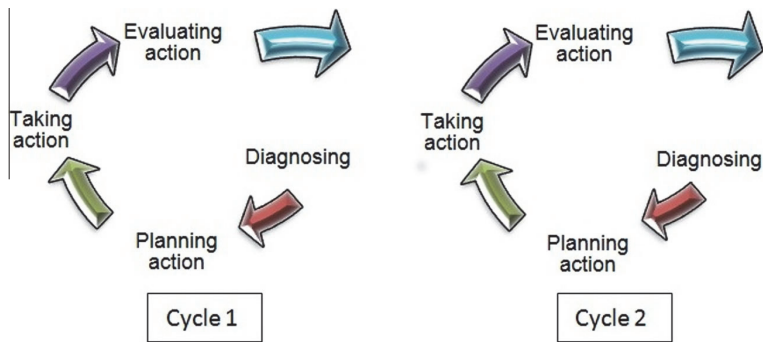

Fig. 2. Stages of PAR cycles (Adapted from Coghlan and Brannick, 2001, p. 19).
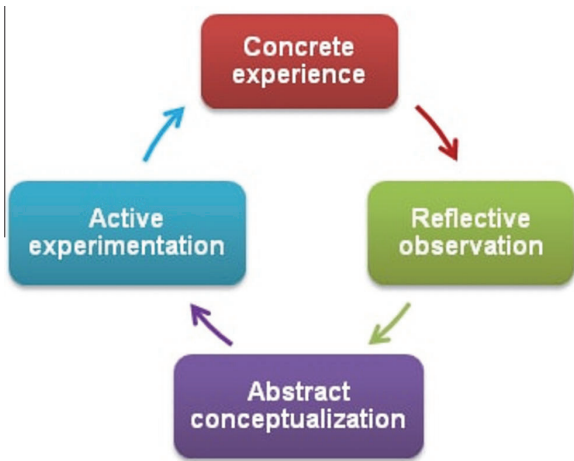

Fig. 3. The Kolb learning cycle (Adapted from Moobs, 2003).

4. Ecotourism, education and 3D printing: a case study

4.1. Educational scenario and approach

The project took place in Zagori, a mountainous area in north-western Greece. In the context of a European Programme for education, training, youth and sport, 11 technical high-school students from Alcochete, a small municipality in Portugal, were received by the EcoMuseum Zagori. The latter is a social cooperative enterprise oriented towards the protection of the local natural and cultural heritage. Students participated in educational ecotourism activities and acquainted themselves with 3D printing technology under the coordination of the P2P Lab (http://www.p2plab.gr/en/), an independent media lab interested in free and open-source technologies and peer-to-peer practices. The educational project lasted 25 days and included the 3D printing of cultural heritage elements which were handed to persons with visual impairments so as to mobilize them towards ecotourism.

The first five days of the educational program involved discussions about the general framework of the procedure, the program flow, the desired objectives and students' expectations of the project. The latter were written by the students and posted on a wall, facilitating the conceptualization of the context and the final evaluation of the project. The functionality of experiential education and the orchestral role of the teacher in the educational process was explained (Papert, 1980). Moreover, the importance of non-formal education and the existence of activities promoting interaction and enthusiasm levels in teaching was highlighted.

An introduction to the following interrelated basic pillars of the project ensued:

- open hardware, which entails step-by-step explanatory manuals for the manufacturing of products,
- creative commons licenses, which enable the free distribution of creativity and knowledge,
- 3D printing, including 3D design programs, major materials used and 3D printed products,
- collaboration, as a crucial factor in educational projects.

Through this procedure, various discussions were triggered, which unveiled students' perception of the abovementioned concepts. Audiovisual and lecture-based exemplary topics took place by frequently switching from theory to practice. For example, students grasped the concept of open sharing knowledge systems by exploring Wikipedia, while they comprehended the idea of distributed production better by printing products. Furthermore, the power of collaboration was showcased by organizing a workshop in which different uses of a spoon were enumerated; at first each student individually, then merging the personal ideas into three-member groups and finally merging all together into the entire class, featuring the power of collective intelligence.

Regarding the allocation of the project's subtasks, there was an intent to form two working groups (involving five to six persons), both of which would handle the same tasks throughout the project. However, due to the high number of tasks and the openness of the educational procedure, smaller working teams were created. Each subteam included two to three persons and was planned to accomplish a part of the subtasks. The spontaneous segmentation of subgroups mainly by the students depended on their interests, skills and friendships and was indicative of the facilitating role of the educator.

During the whole project, students were free to undertake new tasks and work on various ideas via task rotations. To better coordinate the project, common cloud folders and a chatting group were created. At the beginning of each day a presentation of the advancements and new tasks of each team was taking place. Thus, required collaborations between the subteams could be planned and coordinated.

Another noteworthy element was the development of a blog (http://touchtosee.blogspot.gr/), where students could describe the educational project and share their experience. A team in charge of the blog was composed, which worked independently and turned to other subteams when necessary. For instance, the blog team announced the need for logo proposals, a task that was finally outsourced to students from other teams. The blog team also undertook the educational procedure with the aim to decide the blog name by calling their fellow students for brainstorming. Decisions were made through discussions, group collaboration and collective voting since conversation plays a vital role in learning (Papert, 1993). Considering the main goal of the project, the blog name "Touch to See" was born, as meaning that 3D printed objects could guide visitors with decreased vision and visualize the reality for them. Through the blog creation, students put the idea of sharing into practice by enabling the future iteration and improvement of the project.

Having investigated the requirements of the chosen 3D design program, students realized the necessity of making specific photo shootings. Therefore, an excursion for photo shooting local cultural and natural heritage elements was arranged. Particularly helpful for the visualization of the objects was a sketch of a local bridge made by two students (Fig. 4). During the editing stage of the pictures taken, students had to handle problems due to physical obstacles and shadows, which corresponded to holes and dark spots in the 3D model. In an attempt to deal with flaws of the pictures, students tinkered with the contrast and took some new pictures.

Having investigated appropriate software and attended tutorial videos for embossing images, students ended up to use "lithophanes" and printed the depicted image of a canyon (Fig. 5). Echoing Papert (1980), duration of technology use is a key factor for learners to become intellectually and emotionally involved. Having been introduced to 3D printers and design software programs, students had 25 days available to experiment and tinker with the technology and their solutions.
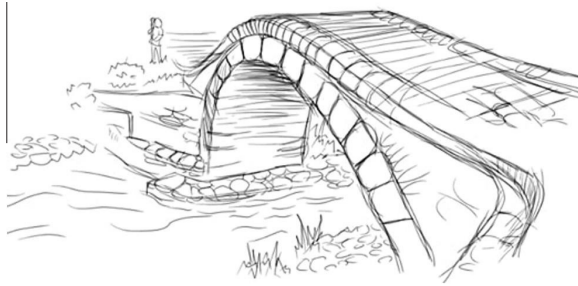
Fig. 4. Sketch of the bridge made by the students.
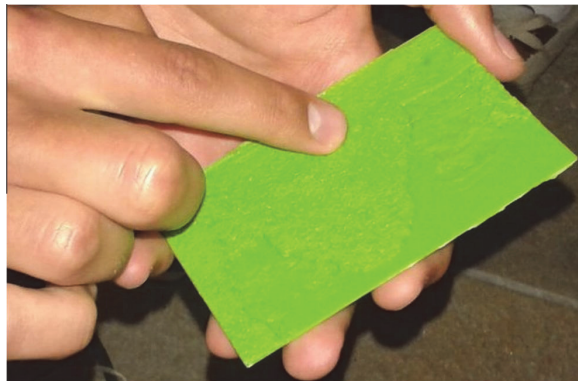
Fig. 5. A palpable lithophane of a local canyon printed by the students.

In the context of their common project, a 3D digital model of a local traditional stone bridge was manufactured by means of "123D Catch" program. In the meanwhile, another subteam offered to make a second design of the bridge through "Photoshop", so as to support the accomplishment of their task in case of the first model's failure. The sketches of the bridge were used for the second model to create a ground model with the landscape of Zagori, on which the first model, including the bridge, was placed. It should be also emphasized that we encountered difficulties in the creation of the 3D models via open-source programs due to their complex operation and their lack of usability. Thus, the proprietary program "123D Catch" was used, hampering the accurate implementation of our initial plan towards a completely open educational procedure.

During the project, learners were allowed to explore the research procedures by performing their own efforts, as it is believed that they learn better being in charge of their own learning processes (Freire, 2000; Papert, 1993). Students worked on appropriate adjustments and corrections of their 3D outputs through trial-and-error and turned to the teacher when needed. Thus, the facilitating role of the teacher was multi-faceted: to suggest cooperative activities among students, analyze their concerns, understandings and misconceptions, direct them towards their common goals and enhance further learning experiences.

Another crucial part of the educational process was the exploration of the blind or partially-sighted world. Role-playing games were organized to enable students to comprehend the reality faced by people with visual impairments (Fig. 6). Inter-net search and communication with the association of blind people of Ioannina city supplemented their deeper empathy of vision difficulties. In coordination with the aforementioned association, a visit of two persons with visual impairments was arranged in the midst of the project. The purpose of the meeting was twofold: first, students could break their possible prej-udices about blindness and become aware of the reality faced by people having visual impairments through their interaction and, second, students could get first-hand preliminary feedback for their artifacts.

At the time the visitors arrived, the first pilot models had been printed and the stone bridge was at the 3D modeling stage. Persons with visual impairments inspired students and gave vital feedback with innovative ideas for practical modifications of the objects. Namely, the existence of a human or animal figure which could contribute to the scale perception of the depicted objects, the addition of felt so as to simulate the different materials and the existence of an orientation symbol were proposed. Most of the indicated modifications for the artifacts were applied by the students, such as the inclusion of a pig (part of the regional fauna) in the bridge model, demonstrating the scale of the bridge.

Fig. 6. Exploration of the blind or partially-sighted world by the students.
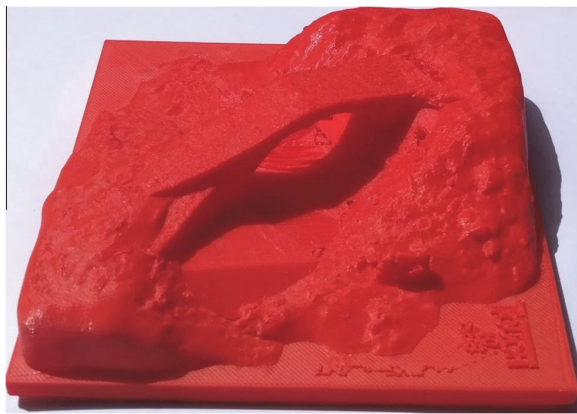
Fig. 7. Final artifact of the bridge.

Students' acquaintance with the Braille system was important for their communication with persons having visual impairments via the implementation of messages on the artifacts. A subteam was composed to translate and print texts to the Braille language. During the research, the subteam realized that the Braille language is not universal and started searching for web translators from English to Braille and from Greek to Braille, since the objects would be handed to Greek persons with visual impairments. Further improvements of the texts were achieved by considering several corrections proposed by the visitors.

Students came up with creative ideas, which derived from their dedication to the project and their interaction with persons having visual impairments. For instance, the existence of a natural stone material on the bridge model or the embodiment of water into the 3D printed bridge (possibly in a small bottle hidden inside the base of the bridge) which would give the sense of the water element, were nominated. Students developed a highly empathic perception of the way that persons with visual impairments perceive the environment. In their effort to substitute parts of the visual senses, students realized the importance of sensations and incorporated their understanding into the final artifacts in a creative and practical way (Fig. 7).

In the context of the experiential learning cycle, reflection was a significant tool to enable conscious learning at all stages of the educational process. Individual self-evaluations were made throughout the process by all students with the aim to recapitulate their previous tasks, check the overall schedule and plan their future steps. Lesson evaluations were taking place both at the end of each day and week, while ideas could be written on the "wall of ideas" anytime. A written idea, suggesting that each student could choose an object, print it and keep it as a memento, was found appealing by the majority. During the final evaluation of the project, students checked their initial expectations, recorded new ones that had emerged and valued the degree to which they had been satisfied.

4.2. Assessment of the educational process

Both primary and secondary research were utilized to complete our qualitative research methodology. Our involvement into the development and the implementation of the educational process was complemented by questionnaires handed to

both students and educators. The reason why we also deploy objective criteria, such as questionnaires from insiders (students) and outsiders (Greek educators), is to avoid prejudiced conclusions stemming from our engagement in the procedure. Next we try to compare our personal experience with the results of the questionnaires.

Students' participation and commitment to the project was expressed as they frequently continued their work beyond the course timetable. Their dedication to the project was also evident through their focus, their high-level cooperation and their creative ideas during the entire educational process. Furthermore, a remarkable incident occurred when the instructor and the substitute instructor had to be absent for two days during the second week. The professor kept contact with the students through the group chat created for the project's coordination trying to organize a creative day. The prompt students' response including a picture of them working and greeting (Fig. 8) unveiled their strong self-motivation.

We acknowledged three basic motivational elements which may had led to the empowerment of learners' engagement in our educational project: the technological, the anthropogenic and the educational factor. Delving into the aforementioned components, 3D printing technologies embody the modularity, creativity and adaptability that education requires. The anthropogenic aspect entails the consideration of the familiarity with the local community together with our intrinsic tendency to empathize. The innovative educational practices of the project encompass alternations among different types of teaching (including formal, informal and non-formal learning techniques) which can trigger pluralistic types of learners.

Six months after the end of this project, we prepared anonymous online questionnaires of four closed-ended questions, which we then forwarded to the Portuguese students and analyzed for content. The reason why we sent the questionnaires after a span of six months is to test the conscious recollection of students' experience of the project. The questions concerned the significance of open-source technologies, their potential and the individual weight of the aforementioned motivational elements (see Appendix).

We received eight out of 11 students' answers, all of which converged towards the catalytic role of open-source technologies (versus proprietary ones) in the teaching process. Students also agreed that they learned more through open-source technology, while one student answered that the use of open-source or closed-source technologies makes no difference in the obtained knowledge. All students except one used open-source technology at least once after the project's end. Among

Fig. 8. Students' engagement in the project during the absence of the professors.

the aforesaid motivational factors, the majority of students (six out of eight) replied that the 3D printing experience springs first to their mind. One student answered that he vividly recalls the meeting with the persons having visual impairments, while another mostly remembers the educational activities.

The effectiveness of the educational scenario was also evaluated by Greek educators of varying disciplines with the aim to communicate and scale our educational approach, so as more teachers could benefit in the future. A workshop was held in Athens, Greece, on the 25th of January 2017, in the context of an innovative program to transform education called Big Bang Academy. At a first stage, the "Ecotourism, education and 3D printing" project was presented to 38 educators, who subsequently had to create, present and reflect their own educational scenario. Based on the three basic motivational elements, teachers proposed creative ideas, such as a 3D printed model of a museum monument visited by the students.

After the completion of the workshop, each teacher was asked to complete a post-workshop online survey with five closed-ended questions. The first two questions pertained to the educators' previous experience and future plans for using open-source technologies. Half of them had already used open-source technologies in their teaching, while a greater portion was eager to use them in the future. In more detail, 57 percent of the teachers were confident enough to employ such technologies, 29 percent supported that they will use them, while the rest (14 percent) were uncertain about whether they will connect such technologies with their curriculum.

Although a significant portion (72 percent) of the educators who hadn't used open-source technologies before the workshop were impelled to do it in the future, there were educators who claimed that they won't use them. Possible reasons for their reluctance to use technological objects may pertain to their current unclear definition and newly-emerged concept. In addition, considering the contemporary socio-economic crisis in Greece, educational systems probably face difficulties in affording technological equipment, even an open-source, low-cost 3D printer.

Regarding the compatibility of the educational procedure with open-source and closed-source technologies, half of the teachers claimed that education is equally compatible with both types of technology. 43 percent positively rated the compatibility of open-source technology with education, while 7 percent assumed that proprietary technologies are more compatible with the educational process. Moreover, 86 percent deem open-source technologies as more suitable for the empowerment of students' critical thinking than the closed-source ones, while the rest (14 percent) view both types of technology as equivalent. The majority of the responses to the latter question accords with the related literature references, which reckon that open-source technologies advance users' critical thinking (Czerkawski, 2010, p. 215; Pellas, 2015).

