Housing of the Future: Housing Design of the Fourth Industrial Revolution

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***Abstract*—The housing problems of the 21st century that include continuous urbanization, overpopulation, pollution, energy deficiency, land shortage and lack of affordable housing cannot be solved by applying housing solutions of the 20th century. The paradigm shift initiated by the disruptive new technological development of the fourth industrial revolution is offering substitution to the conventional understanding of housing design, its production processes and radically change the way we live and work. This paper examines and describes new prospects, opportunities and limits of housing design by the use of innovative advanced 3D printing technologies with CAD/CAM systems that introduce new possibilities to the process of housing design, fabrication and construction. These new possibilities in housing design include research in form, function, structure and materials, and have profound influence on both architectural research design, its production process and significantly reduce overall investments, time and resources, materials and labour use, decrease pollution and energy use.**

Keywords—housing; 3D printing; CAD/CAM systems; fourth industrial revolution; future architecture

I. Introduction

According to the United Nations data on the world population, cities around the world are getting bigger, with 51.6% of today's world population living in the cities [1]. It is expected that the world population in the cities would double, from present 3.5 billion to 6.2 billion by 2050, and almost entire growth is expected to occur in the least developed countries [1]. These factors of continuous and fast urbanization cause problems of overpopulation, land shortage, pollution, energy supply and waste management, etc., further expanding privation of affordable housing and unequal access to housing provision, phenomena that cannot be successfully tackled with the housing solutions of the 20th century.

Housing, as one of the most fundamental human needs, is a vital issue that all stakeholders must deal with systematically and comprehensively, but it seems, however, that our communities fail to find a long-term, sustainable solution.

On the other hand, the 21st century's rapid and inevitable paradigm shift, simultaneous with the fourth industrial revolution, is profoundly reshaping our social, economic, cultural and environmental way of living. The latest progress in new technologies and digital fabrication is transforming the entire systems of production, management and governance, and changing the conventional understanding of housing design.

The fusion of technologies in housing design, combines its natural, physical and digital features by displacing many of the established conventions. This paper argues the consequences of the latest technological developments by introducing some of the most recent digital fabrication technologies in the housing design process, with the aim to discuss implementation of latest technologies to housing and provide a vision of housing in the future, that would be more attainable and affordable.

II. New Prospects. Opportunities and Limits of Housing Design Process in 4.0

The digital revolution offers new methods of design process, fabrication and construction where all stakeholders are participating in transformation of the whole housebuilding industry by pushing the limits of innovative technologies' use with a combination of computer-aided design and other recent industrial manufacturing technologies.

These new prospects and opportunities include developments in housing research of form, function, structure and materials, and are focusing on the investigation of digital fabrication and design robotics, and the corroborating technologies, by the use of Computer-Aided Design (CAD) software, Computer-Aided Manufacturing (CAM) technologies, etc.

The use of these technologicies enlarges the range of prospects for housing design, construction and production. It

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enables reduction in time, material and labour use, overall cost, construction waste and risks, and at the same time it broadens the possibility of realizing complex architectural shapes and all sorts of customization [2].

Sustainability is one of the important factors, in terms of material and labour use, time and resource investment, ecology and energy issues, etc. The use of these technologies can have an impact on urban planning and housing design, construction and maintenance.

However, there are some limitations to broader uses of CAD software and CAM technologies. One of the main obstacles is the fact that it is still in experimental phase, and it is not recognized as construction method in terms of building codes and standards development bodies, that are essential for obtaining planning and building permits. Additional research work should show whether these constructions, material manufacturing processes, as well as the occupancy of buildings and structures meet the building codes of safety, health protection and general welfare.

These technological achievements facilitate and enable architects to explore more novel effects that are of unique architectural aesthetics that now can be realized cost-effectively and easily with the use of fine concrete-composite materials for structures. This design approach includes synchronized interpretation and manipulation of a computational idea. A complex discourse, continuously reconstituting itself into dynamic processes of form, material and technological developing, is crucial for multiplicative capacity housing design evolution.

A. *Mass-production vs. Mass-customization*

The housing crisis of the 20th century was initiated by the lack of adequate housing in the aftermath of the Second World War. In the socio-economic sense, laying ground for the future welfare state and finding housing solutions as a response to the massive need for the roof over one's head, meant that mass housing construction and land resource management needed to be systemized, rationalized and even centralized in order to be implemented effectively and with determination [3].

The new production process methods were based on mass-production, characterized by rationalization and standardization, enabling the production of large quantities whilst meeting the minimal required quality norms, and the efficient use of available resources.

The new housing crisis of the 21st century calls for innovative solutions. The new technological revolution supports the vision of new housing solutions designed and built in a completely different way. One of the major possibilities is participative design, with radical opportunity of efficient design processes, CAD/CAM production facilities and offsite construction technology [4]. The main idea is to replace standard mass-produced models with mass-customized ones.

