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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).

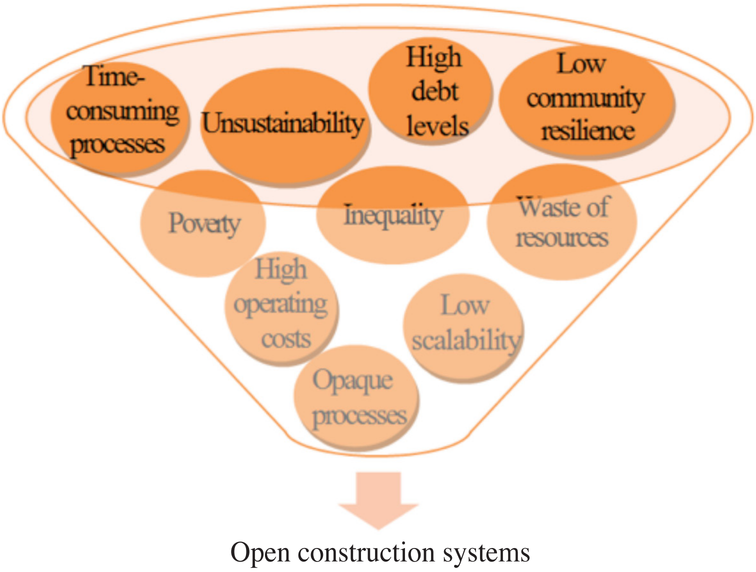

Figure 1. The emergence of open construction systems

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 prefigurative, 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 cocreating 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).

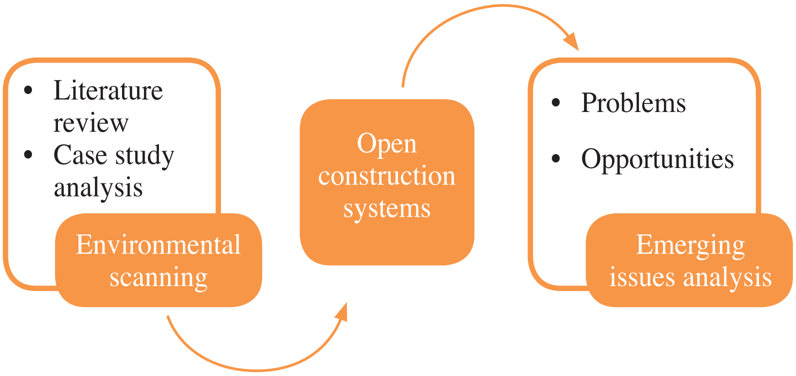

Figure 2. Schematic representation of the research framework

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.

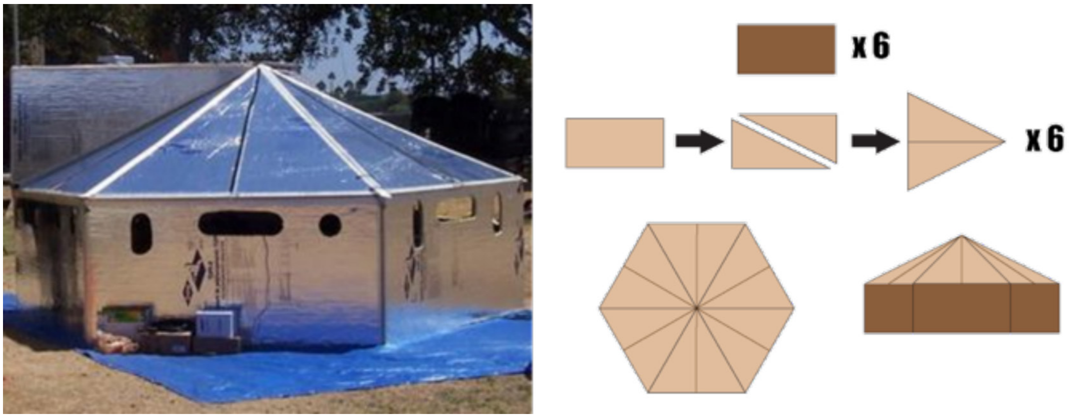

Figure 3. The Hexayurt project and its cutting models
Source: Adapted from Hexayurt, 2018b

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.

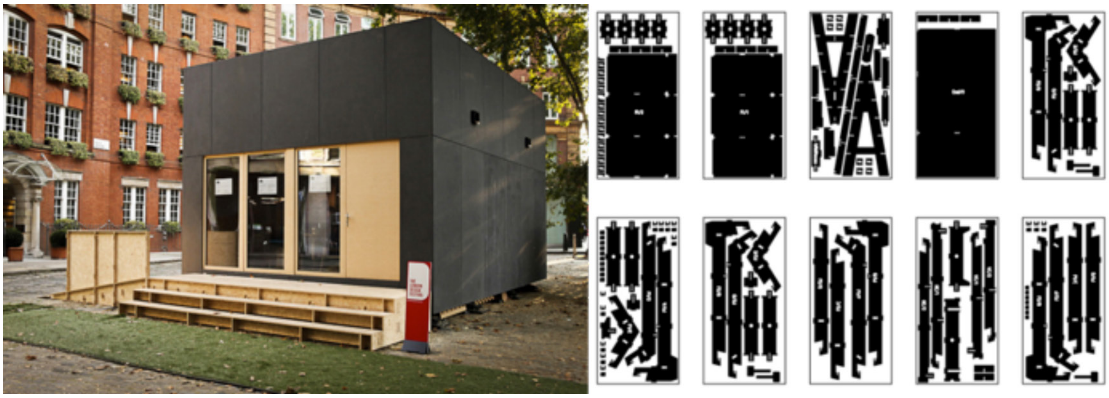

Figure 5. The WikiHouse project and its cutting models
Source: Adapted from WikiHouse, 2018b

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/m^2 (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 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.

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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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