Finally, the question regarding the students' motivational factors was also posed to the educators to enable the comparison between students' and educators' views. According to the educators, the employment of non-formal education in the teaching process serves more as stimulation for students to participate in the learning process (82 percent) than the utilization of technological means or the anthropogenic factor (9 percent). In comparison with students' responses to the questionnaires, Greek teachers valued the educational element of non-formal learning as the most important factor for enhancing students' motivation, while students strongly endorsed the technological factor.

5. Conclusions

The potential of new forms of learning was explored through a case study analyzed in this paper. Towards this goal, we used Kolb's experiential learning cycle and PAR approaches. In an effort to drift away from the notion that schools monopolize knowledge, we investigated alternative ways of fostering meaningful communication and collaboration through open educational practices. Rapid social, economic and political developments require transformative shifts in the educational structure of the contemporary interconnected world (Morgan, 2013). Aiming at the global accessibility of knowledge and the enhanced effectiveness of students' educational attainment, the use of open-source technologies in educational programs has been proposed.

Our 25-day long educational experiment shed light on the potential of open-source technologies as tools for creating and disseminating knowledge and communication. Building upon previous work towards the same direction (Kostakis et al., 2015), our educational scenario served a twofold aim: first, it confirmed the great potential of 3D printing as a motivational learning tool and, second, it added the aspect of 3D printing as a means for meaningful communication among people with and without visual impairments.

Based on the concepts of constructionism in a non-formal educational context, we developed our training model. Students engaged in hands-on explorations and manufactured models of natural and cultural heritage elements of the Zagori region. Via collaborative procedures, they familiarized themselves with project-based problem solving. Among others, they learned how to create three-dimensional models of natural objects, use a 3D printer and create a blog.

The created artifacts were handed to a group of people with visual impairments so as to spur communication with students, empower the educational process and improve the final result. The ultimate goal of the objects was to help persons with visual impairments to experience geocultural tourism. Among the three explored motivational factors for students' participation (technological, anthropogenic and educational), the majority of students claimed that the technological element intrigued them the most. On the other hand, Greek teachers considered the educational component as the most important.

The application of open-source technologies towards flexible and meaningful educational settings is challenging. In the context of contemporary schools, the required time to organize similar educational programs is usually hard to find. The willingness to deal with a considerable amount of uncertainty related to the use of such technologies has also to be

considered. Moreover, the familiarization of both teachers and students with open-source technologies is required as well as their keeping up with the technological advances.

Through internet-based information mechanism, experimentation and discussions, we attempted to transform the afore-mentioned obstacles of open-source technologies into tools for reaping additional benefits of the educational procedure. Of course, wider questions around the implementation of technologies in education, the educational potential of open-source technologies and the contribution of technology to contemporary school problems should be investigated. We hope to provide food for thought and guidance contributing to the development of proper teaching models geared towards learners' inclinations and needs, so as the education of the future could be prudently constructed.

Acknowledgements

Appendix

Descriptive table of students' answers	
1. Do you think that the use of open-source technologies, instead of closed-source ones, made your work:	
Easier	100%
More difficult	0%
Neither easier nor more difficult	0%
2. Do you think that the use of open-source technologies, instead of closed-source ones, made you acquire:	
The same level of knowledge	12,5%
More knowledge	87,5%
Less knowledge	0%
3. Which is the first thing you recall about the educational program?	
Non-formal educational elements	12,5%
The interaction with people having visual impairment	12,5%
3D printing	75%
4. Have you ever used open-source technologies in any way after the educational program?	
No	14,29%
Yes	85,71%

Descriptive table of educators' answers			
1. Do you think that the educational process is more compatible with:			
Both open-source and closed-source technologies			50%
Open-source technologies			42,86%
Closed-source technologies			7,14%
2. Which type of technologies do you think that enhances more students' critical thinking skills?			
Both types equally			14,29%
Open-source technologies			85,71%
Closed-source technologies			0%
3. How possible is it for you to use open-source technologies in a future lesson?			
Very			28,57%
Enough			57,14%
Little			14,29%
4. Had you ever used open-source technologies during your teaching before you participated in the Big Bang education workshop?			
No			50%
Yes			50%
5. Which of the following elements do you believe that motivates students in an educational program? Choose a number from 1 (most important) to 3 (least important).			
	1	2	3

The anthropogenic factor	9,09%	35,71%	38,46%
The technological factor	9,09%	50%	38,46%
The educational (non-formal) factor	81,82%	14,29%	23,08%

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Publication II

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The Emergence of Open Construction Systems: A Sustainable Paradigm in the Construction Sector?

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Abstract

This paper discusses how emerging issues in housing construction could revolutionise the building industry. It focuses on commons-based networks of organisations, technologies and users that form a niche practice on the margins of the dominant paradigm. This practice can be understood as "Design Global, Manufacture Local" and is exemplified by the Hexayurt, the Open Source Ecology Microhouse and the WikiHouse. Using these descriptive case studies, light is shed on the challenges and opportunities of open construction systems with regard to technological, institutional and social perspectives. Notwithstanding the positive dynamics, certain issues need to be addressed, so that a sustainable built environment could flourish.

Keywords: Construction, Sustainability, Digital commons, Open Design, Building, Open Hardware.

Introduction

In the framework of technological developments, efforts to make progress in the field of digital manufacturing have intensified. Both subtractive, such as computer numerically controlled (CNC) machines or laser cutters, and additive methods, such as three-dimensional (3D) printing, have been used for constructions in the built environment. Since these technologies are fed with digital 3D file types, digital design forms a vital part of the construction process.

Early attempts at deploying 3D printing in the built environment were limited to the production of architectural models (Bonwetsch, Kobel, Gramazio, & Kohler, 2006; Pantazis & Priavolou, 2017). More recently, buildings, bridges, and other building elements1 have been erected layer by layer using 3D printing technology. Besides, employing CNC machines sheets of various materials can be cut or milled accurately, which represent the entire wall panels of a building (Staib, Dörrhöfer, & Rosenthal, 2008).

At the same time, apart from technocratic-oriented approaches to foster innovation towards profit maximisation, hybrid forms of new organisational models have emerged. These models focus on the social context that defines and shapes the technological artefacts (Mumford, 1934). They take the form of localised, peer-to-peer networked communities of practice and adopt consensus-driven decision-making systems. Through

their participation and sharing of infrastructures, members of these communities collaborate and strive to attain their common goals.

Commons-based peer production (CBPP) emerged as an innovative way of creating value in a globally networked information society (Bauwens, 2005; Benkler, 2006). It involves collective attempts of communities, which utilise technological capacities to produce solutions and publicly share them. The outcome is that such communities empower others to use and broaden the recorded digital information for making products under specified protocols.

The advancement of information technology has reinforced the propagation of the CBPP movement. Through the use of online capabilities, intangible digital resources (such as information, software, and designs) can be distributed at low costs. Co-creation can then take place locally in distributed makerspaces equipped with simple tools and desktop manufacturing technologies (Troxler, 2011).

The convergence of the digital commons with local manufacturing technologies brought about a specific form of CBPP: the Design Global, Manufacture Local (DGML) model. The latter constitutes an iteration of the CBPP mode of production with commoning both in the design and the manufacturing process. Meanwhile, it is viewed as geared towards sustainability (Kostakis, Niaros, Dafermos, & Bauwens, 2015a; Kostakis, Roos, & Bauwens, 2016b), including economic, environmental and sociopolitical aspects.

As depicted in figure 1, this article is driven by concerns about the current global credit crisis, which dovetails with the bursting of the housing bubble (Holt, 2009). High prices within the current financial turmoil render houses unaffordable and lead to the augmentation of the homeless or those without adequate housing (Homeless World Cup Foundation, 2018). Also, the dominant model in the construction sector manifests low productivity rates and unsustainability, judging from the high percentages of carbon dioxide emissions in the industry (Green Building Council, 2018).
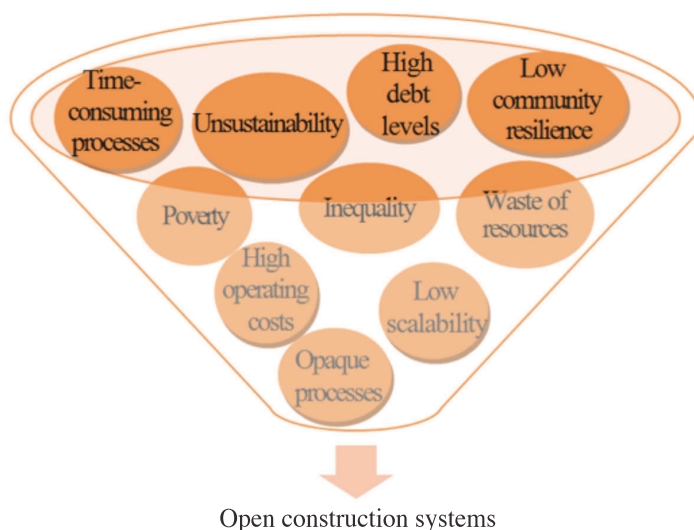

Open construction systems

Figure 1. The emergence of open construction systems

In an attempt to go beyond market-oriented practices and proven unsustainable frameworks of housing provision, the DGML model presents a process innovation in the construction sector. In line with the DGML principles, the concept of open construction systems emerged as a promising solution to pressing issues associated with the construction sector, which could facilitate the transition towards a circular economy.

In such a context, self-organised and collaborative communities exploit the new technological means to achieve their shared goals by utilising the power of collective intelligence under the focus of sustainability. Information exchange between distributed and networked communities fosters innovation. Through open licencing types, these technological innovations directly reach the public with the aim to settle pressing global problems related to poverty, inequality, and waste of resources.

This paper aims to incorporate the existing newly-gained knowledge on DGML practices in the construction sector. Through three prominent case studies of open construction systems, light will be shed on how such practices manifest themselves. These case studies can be understood as pre-figurative, seed forms that have the potential to disrupt and transform housing construction. Future societal implications regarding the implementation of open construction systems in the construction sector will be elaborated through the use of emerging issues analysis.

Literature Review

The concept of the commons dates back to ancient times. It refers to communities of people who collaborate and share common values, principles, and rules towards shared purposes (Bollier, 2014; Ostrom, 1990). These rules need to be set and followed by the community itself so that material resources (e.g., forests, water, land, etc.) can be managed in a fair manner. As a fringe benefit, the wide distribution of Information and Communication Technologies (ICT) has enabled the advent of a "digital commons", which appears in the form of internet-facilitated sharing of digital resources (Hess & Ostrom, 2007; Roos, Kostakis, & Giotitsas, 2016).

Revolving around the same frame of reference, do-it-yourself approaches unveil that the human intention of sharing infrastructures and acquiring autonomy has its roots far into the past. Such methods become evident through the correlated hippie culture of the 1950s, which evolved into the hacker and the maker culture over the following decades (Anderson, 2012; Kostakis, Niaros, & Giotitsas, 2015b; Troxler, 2011). However, when deprived of access to production means and internet connection, communities and individuals often end up reinventing the wheel. In this context, the role of makerspaces has become essential.

Makerspaces set the stage for sharing design processes, expertise, and tools while blurring the line between users and developers (Troxler, 2011). They facilitate the manufacturing process, as they offer physical places for the realisation and the dissemination of ideas (Buron & Sánchez, 2015; Niaros, Kostakis, & Drechsler, 2017). The availability of fabrication tools in makerspaces, and open designs on several websites (e.g., Thingiverse, Instructables, and GrabCad) introduces an entrepreneurial growth potential—that of decentralised and low-cost product development.

Benkler (2002) acknowledges that makerspaces inaugurated new ways of creating value by amalgamating human creativity; by shattering hierarchical barriers of organising production; and by rendering monetary motives secondary. Instead of treating technological artefacts as black boxes, people participate in the production process and have access to professional practices (Mota, 2015). In this way, they become inventive and autonomous by self-producing solutions to serve their needs.

Based on specific human features, such as sharing, intrinsic benevolent incentives and community accountability (Kostakis, Niaros, & Giotitsas, 2015b), CBPP arose as a socially-oriented mode of production (Benkler, 2006). New ways to co-produce solutions facilitated the emergence of free/open-source software (e.g., the Wikipedia encyclopaedia, the GNU/Linux operating system, and the Mozilla Firefox web browser), which, in turn, led to open hardware products (e.g., the Arduino microcontroller board and the Openbionics prosthetic hand) manufactured in local makerspaces.

The production of free and open-source software entails the sharing of technical knowledge and programming-like information by adopting licencing types that enable the free distribution of work. Open hardware goes a step further; it transforms the manufacturing process of physical products. The focus is on retaining the designs open in a growing common pool of information and co-

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creating technological artefacts with professionals (Abel, Evers, Klaassen, & Troxler, 2011; Illich, 1973). As soon as extensive manuals and designs of an object are uploaded, people can download them, experiment and feed suggestions back to the creators. Thus, the documentation can be peer-reviewed and tested globally to enrich the shared pool of information.

As a form of CBPP, the DGML approach introduces a shift from mass-produced solutions to customised ones. It describes the convergence of global digital commons with local manufacturing technologies (including 3D printers, CNC machines, laser cutters, etc.), as well as simple tools (like saws, drills, etc.). It emerged as a promising model of distributed production within the dominant capitalist system (Giotitsas & Ramos, 2017). Further, extensive discussions have triggered about the impact of DGML on culture through the idea of cosmo-localism (Ramos, 2017).

Echoing Kostakis, Latoufis Liarokapis, & Bauwens (2016a), three genuine components of the DGML paradigm include: the removal of planned obsolescence that describes the deliberate production of goods with a limited lifetime towards profit maximisation (BBC, 2017; Guiltinan, 2009); on-demand production, considering that the manufacturing process takes place in local makerspaces, hence transportation and environmental impacts are expected to be lower (Kohtala & Hyysalo, 2015; Kostakis, Fountouklis, & Drechsler, 2013); sharing practices and mutualisation of both digital (such as software and designs) and material infrastructures (such as makerspaces and shared machinery).

Considering recent concerns for sustainability (Taranic, Behrens, & Topi, 2016; Whicher, Harris, Beverley, & Swiatek, 2018), the DGML model could pave the way for sustainable practices in the built environment. This model entails the concept of modular design through the use of recyclable elements that could be deconstructed without damage and reused. Hence, repairability, recyclability, disassemblability, and upgradability of the manufactured components can be achieved (Bonvoisin, 2016).

The DGML approach is also characterised by flexibility in the design of objects via the use of parametric design tools. Digital 3D designs stimulate an ongoing interaction between the participants in the design process since they represent information easily grasped even from amateurs (Yap, Ngwenyama, & Osei-Bryson, 2003). More dimensions, such as financial data, material properties or energy characteristics, can be added to the building geometry through the concept of Building Information Modelling (BIM). The latter allows for advanced simulations—including structural tests, energy analyses, etc.—which enable a life-cycle management of buildings by increasing predictability levels.

Given the complexity of the construction process, few attempts have been made to apply the DGML model in the building sector. The next section illustrates how this emerging model has worked in practice by analysing three case studies, which are part of the environmental scanning process (Marien, 1991; Masini, 1993), as depicted in figure 2. Following the concept of emerging issues (Molitor, 1977, 2003), these case studies are used to shed light on the potential of open construction practices. The aim is to present an overview of recent and emerging issues related to open construction that are likely to have significant implications for the future of construction.

To identify pressing problems and opportunities that accompany open construction, emphasis should be placed on the fringes (Schwartz, 1991). This term refers to exceptional individuals who develop emerging issues, helping us comprehend changes in society (Lang, 1999). In this paper, the fringes in the construction sector will be pursued through the investigation of three case studies of open construction systems. The research framework is depicted in the following schematic representation (figure 2).
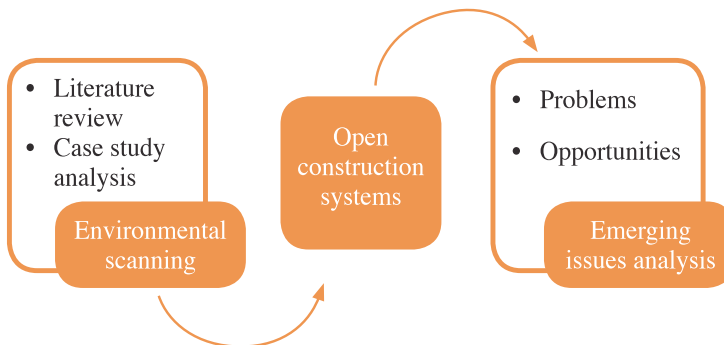
Figure 2. Schematic representation of the research framework

Open Construction Systems

In the absence of examined cases of open construction systems, this paper describes the manifestation of the DGML model in the construction process through three case studies. These case studies prefigure examples of change towards sustainable practices in the construction sector through open collaboration. The primary focus is environmental, economic and sociopolitical sustainability through community-based practices.

Despite the common focus of these projects, each is characterised by special local cultural, economic, social and political features that shape their goals, interests, and actions. For example, the Hexayurt project's target is to provide shelters which could be easily transported by refugee populations in the event of crises. On the other hand, being inspired by recent advancements in parametric design tools and digital fabrication, the Wikihouse, and the OSE Microhouse projects aim at developing sustainable, high-performance and autonomous building structures.

Moreover, these projects utilise different technologies for the construction of their main structure: simple conventional tools for the Hexayurt, 3D printing for the OSE Microhouse and CNC machines for the WikiHouse. The constructability of a specific structure is in fact limited by techno-political constraints. For example, it may seem more feasible for an emerging economy to build Hexayurts than WikiHouses or OSE Microhouses.

However, it is noteworthy that, despite differences between the global North and South (Bauwens & Niaros, 2017), makerspaces are currently spread around the globe (Niaros, Kostakis, & Drechsler, 2017; The Maker Map, 2018). The manufacturing process of all these structures is gradually enabled globally. It is also expected that further expansion of makerspaces and digital fabrication technologies will generate societal transformations (Gershenfeld, Gershenfeld, & Cutcher-Gershenfeld, 2017), leading to a new era of digitally designed and locally manufactured structures.

Differences also pertain to the organisational structures that are developed as part of these projects. For instance, the Hexayurt project surfaced as an open-source volunteer effort, while the community works with Science for Humanity to provide engineering plans of their works. For the WikiHouse project, the WikiHouse foundation was established to support and improve the common infrastructure through its collaboration with a global network of entrepreneurial coalitions, introducing new business strategies. Finally, the OSE Microhouse collaborates with a group of advisers, experts, and professionals who provide expertise on specific areas.

Case studies

The case study approach is useful for studying an emerging phenomenon (Radloff & Helmreich, 1968; White, 1977), as is the development of open construction systems. Out of the various initiatives in this movement, three case studies have been selected to exemplify how the DGML model has functioned in practice so far in the construction sector. Their selection is based on their broad scope and popularity in terms of the actualised projects, open designs available, worldwide replications and community members. Thus, based on the paper's research objectives, purposive sampling was used to study popular DGML solutions that matter most in open-source contexts. Further, the three case studies represent different modes of open construction as mentioned, facilitating an overall view of open construction initiatives and leading to comprehensive conclusions for the future of housing construction.

Considering that openness is a substantial element in this type of ventures, digital web tools are mainly utilised by the communities to document their solutions and communicate them to globally dispersed members. The mining of research data included various information sources of online communities (like fora, articles, social media groups, discussion sections, reports). Moreover, the communication channels of each project were accessed (e.g., WikiHouse Slack, Hexayurt Google Group, OSE wiki, facebook groups) to reach a shared understanding of the projects.

This paper also benefited from constructive discussions with Janek Siidra, manager at 3D Ekspert OÜ Company and lecturer at EuroAcademy and TTK University of Applied Sciences in Estonia. The purpose was to pinpoint established and innovative approaches within the construction sector, which could boost the driving force of the DGML model and act as guidelines for future constructions.

Hexayurt[2]

Geodesic domes are spherical building structures composed of triangular elements. Utilising the most efficient shape of nature, several geodesic domes have been developed through digital fabrication technologies (Buron & Sánchez, 2015). Nevertheless, issues related to the geodesic structure were traced—including high amounts of unused material and the need for specialised skills (Harriss, 2017).

In an endeavour to overcome these problems, the Hexayurt project was introduced by Vinay Gupta in 2002 as a modified geodesic dome. Hexayurt is an open-source construction set made of environmentally friendly building materials (like plywood, Oriented Strand Board, Hexacomb cardboard, etc.). It was developed as a simple disaster relief shelter for areas prone to tropical storms, earthquakes, and tsunamis, like Haiti. Classic, semi-folding and fully-folding Hexayurts can be built with simple tools, such as table saws (Appropedia, 2017).

Moving to the core of the Hexayurt construction system, a synthesis of triangle and rectangle combinations is observed; triangles are formed by cutting standardised sheets along the diagonal, minimising unused material (figure 3). Detailed documentation of the construction process—including information associated with common insulating materials (e.g., R+ Heatshield, thermax, and tuff-R), various types of tape (e.g., foil, bi-filament and vinyl), tie-down techniques (e.g., rope halo and tape-anchors) and the creation of paper models—is available online.
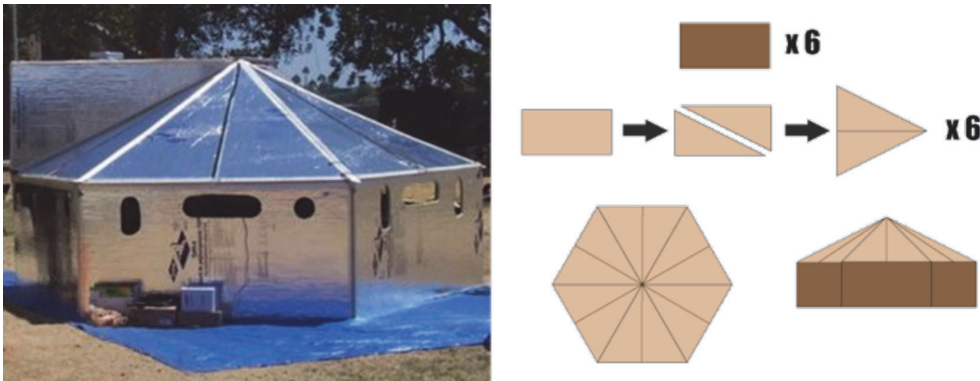
Figure 3. The Hexayurt project and its cutting models
Source: Adapted from Hexayurt, 2018b

Hexayurts are lightweight, fast and easy to build under the supervision of one coordinator, while the most straightforward cardboard-made structure costs approximately $100 (Hexayurt, 2018a). These factors rendered Hexayurts quite popular, as indicated at the annual Burning Man festival (Hexayurt, 2018a). Moreover, their geometry induced the interest of educators, who used it to organise collaborative learning activities for geometry (Banks, Wallace, Searcy, Sedas, & Peppler, 2017).

The Hexayurt prototypes are being developed by volunteers who perpetually improve the designs. For example, being a variation of a previous prototype, H13 Hexayurt was introduced to solve the problem of low door height. There are currently 13 Hexayurt design structures freely available to download, replicate and improve worldwide. The Hexayurt utilities package was developed as a transportable, autonomous infrastructure, including composting toilets, drinking water purification, solar electric lighting and fuel-efficient stoves (Appropedia, 2017).

Concerning future directions of the Hexayurt project, recent attempts focus on the use of more durable and recyclable materials, such as honeycomb polypropylene (Hexayurt, 2018a). Innovations in the development of its construction system have also been made (Erkelens, Akkerman, Cox, van Egmond, de Haas, & Brouwer, 2010). Moreover, additive manufacturing technologies have been applied in the structure, taking the form of 3D printed wall brackets as a way to facilitate the assembly (Eplaya, 2015). Finally, concerns about the structural performance of the Hexayurt and its vulnerability to high winds have led to the materialisation of model tests (Maxwell, Suskin, & Yang, 2012).

OSE Microhouse[3]

OSE is a volunteer collective of diverse disciplines, including designers, engineers, builders, and farmers, initiated by Marcin Jakubowski in 2003 (Open Source Ecology, 2018). The objective is to create a collaborative platform towards social and environmental justice through the manufacture of the Global Village Construction Set (GVCS). The latter includes open-source tools of 50 industrial machines (such as tractors, wind turbines, ovens, cement mixers, etc.) made of widely available raw materials (such as soil, limestone, hay, and wood) at a fraction of the corresponding conventional costs. Rapid prototyping, swarming construction and module-based design are key elements of the OSE initiative.

Sparked in 2013, the OSE Microhouse project targeted at the provision of expandable, ecological, affordable and autonomous housing (Open Source Ecology, 2018). Its modularity enables the concurrent building of different parts—including plumbing, electrical systems, and

building components. Through dedicated volunteers and OSE machines of the GVCS, compressed earth blocks can be manufactured out of soil and assembled by amateur builders (Reinhart, 2013). Thus, transportation costs are reduced, since the primary building material is damp soil subject to compression at high pressures.

In an attempt to democratise housing by using open-source tools and methods, OSE established a partnership with the Open Building Institute (OBI) founded by Catarina Mota in 2016. The aim was twofold: first, to create an open-source web-based library of modular building components (figure 4); and second, to organise theoretical and practical training programmes for the application of building principles (Open Building Institute, 2018).

Figure 4. The OSE Microhouse project and its building modules
Source: Adapted from Open Source Ecology, 2018

The creation of building designs is crowd-sourced and open to contributions. To address the specificities of various locations due to cultural, climate or resource scarcity reasons, the library is essential to grow. The more designs are submitted to the shared pool, the higher value is added to the system. These designs have been inspired by the idea of incremental house, which refers to the expansion of an initially small house to a more elaborate structure, according to the needs and budget of the individuals (Aravena & Iacobelli, 2016).

The library modules can be imported into open-source software applications, such as Sweet Home 3D and FreeCAD (Open Building Institute, 2018). The adoption of share-alike licences enables the free use, modification and redistribution of designs, which in turn encourages the participation of non-experts in the construction process. Sufficient documentation (e.g., construction details, energy properties, and static tests) accompanied by stamped engineering designs is also considered. To cultivate the possibilities of the project even more, advisers, engineers and business experts are recruited or voluntarily offer their expertise in technical details.

All Microhouse prototypes were built in the context of training workshops. In these workshops, participants acquire hands-on experience and training so that they can provide construction services, if necessary. OBI also offers relevant e-books and intends to organise webinars (on code compliance, building techniques, etc.) with the aim to help the public grasp the meaning of building regulations. Workshop tuitions and build service fees constitute sources of revenue for OBI. Moreover, a Kickstarter campaign was initiated in 2016 to support funding for the project (Offgridweb, 2016).

Looking back at the first prototype of the Microhouse, it consists of a 144 square feet tiny house with a loft, a kitchen and a bathroom. Several spaces, such as bedroom, living room, porch, utility room, and aquaponic greenhouse, were added later. The whole structure occupies an area of 2300 square feet in Missouri, USA. Newer prototypes were built based on experience gained

from previous OSE Microhouse versions. For instance, feedback elicited by observations of the construction of the second and the third prototype, respectively, brought out the necessity for detailed documentation and the brittleness of the 3D printed tractor.

With attention fixed on new prototypes, the quality of the structures in terms of thermal, structural and environmental properties was improved. Water-catchment, off-grid sanitation, insulation, and photovoltaics were also added. An 800 square feet aquaponics greenhouse allows for small-scale production of vegetables, fish, and mushrooms while providing passive solar heating in combination with a hydronic heated floor. The water and electric lines of the construction system were placed on easily accessible channels to facilitate their repairability or substitution.

Cost estimations of the OSE Microhouse prototypes indicate reductions of the total expenses at 1/3 of the corresponding conventional costs. Furthermore, the use of OSE machines adds to the acceleration of the building process (i.e., a house can be constructed within five day) and fosters sustainability, decentralised production, and autonomy (Garrido, 2010). Plans for this project include the processing of materials (such as steel, lumber, straw, limestone, and bioplastics) to build up structural strength and energy resilience, the development of mobile structures and the adoption of techniques used in other open-source structures (e.g., the WikiHouse) (Open Source Ecology, 2018).

WikiHouse[4]

The WikiHouse was initiated as a spinoff project by Alastair Parvin and Nick Ierodiaconou in 2011. According to Parvin (2013), the WikiHouse inaugurated a new model of open-source practice. The WikiHouse foundation was established as a non-profit legal entity in 2014 to support the expansion of the project. Among its primary targets, the maintenance of common infrastructures and open-source licences, fundraising and the coordination of co-operation between contributors (individuals, companies, governments, and organisations) stand out.

The idea of the WikiHouse is simple: crowd-sourced and freely downloadable designs are used to manufacture building components locally using CNC machines. It is an initiative geared towards the utilisation of digital infrastructures for the fabrication of CNC-cut wooden structural components (figure 5). The WikiHouse library currently features a house type called "MicroHouse", CNC-manufactured components, an internal door kit and two tools (a CNC-fabricated mallet and a step-up stool) used for the assembly of the chassis system. A GitHub web-based repository is used for file sharing.
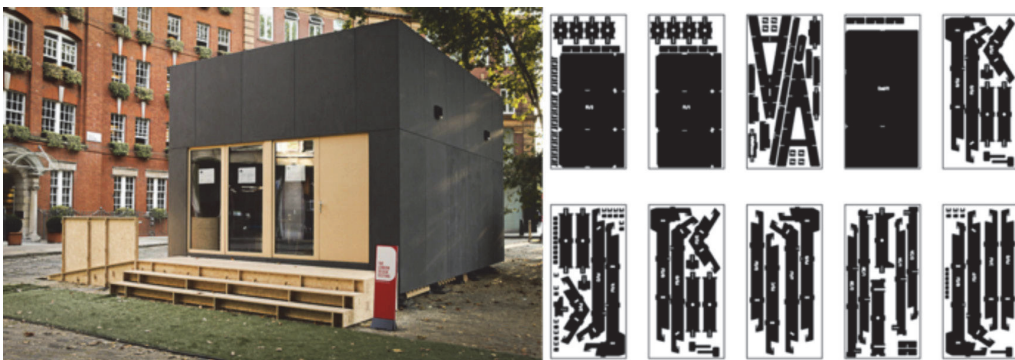

Figure 5. The WikiHouse project and its cutting models
Source: Adapted from WikiHouse, 2018b

There are, however, issues that need to be taken care of; the consistency of the WikiHouse structures around the world with local safety checks and regulations is not guaranteed and should be considered by the users (WikiHouse, 2018a). With this in mind, users should accept liability for the use of data and hire certified engineers or other professionals at certain building stages. For instance, architects should certify that the building complies with local building codes; structural engineers should recommend appropriate types of foundation; electricians or local builders should be consulted for technical support.

Partnership building with individuals, expert groups and companies globally accelerates parametric and hardware development. Entrepreneurial coalitions participate in the research and development of the WikiHouse and support its efficient performance across the building supply chain. To facilitate the entire process, the Builtx platform was founded in 2015 with the aim to perform international construction projects by integrating the digital supply chain infrastructure through digital fabrication concepts and BIM tools. Thus, minimum industry standards for the WikiHouse solutions are maintained, enabling its commercial use. In the UK, the WikiHouse construction set costs approximately £1000/m² (WikiHouse, 2018a).

The WikiHouse frame technology is called "Wren" named (after the eponymous bird). Its development was supported by a structural engineering company (Momentum Engineering Ltd), an architectural studio (Architecture00), a multidisciplinary firm (Arup Associates Ltd) and a social housing company (Space Craft Systems Ltd). In addition, individuals and expert teams are constantly working on its hardware and parametric development universally. The Wren chassis system is derived from a traditional timber-joining technique, which uses interlocked structural wood to produce lightweight and robust structures. Being developed to meet the climate requirements of the UK, widely available low-cost materials, like plywood, are usually used for the WikiHouse construction.

Under the assumption that buildings should be adapted to their local cultural, economic, environmental and political conditions, WikiHouse solutions have thrived in various geographical situations. Through community-led approaches, WikiHouse prototypes were developed by "Architecture00" (e.g., Farmhouse and A-Barn) and by other communities (e.g., dot-Architects Pavilion, WikiTower, and WikiStand, 2014). As the WikiHouse movement grows, experience is gained and returned to the global community, strengthening the digital design commons.

Outside the EU context, the first WikiHouse in Latin America5 was built in 2015 to spark interest for innovation among the favelas of the city of Rio de Janeiro. Moreover, the ongoing WikiLab project6 in Sao Paolo aims to adapt the WikiHouse technology to mild climates. Towards this direction, a large straw roof and a concrete block-based construction at the base of the structure were proposed in an attempt to overcome humidity and water permeability. On such a basis, the hydraulic equipment of the house could be placed on a concrete-composed part; thus, professional builders could build the concrete block part and join it with the wooden structure of the WikiHouse built by non-experts (Medium, 2017).

The "housing atelier" (Woningbouwatelier) is part of an ongoing program in the Netherlands focused on the future growth of the city of Almere. It includes the adaptation of the WikiHouse system to the Dutch building codes (Amsterdam Smart City, 2018). After which, 20 pilot prototypes will be built by non-professionals on a greater scale, yet with expected low costs (Medium, 2017). This project is financed by the City of Almere, the National Government and the Province of Flevoland.

The back-to-back opening of new chapters in the WikiHouse history comes as a testament of this initiative's success. The replication and adjustment of the WikiHouse globally allows its construction potential to be tested in various contexts. By adding their expertise into the common digital pool, contributors manage to raise the bar with respect to the quality of the existing infrastructure.

Discussion

The paper aims to identify the range of issues related to open construction systems and to discuss their broad implications for the future of the construction sector. Although it does not provide a comprehensive review of all the existing solutions or any actual measurements of the sustainability of these systems, it aims to serve as a starting point for relevant discussions.

The analysis of the three case studies provides more confidence in stating what the DGML model may contribute to a solid ground for sharing digital and physical infrastructures with long-term prospects for sustainable development. The three case studies delineate the concept of open construction systems. This section attempts to determine barely discernible issues associated with open construction that are likely to develop in the future.

The prefigurative examples of change presented through the three case studies have significant implications for the future of the construction sector and societal development. The focus is placed on the identification of opportunities and problems faced by these communities to expand the use of open construction systems. Relevant issues are analysed with regard to three interrelated aspects: technological, institutional and social.

Technological aspect

Parametric design tools can support the propagation of open construction systems, given that one-size-fits-all solutions of housing supply cannot work (WikiHouse, 2018a). The complexity of buildings together with a variety of regional contexts (with regard to climate, soil, regulations, etc.) renders the existence of parameters indispensable. Investment in information management through the use of BIM technology can support long-term decision-making processes, while robust planning could address quality and risk-related issues identified by self-build communities (Open Source Ecology, 2018).

Furthermore, communication protocols are necessary so that different stakeholders can address responsibility issues and cooperate harmoniously during the construction process. To facilitate transnational cooperation through BIM, national classification systems should be combined in international scale through the commitment on open standards (such as the Industry Foundation Classes). This would enable the participation of engineering firms in the research and development of open construction systems by offering technical support to communities across the building supply chain.

As far as the design part is concerned, a crucial element for the creation of an international, collaborative puzzle of structures via the use of open construction systems is standardisation. This term refers to the existence of a global dimensional framework to ensure common design guidelines (Open Structures, 2018). In this way, dimensions of the parts that compose a structure could be chosen according to a common global grid. These parts could then be assembled into components, which, in turn, could be combined into flexible structures and superstructures. The construction of a building could, thus, be analogised to the formation of an organism (Open Structures, 2018).

Another integral part of the process is the existence of detailed open-source documentation, as well as its ongoing update. Architectural data (e.g. digital drawings and calculations), construction data (e.g. model tests and building methods), technical, chemical and biophysical details (e.g. weather conditions and subsoil), costs (e.g. materials and equipment) and environmental requirements (e.g. recycling, water and depletion) should be extensively documented, facilitating the widespread replicability of open hardware solutions through easy-to-follow manuals (Bonvoisin, 2016).

Experimentations with new materials could improve open construction systems. Instead of monolithic materials (such as plywood, cardboard, etc.) mainly used during the introduction of these buildings, advanced materials, such as nanotechnology, bioplastics, and composites, could also be

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tested. However, given the difficulty of distinction between organic and industrial materials included in biocomposites, special care should be taken to ensure the recyclability of the new materials. The goal is to attain energy savings, structural capacity, as well as higher resistance to heat and moisture in extreme weather conditions through the use of environmentally friendly materials towards future circularity.

Institutional aspect

Open construction systems are promising, but the regional variation of building regulations and zoning codes is challenging. Although the International Building Codes reflect the best practices based on construction experience and technology, local regulations vary from country to country and from context to context. For example, in parts of Missouri, USA, there are no building regulations (Open Building Institute, 2018), whereas in the UK building permissions can be evaded as specified by a set of laws (Knight & Williams, 2012).

The creation of simplified databases with regulation-related documents per country is believed to give prominence to the benefits of building open construction systems at local levels (Open Building Institute, 2018). Also, by taking advantage of the non-existence or ambiguity of regulations, loopholes in building codes allow communities to operate in a more restriction-free manner (Knight & Williams, 2012).

The embedded modularity of open construction systems allows for the mitigation of spatial barriers, which come from differences between strict building regulations. In that sense, modularity enables flexibility, which, in turn, facilitates compliance with the building codes: by replacing specific modules with others; by substituting materials; by adding or removing modules to meet geometric constraints. Moreover, modular design facilitates the disassembly of a structure into building modules, which can be modified, substituted and upgraded independently, as well as undergo physical tests in response to varying circumstances.

Despite their inability to address issues of inflated land prices and unequal access to resources, open construction systems seem to attract political support, like the case of the ongoing WikiHouse project in Almere. The reason for this could be the increasing demand for sustainable housing in the developing world and the mounting number of low-income groups in the developed countries. Within oppressive austerity policies, it is possible that local authorities will start financing open construction systems as low-cost technological solutions. Otherwise, communities should keep struggling to raise funds, which come from donations or other sources (e.g., selling manuals and offering service-based support).

Finally, the institutionalisation of such dispersed informal teams or individuals is vital for the expansion of these initiatives. These groups strive to advance their initial ideas and engage professional groups in the actualisation of their projects. As more professionals and organisations get involved over time, institutional constraints will be eliminated (Molitor, 1977).

Social aspect

Enabled by information technologies, open construction systems attempt to provision housing in a creative, socialising and convivial way. People enjoy greater potential when working within collectives, leading to the renaissance of pre-industrial architecture through community-based building. In this context, citizen-driven initiatives try to provide affordable and sustainable housing. Digital fabrication technologies may be helpful tools towards this goal, given that they translate digital data into physical objects. Consequently, the thresholds of skills, cost and time needed for the construction are lowered together with the relevant transportation and socio-environmental costs (Kostakis, Fountouklis, & Drechsler, 2013).

Moving beyond market economy systems, low-cost, adaptable and sustainable solutions can be produced in localised settings. The soil nourishing the shared infrastructure of the global

digital commons can continuously be expanded by contributors around the world. Beyond that, the availability of various building types under open-source licences fosters experimentation and the ability to develop combinations of the best or most appropriate elements for each situation.

The implementation of the DGML model in the construction sector introduces a radically different approach from that of the dominant model. In cases like the building process, where stakeholders with various interests are involved, conflicts are unavoidable. For instance, open construction systems may seem as a long-term sustainable solution to global issues for the open-source communities. On the other hand, the sharing of infrastructures may threaten the short-term profit-oriented goals of the construction companies.

A redefinition of roles and responsibilities of all parties involved in the construction process—including governments, self-build communities, engineers, and asset-owners—is required. Thus, we need to witness behavioural change towards resource efficiency and sustainability. For example, supporting services and consultancy could be purchased instead of tangible objects and systems could be developed and monitored in collaborative environments instead of competitive ones.

Considering the newly-published information around open construction, the scalability of such emerging initiatives and their future ability to outcompete the dominant construction model in terms of quality or safety may be questionable. However, the success of open-source initiatives in the past has given prominence to the importance of human participation. The latter may be increased by promoting global awareness of the sustainability features of the open-source movement, as well as of the circular economy features embedded in the use of open construction systems.

By empowering proactive and knowledgeable citizens globally, more individuals, collectives, and firms would be contributing to the improvement of open construction systems and the related policy making. In this way, the development of flexible modular structures via a common dimensional framework could prompt the completion of the universal building puzzle. Yet no one could question the role of education to prepare the participants for new building practices and build resilience at a global scale.

Despite the efforts of these open-source communities to solve pressing future challenges, form new business strategies and become institutionalised, these projects remain marginal. However, their momentum to provide affordable and sustainable housing affects many. Their mounting social impacts increase the chances for these innovative initiatives to evolve into an important issue. Especially by intensifying the testing of solutions with the aid of a global network of contributors, these communities could be integrated into the mainstream and challenge the status quo.

Given the current global credit crisis and sustainability concerns, the DGML model creates new ecosystems with the potential to grow more widely. The key systemic factors that enable this proliferation include: the broad diffusion of low-cost ICT and internet connectivity, the development of the relevant culture around openness and sharing intensified by the widespread means of information sharing, and the ecological crisis that creates higher demand for more sustainable and circular economy-based models.

Finally, the DGML model has the flexibility to adjust to different needs and contexts, as well as provide solutions to various issues, which may correlate to market failures in the global North or the inexistence of relevant infrastructure in the global South. Thus, it may fill the gaps of market-based solutions for sustainable housing through the development of alternative systems of housing provision, while providing affordable housing to the people in need.

Conclusion

This article contributes to the understanding of how individuals, companies, and governments could come together to promote a sustainable built environment. It represents an attempt to shed light on the dynamics of the emerging open construction systems implemented through DGML

approaches. The entire debate regarding open construction systems has gained momentum in light of the growing concern about global pressing issues.

In this context, three case studies were used to elucidate the ways and means by which the DGML model can further sustainability in the construction sector by sharing physical and digital infrastructures. These case studies see the construction process as a community-driven procedure that unfolds outside the market economy. The relevant challenges and opportunities were elaborated upon.

It is concluded that the implementation of the DGML approach in constructions calls for drastic changes in current practices, in the role of various stakeholders and the scale of the processes. Especially new business strategies surface with the involvement of advisers, developers, business and organisational experts in citizen-driven projects, providing expertise on all stages of the building supply chain. The necessity for institutionalisation of the communities involved, as well as the existence of a standard design grid to enable large-scale constructions, could boost the potential of open construction systems, maximising their social impact.

A limitation of this paper is that the problems and opportunities that accompany the implementation of the DGML model in the construction sector were identified but not directly addressed. Technical evaluations of open construction systems could estimate the degree of sustainability of these structures. Hopefully, this article will prompt discussions among industry practitioners and trigger explorations worldwide.

Acknowledgements

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Notes

1. See for example:
   http://apis-cor.com/en/
   http://www.winsun3d.com/En/
   https://www.tue.nl/en/university/departments/built-environment/news/17-10-2017-worlds-first-3d-printed-reinforced-concrete-bridge-opened/#top
   https://www.dti.dk/projects/3d-printed-buildings/36993
2. http://hexayurt.com/
3. http://opensourceecology.org/wiki/OSE_Microhouse
4. https://wikihouse.cc
5. http://wikihouserio.cc/
6. https://wikilab.blog.br/

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Article

Assessing the Openness and Conviviality of Open Source Technology: The Case of the WikiHouse

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Abstract: The housing crisis has received growing interest from academia, industry, and policymakers. Open construction systems have emerged as a promising solution to achieve long-term social, economic, and environmental sustainability. In this paper, extensive fieldwork was conducted to investigate a case of an open construction system, namely, the WikiHouse Den Bosch. The research framework builds on a combined view of two main concepts: "conviviality" and "openness". The aim is to provide an in-depth understanding of the relationship between these two aspects and the literature regarding "Design Global Manufacture Local". The analysis showed that conviviality and openness are complex and context-specific factors. The paper concludes by outlining the need for an "institutionalized conviviality" to open up new pathways for future practice to address sustainability issues.

Keywords: conviviality; openness; commons; open hardware; WikiHouse; open innovation

1. Introduction

With increasing access to information and communication technologies (ICT), the commons, and particularly the production of digital commons is blossoming [1]. Commons-based peer production (CBPP) surfaced as a way of self-organizing communities towards value creation [1,2]. By placing the users' needs and values at the center of attention, globally networked communities use and modify the recorded information to produce customized solutions that best serve their needs. The communities then publicly share their products and offer feedback to enrich and strengthen the existing collective knowledge. The free encyclopedia Wikipedia and free/open-source software initiatives such as the GNU/Linux operating system and the Wikipedia encyclopedia exemplify this new mode of production.

The emerging open source hardware (OSH) phenomenon is transferring open source software principles into the physical realm [3]. Open design and distributed manufacturing have been enabled through networked "makerspaces" [4,5]. Such community-driven places are equipped with desktop manufacturing technologies including digital tools (e.g., three-dimensional (3D) printers, computer numerically controlled (CNC) machines, and low-tech tools) and utilize inclusive decision-making processes to manage common resources [6,7]. Thus, collaboration and access to shared infrastructures are fostered, offering space for people to socialize and co-create [5].

The Design Global, Manufacture Local (DGML) approach has emerged as a production model that focuses on localized production settings via a network of distributed makerspaces [8,9]. It builds on the convergence of global digital commons (i.e., knowledge, software, and design) with local manufacturing technologies, by taking into account the surrounding biophysical conditions [9]. The reduction of transportation costs and the expected low environmental impact of locally produced

solutions are considered as significant benefits of this model [4]. Furthermore, on-demand production, sharing physical and digital infrastructures as well as the production of solutions towards a common good rather than profit maximization are key components of the DGML model [9].

Notwithstanding the positive dynamics of the DGML approach in the production of tangible artifacts, concerns have been raised with respect to: (i) the existence of a comprehensive shared documentation that renders a hardware product "open" [10]; and (ii) the level of autonomy the user has while developing and maintaining that product. To explore such issues, we looked at the construction sector. Considering the low productivity rates and unsustainable practices unveiled through the bursting of the housing bubble [11], the potential to produce more convivial houses through community-driven processes was explored.

By applying DGML principles in the construction sector, we refer to open construction systems as a potentially sustainable approach in housing provision. Through community-driven practices, pressing issues related to the lack of transparent and sustainable processes could be addressed [12]. The embedded modularity of such systems, together with their momentum to provide affordable housing in a collaborative and convivial way, is gradually increasing their social impact, affecting large parts of the Western and non-Western world [13].

In line with the DGML model, open construction systems attempt to provide affordable housing in a creative and convivial way. However, safety issues related to the construction of a DGML house have been identified [12]. Overcoming such issues will potentially inaugurate a new paradigm in building houses where the users feel in control of constructing and maintaining their houses.

An instrumental case study was thoroughly examined to assess certain features of an open construction system, that of a WikiHouse [14]. These features are associated with advantages that refer to the conviviality as well as the drawbacks that pertain to the openness degree of the WikiHouse technology. The latter has been claimed to inaugurate a model of open-source practice towards the democratization of the construction process [15].

In this article, the comprehensiveness of the published data and the relevant practices will be discussed for a specific WikiHouse technology. Through evidence-based analysis of the relevant dynamics, we will shed light on the conviviality and the openness potential of a WikiHouse. The aim is to critically assess the conviviality potential of a DGML artefact and examine the role of openness in enhancing DGML features. An in-depth understanding of the relationship between openness and conviviality as well as their interrelation with the DGML approach for producing technological solutions will be explored.

The rest of the paper is organized as follows. Section 2 describes the theoretical background associated with the DGML approach and the concepts of conviviality and openness. Section 3 provides information on the methods used and the selected case study, while Section 4 reflects on the previous sections by analyzing and summarizing the connection between the above-mentioned concepts, while Section 5 presents our conclusions and provides recommendations for future research.

2. Theoretical Framework

2.1. Design Global, Manufacture Local in a Nutshell

The DGML approach aims to create communities whose incentives and relationships differ from the dominant mass production model [16]. Utilizing democratic procedures and participatory processes, such communities produce and control technologies locally. The produced designs are uploaded, shared, and freely available to further modify and/or upgrade. Thus, innovation is accelerated, while customized low-cost solutions can be developed and maintained by non-experts according to their preferences. Hence, new ways of value creation are inaugurated by utilizing human creativity, removing hierarchical barriers of organizing production, and deprioritizing monetary motives.

The conventional industrial model of mass production differs from the DGML model mainly in terms of scale, incentives, and collaborative features. Focusing on bottom-up value creation patterns,

participatory processes are developed by users who asynchronously collaborate and share common infrastructure. DGML projects produce solutions strengthened by the power of collective intelligence and cooperation [17]. Sharing practices and mutualization of digital (including design and software applications) and physical (including shared machinery in makerspaces) resources are utilized to produce commons-based technologies through democratic decision-making processes.

Another aspect of the DGML model is on-demand local production. Environmental sustainability is fostered, thus reducing the need for the transportation of raw materials and machines and the associated environmental costs [4]. The embedded modularity in DGML artifacts enables the development of structures that can be easily replicated, modified, and customized by separating and recombining smaller parts (modules) of the whole system. Thus, people can work on different modules in an independent and distributed way, making adaptable structures according to their needs.

Finally, following the industrial production paradigm, planned obsolescence tends to force consumers to purchase new or upgraded versions to maintain the functionality of their products [18]. Removing planned obsolescence and profit-oriented incentives through commons-based initiatives signify that such communities prioritize environmental, social, and economic justice [19]. Although no sound empirical evidence has assessed the sustainability degree of a DGML artifact, it is considered that such communities design and produce solutions towards sustainability [16].

2.2. Defining "Conviviality"

Through the analysis of the features of DGML, it becomes evident that conviviality constitutes a core element of this productive model. Ivan Illich [20] introduced the concept of conviviality to emphasize the importance of creativity, autonomy, decentralization, and the construction of technology in a social manner [20–22]. In modern industrial production, people rely on specialists to produce the necessary tools to satisfy their needs. In contrast, conviviality fosters the control of the use of resources and promotes friendly relationships and reciprocity between individuals and their environment [23,24].

Moving away from the planned obsolescence of the industrial paradigm, conviviality provides a new approach to rethink the way of designing products, services, and associated technologies [25]. Such designs empower users to grasp a technological product, experiment, and adjust it.

Illich spoke of "tools for conviviality" that "foster conviviality to the extent to which they can be easily used, by anybody, as often or as seldom as desired, for the accomplishment of a purpose chosen by the user" [20] (p. 22). Although there is no fixed definition of "convivial tools", Illich [20] has formulated a set of criteria/conditions that qualify them: (i) convivial tools are easy to use or require learning by doing (i.e., no preparatory education or certification by specialists is demanded to use the tool); (ii) they are at the user's judgment regarding whether and when they are used; and (iii)s they are adapted to the user's preferences and not the other way around [20,26].

A distinctive example of a convivial tool is the bicycle. As a relatively easy tool to comprehend, repair, and adjust, the bicycle can be considered as a highly convivial tool [23]. New bikes can be produced by reusing spare parts, while several modifications are possible such as adding a child seat or an electric motor based on the user's preferences. Furthermore, individuals can autonomously transport themselves, hence decreasing their reliance on other expensive transportation means [23].

It should be noted that conviviality is not applied only to low-tech tools, but is also relevant to more sophisticated technologies. Highly complex OSH products combine several technologies that consist of different parts and are designed to meet demanding needs [27]. Still, all tools have a conviviality potential, provided they meet the requirements mentioned earlier in this section. However, the distinction between "convivial technologies" and "convivial tools" should be highlighted. While Illich [20] spoke of "tools", referring not only to artifacts but also to rationally designed institutions such as schools, other scholars have shed light on different aspects of technology. These might entail processes like the design phase of an artifact as well as the relevant know-how concerning the manufacturing, use, and maintenance of a product [28,29].

Indeed, Illich [18,20] concentrated on the use of tools, without considering the production phase. The latter was taken into account by Andrea Vetter [30], who developed the "Matrix of Convivial Technologies". This matrix aims to define and measure the conviviality potential of a technological artifact during several phases of its development process through empirical research (see Section 3.1).

Although conviviality is seen as an essential factor while practicing DGML, it might not be sufficient to secure the successful realization of this productive model. Hence, this article also explored the concept of openness, which is a core value in the DGML setting.

2.3. The Concept of "Openness"

Echoing Balka et al. [3] and von Hippel [31], openness pertains to (i) transparency (freedom to study); (ii) accessibility (freedom to edit/modify); (iii) replicability (freedom to make); and (iv) commercial usability (freedom to distribute) of information required for a product's sustainable development. These four criteria are respectively met when: (i) Computer-aided design files and schematics are published; (ii) all published information is editable, therefore enabling others to participate in the design process; (iii) the bill of materials and assembly instructions are published; and (iv) the commercial usage and free redistribution of the published information are permitted via relevant licenses [10].

Furthermore, Aitamurto et al. [32] focused on two aspects of openness related to the process (whether it is open or closed), and the product (whether the outcome is open or closed). However, defining a work as open or closed is rarely a binary decision. The spectrum of openness is quite broad, encompassing several degrees of openness. At one end, the work is "closed" if the creator excludes others from its use, while, at the other end, an "open" work is available to and modifiable by all. Hence, the question should be "how open" a process or a product is [33].

Attributes such as transparency, accessibility, and replicability determine the degree of openness of a particular work. Nevertheless, restrictions on observing, modifying, or replicating a work may be applied including the exclusion of commercial use or a membership requirement [3]. Intellectual property rights in licenses may be used to set the degree of a product's openness [34].

It is generally acknowledged by both scholars and practitioners that sharing a piece of hardware online is much more complicated than sharing a piece of software, while software is digital by nature, hardware may require more sophisticated tools to be displayed such as modeling and design tools [35]. Furthermore, based on the evaluation of 20 OSH projects that included both hardware and software components, Balka et al. [3] argued that hardware components were less documented than those of software. This fact raises the question of whether a poorly documented piece of hardware is open source or not.

Through the increased utilization of ICT, the benefits of openness are becoming more evident and are likely to grow [33]. Once the design of a product is openly shared, billions of people have access to it. This diffusion enhances the reputation of the product, while often positive network effects are applied [36]. Additionally, those who can manipulate the design can improve or suggest improvements to the product, benefiting both the innovator and users [33,34]. Finally, keeping a design closed may be much more costly when compared to leaving it open to others to access and use [34].

These benefits, along with the power and ethics of openness, have led to the creation of a strong brand that is universally admired and respected. Users have a growing desire to experience transparency in their services, so openness is becoming a key feature [37]. Hence, many organizations wish to associate with it. However, if an organization cannot adjust its business model to become open, then it redefines the meaning of "openness" to fit their practices. Members of the open community usually recognize such behaviors and describe them as openwashing (i.e., "to spin a product or company as open, although it is not.") [38].

3. The Case of the WikiHouse Den Bosch

The WikiHouse Den Bosch is an ongoing initiative in the Netherlands. It aims to respond to the housing crisis via the development of innovative forms of housing. As explained in this section, our case study was chosen since it exemplifies the DGML model and allowed us to explore the conviviality and openness dynamics of the WikiHouse technology.

3.1. Materials and Methods

Given the importance of mixed research approaches and data gathering techniques in case study research [39], several methods were implemented to achieve our specific goals (see Figure 1). First, personal communication with key informants [40] was useful to obtain first-hand information on the WikiHouse technology apropos the Dutch context as well as the development of the case of WikiHouse Den Bosch. Four interviews, supplemented with informal discussions with key stakeholders of the initiative, took place over three weeks in the Netherlands in October 2018. Semi-structured interviews were selected, offering the opportunity to the interviewees to discuss what they deemed most important and reach a common understanding regarding the issues explored. The core questions of the interviews attempted to reveal the goals, internal processes, values, and interests of the researched groups.
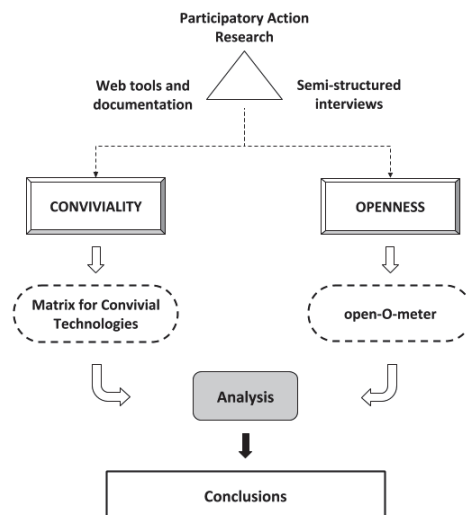

Figure 1. Research framework.

Additionally, a participatory action research approach [41,42] was utilized to provide experiential insight into the construction of a WikiHouse through collaborative processes. Field observations were conducted at Minitopia Poeldonk, where the WikiHouse Den Bosch will be placed once completed. During the aforementioned period of stay in the Netherlands, one of the authors assisted in the construction of the WikiHouse Den Bosch, where interaction with members of the case study took place on-site, attaining a more unobstructed view of the internal processes of the groups observed [39]. While one of the authors actively participated in the development of the selected case study and provided critical checks regarding the responses of the community members, to avoid bias and preconceived notions, the other author critically examined the overall process.

Furthermore, digital web tools and other documentation were also used for triangulation [43]. Online platforms, discussion sections, and available forums as well as email communications with individuals from the case study were utilized for data gathering. Several documentation tools and

sources including reports, articles, audio-visual material, and blog posts were easily accessed due to the openness element that permeates open source initiatives.

In this paper, the conviviality and the openness aspect of the WikiHouse were explored through a case-study by utilizing two tools (Figure 1): a qualitative one (the matrix of convivial technology, MCT) and a quantitative one (the open-O-meter). The former was used to discuss the WikiHouse technology in a structured manner, highlighting the importance of the social construction of technology. By empirically assessing Illich's theory on conviviality, the matrix of convivial technology has been developed, enabling the self-assessment of groups that use or adapt technology towards a social, economic, and ecological transformation [30].

The MCT includes the four life-cycle levels: material, production, use, and infrastructure. Each of these levels is correlated with five dimensions that define convivial technologies based on the group's values and practices. These dimensions are (i) relatedness, which refers to the human capability to relate to others; (ii) accessibility, which answers the question of who, where, and how can build or use a technology; (iii) adaptability, which explores someone's willingness to be independent (through the concepts of modularity and scalability) or linked; (iv) bio-interaction, referring to the usefulness of the produced materials for the living organisms; and (v) appropriateness, which correlates the input and output considering the local context. Although the MCT was developed so that it could cover a wide range of technologies, each technology needs to be adapted to the local needs. Thus, the MCT was developed in word-pairs including antagonistic terms that can be omitted and/or adapted to the users' needs (see Appendix A).

The second tool used, the open-O-meter [44], refers to the degree of openness of the WikiHouse technology, which enables its democratization and widespread replicability [45]. It is a simple quantitative tool that uses eight criteria to calculate the openness index of a technology. These criteria include the publication of the design files, assembly instructions, a bill of materials, the availability of all of the information in an editable format, a contribution guide, and the free distribution of this information under a license allowing commercial reuse [44]. If a product fulfills all of these criteria, its openness index equals eight (see Appendix A).

3.2. The WikiHouse Den Bosch

Across a broad spectrum of open construction systems, the WikiHouse project was selected. The latter allows for the production of modular, lightweight, and structurally-robust buildings through its Wren chassis system (Figure 2). It was initiated in 2011 by Alastair Parvin and Nick Ierodiaconou as an innovative way of designing and sharing construction packages online [46]. The power of the WikiHouse rests on its ability to globally share designs, while testing, improving, and enriching knowledge via digital fabrication tools. All this information is maintained by a non-profit legal entity based in the UK, the WikiHouse Foundation, which aims to promote collaboration and create feedback loops among the ever-growing global WikiHouse community [46].
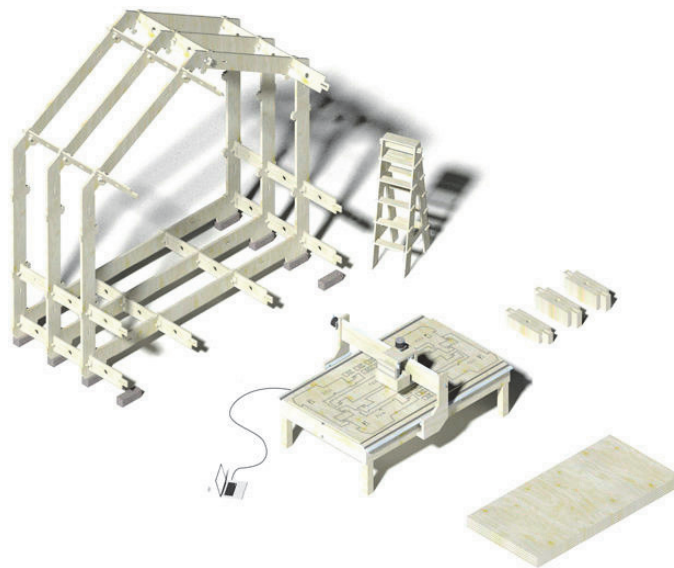
Figure 2. The WikiHouse building parts (Wikiparts). Source: WikiHouse.cc.

The expansion of the WikiHouse project renders it a popular construction system in the Western and non-Western world [47]. Our research focused on the Netherlands due to ongoing local activities related to WikiHouse development. Following the growing demand for affordable housing, several WikiHouse initiatives have emerged in the country, ranging from individual houses to collective efforts on a larger scale. Such initiatives are supported by the WikiHouseNL Foundation, the Dutch department of the WikiHouse Foundation [46].

For instance, the Woningbouwatelier ("housing atelier") in Almere brings together new concepts, knowledge, and experience of innovative parties in the field of housing. The goal is to produce WikiHouse buildings that can be easily assembled by non-experts that conform to the local building codes [48]. Another example is that of Minitopia in 's-Hertogenbosch (colloquially known as Den Bosch), where experimental forms of housing including a WikiHouse are being developed as a response to the high housing demand [49].

Minitopia was launched in 2016 in 's-Hertogenbosch by Rezone, an initiative that develops projects at the intersection of architecture and art. Minitopia aims to create small, temporary, cheap, and sustainable houses with increased citizen engagement [50]. At first, Minitopia was located at Eekbrouwersweg, using a property owned by the housing corporation Zayaz. In June 2018, Minitopia moved to Poeldonk, an industrial estate owned by the Municipality of 's-Hertogenbosch. This new location can host up to 25 temporary houses that residents will build in part or entirely by themselves and may use for a maximum of five years (Figure 3).

Figure 3. The Minitopia Poeldonk area. Source: Tessa Peters and Rolf van Boxmeer.

Patricia Sips was one of the five tenants allowed by Zayaz to build their own home in Minitopia. She opted for the WikiHouse, and like all participants in Minitopia, she received a residents' budget to bring her ideas to life with the help of volunteers around the globe. Her initiative was called WikiHouse Den Bosch (Figure 4).

(**A**)   (**B**)

Figure 4. (**A**) Constructing the WikiHouse den Bosch. Source Tessa Peters and Rolf van Boxmeer; (**B**) Placing the WikiHouse Den Bosch. Source: Tessa Peters and Rolf van Boxmeer.

Its construction began in September 2018 and it finally opened its doors in March 2019 [51]. The community of contributors consisted of 22 people, aged between 25 to 65 years old. Five were consistent members throughout the construction process, while the rest of the contributors spent from three to 30 days. The gender balance was equally divided between females and males. In terms of the available expertise, it ranged from artists to business consultants, teachers, and engineers including both university students and retirees.

The design of the WikiHouse Den Bosch was developed by both Rezone and Patricia Sips [52]. Two main aspects were taken into account: (i) design for modularity (four distinct units could be combined, taken apart, and transported separately); and (ii) design for sustainability (second-hand and reusable materials were preferred). Special attention was paid to increase energy-efficiency and affordability. Hence, a 44 square-meter structure was built (Figure 5) that cost less than 38,000 euros [52].

Figure 5. The WikiHouse Den Bosch. Source: Tessa Peters and Rolf van Boxmeer.

4. Analysis

In this section, the conviviality and openness potential of the WikiHouse Den Bosch are discussed. The analysis refers to the WikiHouse as a complete house to live in including building structure and utilities. We will first elaborate on the conviviality potential through the examination of the MCT's responses and then critically discuss the openness aspect based on the open-O-meter tool.

4.1. The Conviviality Aspect

The assessment of the WikiHouse's conviviality was facilitated through the use of a range of values attributed to the antagonistic terms of the matrix. To fit the specific characteristics of our case, the MCT was simplified by erasing certain pairs of antagonistic terms (see the original and the adapted MCT table in Appendix A).

The MCT was filled in by 10 people who contributed to the construction of the WikiHouse Den Bosch. The selected group can be considered as a representative sample since it reflects the main characteristics of the overall community. More specifically, the age range was similar (25 to 65 years), the gender balance was equally distributed and most of the respondents had a non-engineering background (see Appendix B).

The analysis followed the four life-cycle levels identified in the MCT (i.e., materials, production, use, infrastructure). To begin with, the respondents mentioned that the materials were easily accessible through various sources. Furthermore, it was possible to choose out of a variety of materials according to local needs and conditions. Regarding the cost of the materials, the responses were divergent due to the subjectivity of the question. Since the origins of the respondents varied, different answers were received; most of them deemed it to be of low-cost whereas others found it cost-intensive. Considering the Dutch context, the construction was deemed affordable. The tools needed for the processing of materials were characterized either as specialized (by non-engineers) or everyday tools (by engineers), based on the skills of each respondent. The presence of engineers among the contributors was important in overcoming obstacles during the construction. Additionally, all respondents highlighted the necessity of having access to a CNC machine. Finally, although the WikiHouse Den Bosch was built out of reused and easily recyclable materials, there were toxic emissions related to the processing of materials.

The production phase was seen as a collaborative and constructive process that allowed for joyful work. Contributing to the assembly of the Wikiparts was easy since no special tools were needed. The assembly could take place asynchronously and autonomously, thanks to the appropriate instructions and detailed designs provided by the architects of the project. Dismantling the parts of a house once finished is difficult, but life-time changes rarely demand it. However, the addition of new parts according to the users' needs is possible. These characteristics designate the WikiHouse as a modular structure. Despite the some waste emissions, there was no significant environmental impact during the production phase.

Regarding the use level, the respondents described the WikiHouse Den Bosch as "usable by anyone", since it fulfills the basic needs of the user and provides flexibility in selecting the infrastructure. Concerning its maintenance, the WikiHouse Den Bosch was characterized as "repairable by some". Although it was argued that most of the parts could be repaired quickly, additional skills may be needed to maintain certain infrastructure such as plumbing. The need for experts within the community seems to be vital for maintaining both the WikiHouse structure as well as the community itself. The fixed costs are not significantly decreased due to the installed energy and water systems. No solar panels or water reuse systems are available at the WikiHouse Den Bosch due to time and cost limitations.

Furthermore, issues associated with safety checks and local regulations need to be addressed by the users. In the case of the WikiHouse Den Bosch, the structure was exempt from the need to conform to the local building codes due to its experimental and temporary character. In addition, the WikiHouse Den Bosch was understood as a locally operable construction that could be easily adapted to the local setting. Nevertheless, following the respondents' feedback, the durability of the structure was not ensured.

Finally, a common element present throughout all phases was the increased community engagement that was enabled by the nature of the project. Collaboration and sharing were promoted, which allowed for the development of friendship and feelings of being useful.

4.2. The Openness Aspect

This assessment refers to information such as designs, CAD files, bill of materials, and assembly instructions. A web-based repository such as GitHub is used for file sharing in most WikiHouse projects. However, fragmentation issues arise since there is not a comprehensive online platform used by all communities that develop WikiHouses globally. Contrary to software components, sufficiently documenting a piece of hardware is challenging [3]. Problems pertain to the documentation adequacy of the WikiHouse solutions, and the ease in tracking the relevant information [53]. Consequently, concerns have been raised with regard to the openness degree of hardware solutions like the WikiHouse.

A first attempt in filling the open-O-meter for the WikiHouse concept was realized in the context of a French–German research project called OPEN! – Methods and tools for community-based product development [54]. Following this assessment, the WikiHouse was rated five out of eight. The missing points were due to the provision of non-editable assembly instructions, a non-editable published bill of materials, and the lack of a published contribution guide.

However, apart from the open-O-meter evaluation via simple binary criteria, the quality of the published documentation of each WikiHouse project should be examined. The comprehensiveness and clarity of the published information increase the replicability and diffusion of the product. Thus, our contribution was to critically examine and enrich the existing assessment of the WikiHouse's openness based on the expertise of three main stakeholders of the WikiHouseNL Foundation (see Appendix B).

First, concerning the publication of the design files, the interviewees agreed that many WikiHouse design files were shared on GitHub in different stages of construction. However, most of them were uncategorized and not engineered. The respondents mentioned that when private companies were involved, the publication of all designs was not assured. For instance, although most of the WikiHouse Den Bosch designs were published in an editable format, those related to its structural analysis were not

shared. In addition, the modification of existing designs may be more time-consuming than drawing new ones.

Detailed manuals with the assembly instructions are available on Github. For the editability of the instructions, Tessa and Rolf mentioned that they decided to draw new manuals since the original model could not be easily modified for the needs of the WikiHouse Den Bosch. Vincent stressed the importance of being an experienced user in dedicated software to fork the assembly instructions.

Regarding the bill of materials, the publication of information for the whole building depends on the parties involved. For instance, the bill of materials can be obtained for the structural components of the WikiHouse, but not the cost-related data of the building. Acquiring a complete bill of materials for a WikiHouse is complicated, since it depends on the local needs and conditions. Although such a bill of materials for a WikiHouse does not exist, Open System Labs [55] is currently working on a platform for sharing customizable designs with detailed descriptions of the materials (including economic data, energy, and environmental factors).

Furthermore, a contribution guide should be provided through transparent processes to enable the unconditional participation of individuals. Considering the uniqueness of a WikiHouse project, each one has guidelines that should fit the local needs and regulations. In the case of the WikiHouse Den Bosch, the instigator provided conditions for participation in the construction process that were readapted regularly to serve the changing needs of the project [56].

The licensing guidelines [57] of the first WikiHouse building type (i.e., the Microhouse [58]) indicate that the published content can be shared and adapted, even for commercial use. The latest version of this license, Attribution-ShareAlike 4.0 International: CC BY-SA 4.0, was used in the WikiHouse Den Bosch case [59].

In all, it becomes evident that every WikiHouse initiative is unique and should be evaluated based on its distinctive characteristics and rules. Following the responses of the interviewees, the WikiHouse Den Bosch scored six out of eight since it lacked editable assembly instructions and an editable published bill of materials. Nevertheless, although some of the open-O-meter factors received a positive degree, critical issues should be addressed to enhance the diffusion and replication of the WikiHouse technology.

5. Conclusions

Both conviviality and openness are ambiguous terms. Whether an artifact is convivial or open is not a binary decision. Instead, there is a spectrum and degree of each of these aspects that characterizes a technological artifact. For instance, defining conviviality and openness may be easier when engaging with software or low-tech products than high-tech hardware.

The WikiHouse Den Bosch is a sophisticated construction that consists of different parts and requires certain skills for its construction and maintenance. The conviviality potential of such a complex artifact ends up being subjective. Based on our results, it is evident that the level of the respondent's expertise is crucial when assessing conviviality. The potential lack of certain skills needed to manufacture or maintain an artifact could lower the artifact's conviviality. However, the existence of a community around that artifact could possibly alleviate this issue via the diffusion of knowledge amongst its members.

Furthermore, the available expertise of the contributors allows for enhanced autonomy in both the construction and maintenance stages. In this sense, conviviality is stronger at the collective level than at the individual one. Additionally, openness adds to the conviviality potential of the project, thus boosting the autonomy on all levels by providing access to relevant information.

The aforementioned potential is arguably linked to the attributes observed in the DGML approach. In an attempt to generalize the conviviality of DGML artifacts, we proposed achieving "institutionalized conviviality" through more structured processes. For instance, modularity can be considered as a characteristic that could reduce the complexity of artifacts. In addition, standardization of the design

parts as well as the existence of detailed open-source documentation could facilitate the replicability of open hardware solutions through comprehensive manuals.

Overall, however, DGML artifacts may be quite varied in their conception and development, so the community aspect is crucial. Once there is an engaged community with a strong supporting network, the level of conviviality may be high, despite potential complexities that would otherwise hinder it. Nevertheless, given that such projects are driven by specific local or regional socio-economic and political characteristics and goals, the generalizability of our conclusions is confined. Hence, further research should focus on different contexts, locations, and artifacts to provide a wider understanding of the understudy phenomenon. Finally, a comparison of an industrially produced house and an open construction system through technical evaluations such as the life cycle assessment would be valuable.

Appendix A

Dimensions //	Materials	Production	Use	Infrastructure
Levels →	*Harvesting, processing and disposal of raw matter*	*Assembling raw materials and preproducts*	*Procuring the task it was built for*	*Needed environment for using*
Remarks on Levels -->				
Relatedness *What does it bring about between people?*	Process fixed – Right to creative input; Fixed world concepts – Learning from different sources; Market-driven – Need-driven; Top down control – Bottom-up control; Organization centralized – Organization distributed; Alien implementation – Respects local traditions	Fosters competition – Supports trust; Distance-creating – Conjoint experience; Market-driven – Need-driven; Top-down control – Bottom-up control; Organization centralized – Organization distributed; Process fixed – Right to creative input; Creates borders – Integrates; Alien implementation – Respects local traditions; Creates senselessness – Creates art; Uglifying – Creates beauty	Fosters competition – Supports trust; Fosters individual advantage – Supports community; Prefigured use only – Allows creativity; One solution fits all – Respects local traditions; Discourages care – Simplifies care; Uglifying – Creates beauty; Creates senselessness – Creates art; Alienating from own body – Useful body enhancement; Heteronomy – Self-determination; Compulsory – Voluntarily	Fosters competition – Sustains trust; Distance-creating – Connects with eco processes; Market-driven – Need-driven; Top down control – Bottom-up control; Fosters individual advantage – Supports community; Creates senselessness – Creates art; Uglifying – Creates beauty; Humans as inferior part of a system – Humans an equal part of a complex system; Discourages care – Simplifies care
Access *Who can produce/use it where and how?*	Elitist – Open to anyone; Investor-owned – Producer-owned; Cost-intensive – Low-cost; Secret or patented – Knowledge freely accessible; Need of foreign expert – Use of local knowledge; Specialized processes – Standardized processes; Hinders skill building – Supports skill building; Abstract – Comprehensible	Elitist – Open to anyone; Investor-owned – Producer-owned; Cost intensive – Low Cost; Secret or patented – Knowledge freely accessible; Hinders skill building – Sustains skill building; Need of foreign expert – Use of local knowledge; Abstract – Comprehensible; Not able to fulfill needs – Fulfilling basic needs; Opaque organization – Transparent communication; Specialized processes – Standardized processes	Unable by an elite – Usable by anyone; Investor-controlled – Open; Cost intensive – Low Cost; Need of foreign expert – Use of local knowledge; Not able to fulfill needs – Fulfilling basic needs; Abstract – Comprehensible; Repugnant – Attractive; Enforces cultural restraints – Transforms cultural restraints	Usable by an elite – Usable by anyone; Abstract – Comprehensible; Enforces cultural restraints – Transforms cultural restraints; Not able to fulfill needs – Fulfilling basic needs
Adaptability *How independent and linkable is it?*	Special machines – Everyday tools; Big scale economical – Small scale economical; Special conditions – Everywhere possible; Special materials – Standardized materials	Fixed once finished – Permanently changeable; Isolated – Interoperable; Size fixed – Scalable; Special machines – Everyday tools; Big scale economical – Small scale economical; Heteronomous – Self-determined; One way processes – Dis-/reassembly possible; Special conditions – Everywhere possible; One piece – Modular	Fixed once finished – Permanently changeable; Isolated – Interoperable; Size fixed – Scalable; One-dimensional – Multi-functional; Infrastructure needed – Independent use possible; Repairable by experts – Repairable by skilled; Close survey needed – Uses self-regulation; Monolithic – Interchangeable; One solution fits all – Encourages diversity; One piece – Modular	Fixed once finished – Permanently changeable; Isolated – Interoperable; Size fixed – Scalable; One-dimensional – Multi-functional; Centralized – Distributed; One solution fits all – Encourages diversity; Compulsory – Voluntarily; Linear systems – Non-linear systems; Repairable by experts – Repairable by skilled; Operable only from distance – Locally operable
Bio-Interaction *How does it interact with living organisms?*	Illness/death – Supports health; Deteriorating soil – Improving soil; Water-polluting – Improving water quality; Air-polluting – Supports clean air; Violent – Nonviolent; Hazardous potential – Safety proven and tested; Toxic waste – Biodegradable; Suppresses organic processes – Allows co-productivity	Illness/death – Supports health; Deteriorating soil – Improving soil; Water-polluting – Improving water quality; Air-polluting – Supports clean air; Violent – Nonviolent; Hazardous potential – Safety proven and tested; Suppresses organic processes – Allows co-productivity	Illness/death – Supports health; Deteriorating soil – Improving soil; Water-polluting – Improving water quality; Air-polluting – Supports clean air; Violent – Nonviolent; Hazardous potential – Safety proven and tested; Toxic waste – Biodegradable; Suppresses organic processes – Allows co-productivitys	Illness/death – Supports health; Deteriorating soil – Improving soil; Water-polluting – Improving water quality; Air-polluting – Supports clean air; Violent – Nonviolent; Hazardous potential – Safety proven and tested; Toxic waste – Biodegradable; Suppresses organic processes – Allows co-productivity
Appropriateness *What is the relation between input and output considering the context?*	Non renewable – Renewable; Far away – Locally available; New – Re-used; Non recyclable – Easily recyclable; Nondurable – Durable; Needs painful worktime – Allows joyful worktime; Fossil energy – Renewable energy	Thriftless material use – Frugal material use; Special tools – Standardized tools; Against local settings – Uses local settings; Needs painful worktime – Allows joyful worktime; Fossil energy – Renewable energy; Creates waste – Byproducts are used	Encourages waste – Sustains sufficiency; New – Re-used; Nondurable – Durable; Against local settings – Uses local settings; Needs painful time- – Allows joyful time; Fossil energy – Renewable energy; Creates waste – Byproducts are used	Thriftless material use – Frugal material use; Encourages waste – Sustains sufficiency; New – Re-used; Nondurable – Durable; Against local settings – Uses local settings; Needs painful time- – Allows joyful time; Fossil energy – Renewable energy; Creates waste – Byproducts are used
	Materials	**Manufacturing**	**Use**	**Infrastructure**

Figure A1. The original version of the matrix of convivial technologies (MCT).

Dimensions // Levels →	Materials — Harvesting, processing and disposal of raw matter	Production — Assembling raw materials and preproducts	Use — Procuring the task it was built for	Infrastructure — Needed environment for using
Remarks on Levels -->				
Relatedness — What does it bring about between people?	Process fixed -- Right to creative input; Fixed world concepts -- Learning from different sources; Market-driven -- Need-driven; Top down control -- Bottom-up control; Alien implementation -- Respects local traditions	Fosters competition -- Supports trust; Organization centralized -- Organization distributed; Process fixed -- Right to creative input; Creates borders -- Integrates; Alien implementation -- Respects local traditions	Fosters competition -- Supports trust; Fosters individual advantage -- Supports community; One solution fits all -- Respects local traditions; Compulsory -- Voluntarily	Distance-creating -- Connects with eco processes; Market-driven -- Need-driven; Fosters individual advantage -- Supports community; Humans as inferior part of a system -- Humans as equal part of a complex system
Access — Who can produce/use it, where and how?	Elitist -- Open to anyone; Cost-intensive -- Low-cost; Secret or patented -- Knowledge freely accessible; Need of foreign expert -- Use of local knowledge; Specialized processes -- Standardized processes	Elitist -- Open to anyone; Cost intensive -- Low Cost; Secret or patented -- Knowledge freely accessible; Hinders skill building -- Sustains skill building; Need of foreign expert -- Use of local knowledge; Specialized processes -- Standardized processes	Usable by an elite -- Usable by anyone; Investor-controlled -- Open; Cost intensive -- Low Cost; Need of foreign expert -- Use of local knowledge; Not able to fulfill needs -- Fulfilling basic needs; Enforces cultural restraints -- Transforms cultural restraints	Usable by an elite -- Usable by anyone; Cost intensive -- Low Cost; Enforces cultural restraints -- Transforms cultural restraints; Not able to fulfill needs -- Fulfilling basic needs
Adaptability — How independent and linkable is ity?	Special machines -- Everyday tools; Special conditions -- Everywhere possible; Special materials -- Standardized materials	Fixed once finished -- Permanently changeable; Size fixed -- Scalable; Big scale economical -- Small scale economical; One way processes -- Dis-/reassembly possible; Special conditions -- Everywhere possible; One piece -- Modular	Fixed once finished -- Permanently changeable; Size fixed -- Scalable; One-dimensional -- Multi-functional; Infrastructure needed -- Independent use possible; Repairable by experts -- Repairable by skilled; One solution fits all -- Encourages diversity	Fixed once finished -- Permanently changeable; Size fixed -- Scalable; One solution fits all -- Encourages diversity; Compulsory -- Voluntarily; Repairable by experts -- Repairable by skilled; Operable only from distance -- Locally operable
Bio-Interaction — How does it interact with living organisms?	Deteriorating soil -- Improving soil; Air-polluting -- Supports clean air; Violent -- Nonviolent; Toxic waste -- Biodegradable	Air-polluting -- Supports clean air; Violent -- Nonviolent; Hazardous potential -- Safety proven and tested; Suppresses organic processes -- Allows co-productivity	Deteriorating soil -- Improving soil; Water-polluting -- Improving water quality; Air-polluting -- Supports clean air; Hazardous potential -- Safety proven and tested; Toxic waste -- Biodegradable	Deteriorating soil -- Improving soil; Water-polluting -- Improving water quality; Air-polluting -- Supports clean air; Hazardous potential -- Safety proven and tested; Toxic waste -- Biodegradable
Appropriateness — What is the relation between input and output considering the context?	Far away -- Locally available; New -- Re-used; Non recyclable -- Easily recyclable; Nondurable -- Durable; Fossil energy -- Renewable energy	Special tools -- Standardized tools; Against local settings -- Uses local settings; Needs painful worktime -- Allows joyful worktime; Fossil energy -- Renewable energy; Creates waste -- Byproducts are used	Nondurable -- Durable; Fossil energy -- Renewable energy; Creates waste -- Byproducts are used	New -- Re-used; Nondurable -- Durable; Against local settings -- Uses local settings; Fossil energy -- Renewable energy; Creates waste -- Byproducts are used
	Materials	**Manufacturing**	**Use**	**Infrastructure**

Figure A2. The modified version of the MCT.

Table A1. The open-O-meter tool.

open-O-meter		
Which sources have you opened?		
	YES	**NO**
1 Are the design files published?		
Technical components of the product are publicly available (CAD-files, computer code etc.)		
2 Are the assembly instructions published?		
Instructions for how to assemble are quickly available		
3 Is the bill of materials published?		
The product's bill of material is publicly available		
4 Is the contributing guide published?		
A guide for how users can contribute is available		
5 Are the published design files in editable formats?		
One or more of the file formats used is in editable format		
6 Are the published assembly instructions in editable formats?		
The assembly instructions are published in editable format		
7 Is the published bill of materials in editable format?		
The bill of materials is published in editable format		
8 Is all this information published under a license allowing commercial reuse?		
An open source license is used that allows users to commercially reuse the product		

Appendix B

Table A2. List of names, gender, expertise, and roles of the contributors to the MCT.

Respondents	Gender	Expertise	Engagement in the Construction
Respondent 1 (Instigator)	F	Art therapist	Consistent
Respondent 2 (Adviser)	M	Project manager	Consistent
Respondent 3	F	Social worker	Consistent
Respondent 4	F	Engineer	Occasional
Respondent 5	M	Business consultant	Occasional
Respondent 6	F	HR specialist	Occasional
Respondent 7	F	Artist	Occasional
Respondent 8	M	Teacher	Consistent
Respondent 9	M	Economist	Occasional
Respondent 10	M	Engineer	Consistent

Table A3. List of names, gender, expertise, and roles of the contributors to the open-O-meter.

Respondents	Gender	Expertise	Organization/Project
Vincent Muller	M	Architect	Co-founder of WikiHouseNL Foundation, WIkiHouse in Almere
Rolf van Boxmeer	M	Architect	Co-designer of WikiHouse Den Bosch/Minitopia
Tessa Peters	F	Architect	Co-designer of WikiHouse Den Bosch/Minitopia

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Publication IV

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Research article

To BIM or not to BIM? Lessons learned from a Greek vernacular museum building

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Abstract: The environmental impact of buildings has stimulated efforts to promote sustainable development in the construction sector. Technological development aims to provide an effective framework for the design, construction, and management of buildings through the use of tools such as Building Information Modeling (BIM). This paper critically assesses the use of BIM technology in vernacular design and analysis through the case study of a Greek vernacular museum building. Based on software application as well as in-situ observation and interviews, accurate energy analysis and safety were proved to be important advantages achieved through BIM technology. On the contrary, the inability to capture tacit knowledge and the lack of adaptability to local specificities appear to be the main weaknesses of BIM technology. Certain measures to enhance the use of BIM technology for the design and analysis of vernacular buildings are proposed.

Keywords: Building Information Modeling (BIM); standardization; sustainability; design; construction; energy analysis; vernacular architecture

1. Introduction

The impact of buildings on the environment has been gaining attention over the last decades [1]. The conventional way of producing buildings has been notorious for its significant amounts of waste [2]. Indicatively, demolition processes account for 40% of total solid waste, while the operation stage of buildings produces 30% of the total greenhouse gases [3,4]. Hence, the need to improve the life cycle performance of buildings is imperative.

In an attempt to enhance sustainability in the construction sector, the adaptation of practices that

improve the energy and environmental performance of buildings has been suggested [5]. The sustainability of buildings is based on factors such as water conservation, energy efficiency, and appropriateness of building materials, which are influenced by architectural planning. To this end, there is an urgent need to create new design models through the implementation of an integrated strategy [6].

The attention of the global construction industry is geared toward approaches that reduce construction and operation costs while improving the quality of buildings [7]. Design decisions regarding energy consumption have a great impact on the life cycle of buildings given the long operation stage of buildings [8]. Some scholars argue that Building Information Modeling (BIM) offers the opportunity to achieve these goals via time and money savings [9,10]. Nevertheless, others [11,12] are sceptical in regard to the adoption of such practices mainly due to resistance to change in construction practices, lack of government incentives, and relevant costs.

In this study, BIM technology is implemented for the architectural design and the energy analysis of a Greek vernacular museum building model. The whole process is then assessed based on the real performance of the building after 25 years of operation. The dynamics of BIM technology to design and analyze complex architectural elements of vernacular buildings, as well as its ability to incorporate tacit knowledge of the vernacular process in building design is critically assessed. In addition, sustainability features observed in the vernacular process followed by the owner of the museum to construct the building are also discussed.

The main aim of this paper is to explore the challenges and opportunities of applying BIM technology to the design and analysis of vernacular buildings. What innovations does BIM technology introduce for the simulation of vernacular buildings? Is there room for improvement for BIM technology, and if so, in which direction? These are the main questions attempted to be answered through the application of BIM technology to the analysis of a vernacular museum building. In that sense, it aspires to elaborate on the potential of BIM to be used as a tool to foster vernacular design processes, instead of being used as an engineering analysis tool solely. By expanding the scope of BIM applications to vernacular buildings, BIM will enable the preservation of sustainable features embedded in vernacular processes.

First, the conceptual background of BIM technology as well as its relation to sustainability are presented. Then, the concept and basic principles of vernacular architecture are discussed. The methodology chapter follows where the research framework is outlined. The next chapter describes the vernacular building process and the BIM-based approach of analyzing the museum building model. In the discussion section, relevant challenges and opportunities observed through the analysis are elaborated. Finally, the conclusionsm section summarizes the findings of this research.

2.   State of the art

2.1. Vernacular architecture and sustainability

The term vernacular architecture was coined to describe simple structures composed of indigenous materials [13]. Vernacular architecture utilizes traditional building methods to produce various types of buildings [14]. The plurality of such buildings derives from diverse local identities and construction practices that have evolved over time through experiential knowledge. The term "identity" is a blend of natural (such as climate and topography), human (such as society and community) and cultural factors (such as customs and religion) that defines the traditional building methods in a local context [15].

Vernacular architecture is designed by people who have gained tacit knowledge from observations of the natural environment. Such knowledge relates to technical skills, available materials, construction techniques, and local identity. In an attempt to respond to the rapidly changing reality, vernacular architecture has been evolved through trial and error. Thus, it is believed that vernacular architecture embodies a comprehensive wisdom accumulated in a local context.

Vernacular architecture is a valuable source of reference for bioclimatic design of buildings [16]. The latter aims to provide conditions of thermal and visual comfort, utilizing natural local resources (such as soil, vegetation, and wind). By leveraging the interactions between the building and the natural environment, energy demands for heating, cooling and lighting of the building can be moderated. However, research shows that this way of fostering sustainability may not always be sufficient especially in regions under extreme weather [17].

Natural and economic limitations, such as topography, climate, and availability of building materials in the surrounding area, are imposed on vernacular buildings. In that sense, vernacular architecture is grounded in inherently sustainable rules with the aim to fulfil human needs with respect for the cycle of life [15,18,19].

Vernacular processes can provide useful insights for boosting the sustainability of contemporary building design and construction [20]. Current environmental concerns justify the increasing interest in vernacular architecture studies. Hence, the need to preserve the sustainable principles and values embedded in vernacular buildings has been highlighted in the research community [21,22]. In this context, this study will investigate the potential of BIM to design and analyze vernacular buildings.

2.2. The advent of BIM

During the 1980s, the tendency to switch to electronic drawings became evident. The advent of information and communication technology appeared to have significant economic and social implications [23]. Simultaneously, developments in programming languages led to the emergence of parametric technologies that enabled the digital representation of buildings [24].

Given the complexity of construction projects, the need for the automation of the relevant processes has surfaced. Parametric design tools, such as BIM technology, perceive building elements as dynamic systems, which form a variety of morphological representations subject to transformations. In that sense, entire systems, such as buildings, are composed by multiple interacting subsystems (such as beams, columns, and pipes) with endless possibilities for their functional interrelationships.

As an integrated digital representation of the physical and functional features of a building [25], BIM technology is a tool for automation of the construction process but also a means for specialization that contributes to higher productivity levels of buildings [26]. By gathering all information about a building in a central model, building information management processes are facilitated. The validity of the construction schedule is ensured by monitoring relevant processes [27].

Time-related information is regarded as the fourth dimension in BIM technology, empowering data scheduling and sequential visualization of the buildings' development. Cost calculations are often considered the fifth dimension in BIM technology, offering the possibility to evaluate buildings from an economic point of view [28]. Building lifecycle data, including operation manuals, maintenance and manufacturer data, can be managed, while sustainability analyses can be performed adding more dimensions to BIM technology [29].

According to Migilinskas et al. [30], the more collaborative a project is, the more benefits from BIM applications arise. The establishment of open standards in BIM applications is expected to catalyze the application of diverse types of analysis and accelerate the adoption of innovations [31]. Data exchange between BIM technologies should be enhanced to develop collaborative environments. Such attempts are made through non-proprietary file formats, such as Green Building XML (gbXML) and Industry Foundation Classes (IFC), which aim to facilitate compatibility between BIM software applications [32]. However, so far they have failed to provide a fully collaborative environment for BIM applications [33].

2.3. BIM and sustainable construction

The concept of sustainable constructions entails the minimization of environmental footprints through the efficient use of natural resources, social cohesion and cost-effective building methods that meet the requirements of users [34]. Conventional design methods have failed to develop sustainable buildings so far mainly due to fragmented data [35]. Given the significant impact of the construction sector on the environment, the need for sustainability integration in buildings has recently attracted attention [36,37].

The assessment of sustainability in buildings during the design phase is hampered by the lack of data and expertise in the field [38]. Further, the complexity of the building sector hinders the development of an internationally comparable inventory for the application of Life Cycle Assessment (LCA) methods [39].

Despite its immature form, BIM technology holds potential for enhancing sustainability over the life cycle of a building [40–42]. Sustainability-related factors can be incorporated in BIM software, benefiting the environment, the economy, and society. According to Krygiel and Nies [43], BIM technology can be implemented to improve certain aspects of sustainability in buildings utilizing multidisciplinary data. These aspects include analyses related to building orientation, energy performance, and sustainable materials, which can lead to cost savings and environmental gains.

Considering the collaborative aspect of BIM technology, digital information associated with sustainability can be shared, advancing the field of knowledge commons [44]. In that sense, innovation is fostered, while visualization enables the engagement of non-experts in the design process. Moreover, BIM designs comprise interchangeable modular units that correspond to building components, encouraging reversibility and replacement of components.

Although BIM technology does not provide a comprehensive life-cycle management of environmental sustainability of buildings, it has been applied in the early design and construction [40]. Sustainability analyses can be performed through external evaluation tools and cloud-based technologies. Further, online open inventories can be used to evaluate alternative design options, which correspond to different energy efficiency levels [38]. Such platforms foster collaboration among the participants concerning the decision making processes of construction projects via shared models.

Despite the potential of BIM to promote sustainability, the resistance of relevant parties to change conventional practices and invest in software and skills development prevents the implementation of BIM to its fullest capability. Further, interoperability issues should be addressed to promote collaboration and accurate analyses through BIM technology [40,45]. Notwithstanding such limitations, political measures foster the implementation of BIM technology in constructions, increasing its impact on building design [46].

3. Materials and methods

In order to study highly complex objects, such as vernacular buildings, the BIM ecosystem, and their interrelationship with society, investigations in multi-dimensional ways are needed. For this reason, the case study approach was used since it allows the investigation of phenomena from diverse aspects [47]. Further, it enables an in-depth examination of single cases [48].

The specific case study was selected because it represents a distinctive type of vernacular building that encompasses special architectural features, as described in the following section. This argument was also reinforced via testimonies of the interviewees. By investigating such a complex building from an architectural aspect, it is expected that the challenges and opportunities of BIM technology for designing vernacular buildings will become more evident [49]. Further, most studies on vernacular architecture focus on houses, while recent studies indicate the necessity to investigate public buildings as well [16].

The research framework of this study is illustrated in Figure 1. First, theories on BIM technology were studied, as well as relevant literature on the connection of BIM with sustainability. The concept and principles of vernacular architecture followed. The case of Pavlos Vrellis museum was then analyzed, elaborating on the approach taken by the creator of the museum to construct the building. Web tools, a semi-structured interview with the current owner of the museum and semi-structured interviews with local builders of the wider area took place. The aim of the interview with the owner of the museum was to obtain the required information for the case study, while the interviews with local builders shed light on local building practices and vernacular processes of the wider area. Web tools included data gathered from online platforms, discussion sections and the official website of the museum [50] as well as email communications with BIM experts.
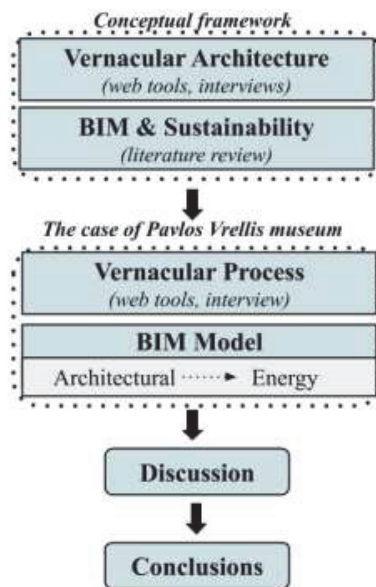
Figure 1. Schematic representation of the research framework.

The interview with the current owner of the museum was structured around core questions that attempted to enlighten data regarding the current state of the museum, details about other contributions to its development, the main desires and goals of the creator of the museum, as well as relevant challenges and barriers to progress. The interview took place on site, allowing for observations of the building.

Nine local builders aged between 65 to 90 years old participated in the interviews. Most of the interviewees had previously participated in the construction process of a vernacular building, which was usually their private house or house of a relative of theirs in the wider area of Ioannina city. In terms of their expertise, all of the interviewees were farmers. The questions revolved around their experience of participating in the vernacular process and the entailed challenges and opportunities.

The application of BIM technology followed to illuminate the limitations and advantages of BIM software for the design and analysis of vernacular buildings. In this study, a specific BIM software (i.e., Autodesk Revit Architecture) was implemented for the architectural design of a vernacular museum building model. Further, an energy analysis tool included in the software package (i.e., Revit Conceptual Energy Analysis-CEA) was applied. The results were compared with the actual data of the building's performance available through testimonies of the owner of the museum. The information needed for the BIM model, including geometrical and topological data, derived from the design drawings of the museum, narratives of the owner, as well as information provided by the creator at the website of the museum.

4. The case of Pavlos Vrellis museum of wax effigies

4.1. Traditional design and construction process

In line with the principles of vernacular architecture, the buildings of the area under study are made of local stones (usually left unused), wood and mud. Lime, straw, bricks (frequently sun-baked), porcelain, iron, glass and sand are also used. Most of these materials are environmentally friendly since they come from the surrounding environment and they do not require high transport costs or material processing.

Given the steep slopes, rocky terrain and severe winters of the wider region of Epirus (Greece), people had to compromise with constraints set by nature and techno-economic conditions. These techno-economic limitations imposed a certain degree of standardization on the construction of the buildings in terms of available materials and their processing ability. At the same time, the accumulated empirical wisdom and local knowledge exchange practices facilitated the development of inventive building solutions against physical stresses, such as earthquakes and landslides.

Regarding the building structure of the museum, stone walls are thick enough to insulate the building. The windows of the museum are few and small placed at the lower levels of the ground floor for safety reasons. In the upper floor, windows are spacious to ensure ventilation. On the south side, openings are large for storing solar radiation. The rising hot air is concentrated at the roof level and exits through skylights.

Fireplaces and chimneys were some of the most elaborate elements of the museum. Craftsmen composed a variety of decorative volumes and forms in the building structure as an indication of wealth and luxury. Chimneys were used to create a vertical stream of air that contributes to the cooling of the space. On the south side, trees were planted to provide coolness in summer, while in winter they

lose leaves, allowing the sun's rays to enter the building. Further shading was provided by the brown covers of the windows by filtering out the sunlight. In addition, the surrounding vegetation contributed to the shading, sun protection and insulation capacity of the museum.

Pavlos Vrellis, the creator of the museum, was inspired by local traditional mansions. First, he laid out roads and squares that lead visitors to the building. He took special care to harmonize the building with the harsh natural environment. Large rocks and rubble taken from excavations were used to create retaining walls and stabilize steep slopes. The processing of the materials was kept simple, utilizing physical processes and natural resources, such as the sun and water. For example, to make the rocks of the garden look natural, they were left two winters to be washed away from the rain and ice and were wrapped with fine fluid cement.

Figure 2. Pavlos Vrellis museum of wax effigies.

To grasp the volume of the museum, the creator built maquettes of both the exterior and the interior space. To issue the building permit, local counterparts undertook the planning procedures and the creation of linear drawings. Decisions regarding the building's orientation, the selection of proper materials, and the structural behavior of the building were taken through knowledge exchange practices.

Considering that the museum counts 25 years of operation, the current owners focus on monitoring and maintaining the building, preserving its original typology and morphology. The first intervention on the building took place in 2008 when significant operational problems appeared on the roof, while specialists were commissioned later to replace some of the windows to reduce energy losses.

4.2. Architectural design and energy analysis through BIM

The architectural design of the museum building was modeled in Revit Architecture software of Autodesk, while Revit CEA was implemented to convert the architectural design into an energy analytical model. Such a model provides the means for an integrated energy analysis.

The museum consists of two separate buildings: the ground floor, which hosts the library and the laboratory, and an underground space, where the exhibits are placed. Due to the complexity and cave-like shape of the underground space, only the ground floor of the museum space was analyzed. To

imprint the underground space, diverse assumptions should be made considering the lack of relevant technological equipment, such as laser scanning.

First, the architectural design of the building was created. After establishing the location of the project, including its longitude and latitude, the creation of "families" took place. This term refers to the ability of an object to have many types within it so that diverse sizes and shapes are created, as the definition of parametric design stipulates. Families were realized directly into the model or were modified separately and employed based on the requirements of each building component. In this way, flexibility was added to the software by personalizing objects of a category according to the relevant needs.

For example, floor projections arose from the composition of different elements that belong to the "wall sweep family". The protruding volumes of the floor at the corners of the building are supported via wooden components, which create decorative panels. These components were modelled in Revit as structural framing elements.

(A)   (B)

Figure 3. Structural framing elements of the museum. (A) Real building, (B) BIM model.

The museum building retains special local architectural elements that allow for the exploration of the flexibility of BIM technology. Such elements include chimneys and skylights at the central part of the building. Also, extended portions of the roof at the perimeter walls are formed to facilitate the flow of rainwater directly to the ground. Most of these elements resulted from the transformation of existing families that were properly modified to simulate the real building components.

Then, the energy analysis of the building followed. An energy analytical model was created by sorting the building space into discrete spaces. The analysis aimed to forecast energy consumption levels of the building during the stages of the construction and operation. At the same time, it took into account certain characteristics of the building, such as its type, opening hours, and location. The model was also linked to the geospatial world through an online mapping system.

The results of the analysis enable the evaluation of alternative scenarios for energy efficiency. They include carbon dioxide emissions, electricity costs, and energy consumption rates on an annual and a monthly basis (see Appendix). Monthly heating and cooling loads are calculated, indicating the months with the largest demand for heating and cooling (i.e., January and July respectively). Also, graphical representations of wind speed and direction data are offered, facilitating decisions for natural ventilation.

The sensitivity of each building element to the total energy performance of the building is shown in the "Potential Energy Savings/losses" tab. The building elements with the greatest potential for energy savings are listed on top. The bar size indicates the energy-saving potential of the specific element. Therefore, a change in elements with large bar sizes can have a major impact on the energy performance of the building.

(A)   (B)

Figure 4. Architectural design of special elements. (A) Chimney, (B) Skylight.

Following the results of the CEA, roof insulation has the most significant influence on the energy use of the museum building, as indicated in Figure 5. In particular, a change in the roof insulation element has the potential to contribute to the energy savings of the building by 23% approximately. Wall insulation is another sensitive building element from an energy point of view.
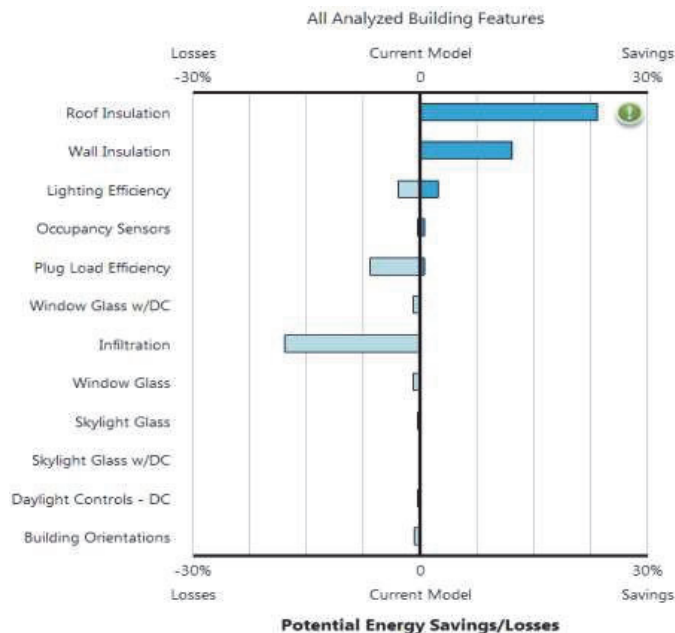
Figure 5. Energy sensitivity of the building elements.

BIM technology can also be used to conduct preliminary assessments for the optimal design and management of buildings. The creation of photorealistic models via online services took place to visually test the integration of the museum building into the surrounding area as depicted in Figure 6. Finally, solar and shading studies can be conducted utilizing representations of the sun path.

(A)   (B)
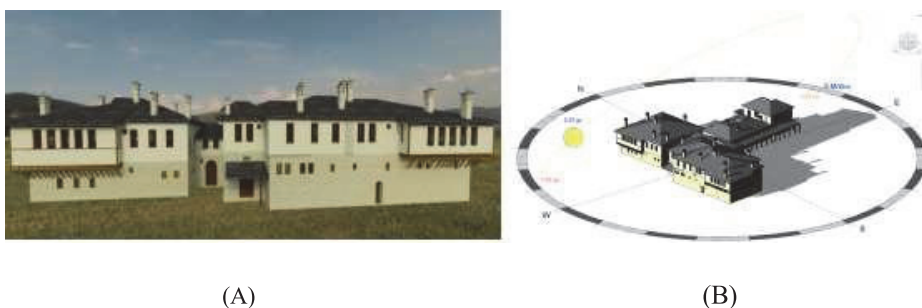
Figure 6. Photorealistic model of the museum (A). Sun path representation (B).

5.   Results and discussion

The simulation of the museum building in Revit verified certain advantages of BIM technology. Among them, the visualization of the building process, the enhancement of safety levels, and the predictability of future failures are mentioned. Considering the inaccessibility of the area where the museum was built, the use of BIM technology is particularly important for safety reasons. By creating a BIM model, tests and applications can take place within BIM software, saving construction time and effort.

Through BIM technology, the building can be decomposed into elements, which can be analyzed independently. In this way, the researcher can focus on particular elements and perform on-demand simulations. In this case study, the functionality and effectiveness of the energy analysis software were tested based on the current state of the museum building and the interventions implemented therein.

The simulation results of the energy model appeared to be representative of the real situation. By conducting this analysis, cost reductions can potentially be achieved as certain failures that emerged in the building could have been predicted through proper actions and, thus, avoided. However, the exact time when the failures will take place or the way in which specific building components need to be modified to avoid failures could not be specified through this analysis.

Based on this study, the advantages of BIM correlate with the definition of the parameter itself. Given that buildings are dynamic entities confronted with varying conditions, their ability to handle diverse situations is necessary. Although theoretical descriptions of parametric relationships allow for infinite changes in shape and form, parameterized models operate on fixed rules, reducing thousands of objects to minimal parameters. These parameters explicitly describe the internal relationships between building components so that the software can understand relevant functions. This fact limits to some extent the capability to create complex building elements without restrictions imposed by BIM technology [27]. Thus, a kind of standardization in construction emerges due to the parametric nature of BIM technology.

Concerning vernacular design development, each vernacular building is by definition unique and is designed as such. Consequently, there is little standardization in building design of vernacular components and new choices need to be made for each situation. The construction of the architectural and energy model of the museum proved to be a complex and time-consuming process in this study. It was often necessary to depart from the usual modeling in Revit by creating new families that precisely represent the building elements of the museum. Besides, high levels of familiarity with BIM software were required, as well as constant communication with experienced users.

Given the complexity of vernacular buildings, the creation of simulation models is challenging since contradictory factors need to be balanced. On the one hand, the model has to be kept simple enough, so that it can be easily designed and constructed. On the other, it has to be complex enough to be able to represent as accurately as possible the blend of factors that compose a vernacular building.

The initial direction of this research was to create a BIM model of the entire museum. However, due to the sheer complexity of this cave-like space and the lack of technological means, it was impossible to imprint this space. Specifically, there were no semi-automated tools used, such as laser scanning, to provide accurate as-built BIM data of the underground space. Besides, it is typical that the creator built this space by following the geomorphology and terrain of the area without being able to conform to design plans.

Having been developed for modern constructions mainly, BIM software presents limitations when applied to the design of complex elements of vernacular buildings. Besides, building elements of vernacular buildings must be dynamic entities to be able to reflect the evolving cultural, economic, and environmental features of a local society. To this end, the use of open-source templates could facilitate the codification and sharing of parameterized object libraries. The development of building components in a shared database would lead to the integration of the construction industry by creating common communication protocols.

Further, to produce a faithful representation of vernacular buildings, careful consideration must be given to precisely assign the elements of the model to the actual building components. Parametric design through BIM enables adaptability and diversity, facilitating the encoding of the tacit knowledge embodied in vernacular buildings. However, the analysis disregarded the role of environment-related elements, such as local vegetation and soil conditions, for enhancing the building performance. Moreover, the knowledge and building practices used by the creator of the museum could not be incorporated into BIM software (including, for example, the method followed for the processing of the rocks, as described in the previous section).

Hence, it is evident that tacit knowledge cannot be easily captured through BIM. Future research should focus on providing additional smart features to BIM technology. For instance, tacit knowledge could be reflected in the architectural model through the incorporation of local materials and environment-related components (such as foliage cover and vegetation types). Geospatial technologies could play a great role in detecting construction materials in the surrounding area. BIM users could, thus, evaluate alternative options regarding the suitability of materials on a context-specific basis. Finally, by embedding commenting abilities into BIM technology, local building practices could be preserved, opening up the design process to the world and enabling beneficial effects for society.

6.   Conclusions

Sustainable design of buildings is a complex interplay of diverse factors, which include social, technological, economic, and environmental features. Although vernacular architecture seems to be forgotten in contemporary architecture, it arguably provides a worthwhile source of knowledge that fosters environmental, economic and social sustainability. This   study explores the challenges and opportunities of using BIM technology for the architectural design and the energy analysis of a vernacular museum building.

Parametric technologies, such as BIM, can adapt to dynamic conditions as the definition of the parameter itself dictates. Given that parameterized models operate on fixed rules, thousands of objects are reduced to a few parameters that describe their interrelationships. This leads to a degree of standardization in construction, which enables the implementation of BIM technology for a well-defined type of building. In that sense, BIM technology could cover a wide range of simulations and analyses needed for this particular building type through an integrated set of applications.

However, in this study, BIM software presented limitations when applied to the design of complex architectural elements of vernacular buildings. Considering the uniqueness of each vernacular building, standardization limits the flexibility needed to design vernacular components. New   families were created to accurately represent certain building components of the museum, which   was a time-consuming process that required high levels of familiarity with BIM software and constant communication with BIM experts.

Further, due to the complexity of the underground cave-like building and the lack of relevant techno-economic means, the creation of the corresponding BIM model was impossible. Nevertheless, based on the interview with the owner of the museum and the software application, it was concluded that the results of the energy analysis were representative of the real state of the museum. Although the exact time or type of imminent failures could not be determined through the software application, the most sensitive building components from an energy point of view were detected.

Among the limitations of BIM technology, its inability to capture tacit knowledge and adapt to local specificities was discussed. Environment-related elements, including soil properties and local vegetation, as well as local building techniques used for the construction of the vernacular museum could not be incorporated into BIM software. Thus, despite being parametric in nature, BIM lacks the ability to capture and encode tacit knowledge embodied in vernacular buildings in its current form.

Hence, the need to enable the incorporation of commenting abilities into BIM becomes evident to preserve local building practices and facilitate the opening of the design process to the world. A common pool of parameterized data structures could be developed and linked to codified international datasets. Thus, the construction industry could become more integrated since various building components could be described and communicated using a common language.

Future research could also explore the capabilities of BIM to analyze other aspects of manufacturing activities, such as the environmental footprint of building components and the capacity of BIM to be adapted to different local contexts. At the same time, open-source applications in the construction sector are areas of increasing interest that could mitigate problems of conventional design and build practices, such as interoperability and construction standardization.

Further, the addition of smart features and the incorporation of environment-related components into BIM technology should be investigated. The use of geospatial technologies for the detection of locally available construction materials could be considered to facilitate the evaluation of alternative design options on a context-specific basis.

The sustainability features embedded in vernacular design processes are gradually lost. The incorporation of such valuable knowledge in current design processes could provide a flexible way to accommodate human needs, reinforcing the link between society and the environment. Thus, future studies on vernacular buildings should be conducted to enable the preservation of local building techniques in contemporary design practices (for example, by examining the compliance of vernacular buildings with local zoning and building regulations and proposing relevant law reforms).

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Conflict of interest

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