The introduction of design process automation will enable housing customization by the users in terms of housing design, choice of size, shapes and materials, etc. The requirement for new manufacturing techniques is the cost-effectiveness, as an approach in translating housing design into innovative construction solution and producing custom-shaped housing. These manufacturing strategies enable the flexibility of the whole production system in order to fulfil unique intensities of customer's choice.

B. *Affordability*

The lack of affordable housing affects an estimated 1.2 billion people worldwide, from megalopolises to rural areas [5]. Some of the creative housing solutions implemented are micro-apartments, tiny houses, and modular and prefabricated housing. However, only radical proposals can create a real impact. The achievements of introducing automation to housing design process, with special design software package enables besides customization, one of the major benefits – the affordability.

The fourth industrial revolution in technology and manufacturing processes empowers the delivery of mass-customized housing solutions, characterized by extremely high quality and reliability, however at affordable cost. Besides the technology used, it is important to observe that there is an important gap between the developed and the developing countries, in terms of materials used and their limitations. Therefore, in order to achieve affordability, it is important that building materials used are low cost and easy to supply. This would enable access to housing for wider groups of population, and support more efficient solving of the housing shortages.

C. *Efficiency*

The efficiency of new technological housing design emerges once the automation goes beyond the design phase. The modern architecture itself has relied on industrialized components and building systems, such as the precast concrete post, beam and panel systems, and components such as bricks, blocks, tiles, etc. As opposed to these practices, computer-controlled offsite methods can open design and choice to prospect in creating an indefinite amount of individualized parts in process of housing design.

The housing production line, in the ultimate process of technological integration, advances construction techniques design and delivery with the reduction of overall cost and environmental impact. This 3D-printing automation process has proved to be efficient by significantly reducing construction time and waste, energy and material use, labour costs, etc. Beside this, these structures are far more resilient and energy-efficient, as they have high thermal mass making them reasonably durable and disaster-resistant.

III. The Future is Now: From Protoypes to Permitted Housing Solutions

In recent years, the use of novel digital technologies enables the development of different approaches in housing design research, experiments and findings. The creative and generative potential of numerous early prototypes through the use of digital technologies, fabrication, 3D-printing advances, are opening up to the new dimensions in housing design, with the aim to continue developing and refining these innovative technologies.

Fig. 1. WinSun Co. The first 3D-printed house in basic components and then assembled on the site, Shanghai, China, 2014

Some of the first prototypes were developed in China and Russia. Shanghai-based private firm WinSun Co., printed 10 full-sized single-story detached houses within 24 hours, costing only 4.800$ per housing unit, in 2014 [6]. Essentially, these houses are not the preeminent examples of 3D-printing, as houses have been printed in basic components separately and later assembled on site, Fig. 1. The concrete aggregate, part-formed from recycled construction waste was the material used for 3D-printing of the houses.

Fig. 2 shows an example of 3D-printing directly on site. The 38 square meter housing prototype was developed by the Russian startup Apis Cor. and PIK Group, and was built within 24 hours, at the cost of 275$ per square meter, on a site near the City of Moscow [7].

Fig. 2. Apis Co. and PIK Group, The first 3D-printed house completely on the site, Moscow, Russia, 2016

Apis Cor's 3D-printer processed layer by layer of concrete mixture that can last for 175 years according to the manufacturing company and it has preferable voids between walls, with fiberglass reinforcement rods, that can be filled with thermal insulation material. According to Apis Cor's calculations, the cost reduction reaches in average 40 percent in comparison with the usual concrete analogue.

The Canal House, a prototype initiated by DUS Architects, is a full-scale 13-room home, classic canal side house in the centre of Amsterdam [8]. Partly funded by the municipality of Amsterdam, it is being established as a publicly available research project to investigate the potential of various materials and techniques. The facade layers are printed as one element that has final finishing on both interior and exterior sides. The void in-between of the facades are filled with a specially produced foaming eco-concrete that has both structural and thermal functions. Innovative material of sustainable bioplastics has been used, containing over 80% of vegetable oil. This homogeneous liquid of melted granular plastic is being extruded from 3D-printer to create each component on site and then assembled.

Fig. 3 shows the first habitable 3D printed house project, known as Project Milestone, being presently designed jointly by Eindhoven University of Technology and Studio Houben & Van Mierlo Architecten. The plan is to build five different housing typologies, on site and within a five year span. The first house will be a single-storey, three-bedroom bungalow, expected to be completed in 2019 [9], followed by four multi-level homes. The gradual development is planned on purpose in order to allow the design team to learn from each housing solution, first by printing construction elements at the university site, with the final goal of printing the whole house on the construction site. According to the team, the final house will be fully printed and assembled on site.

One of the first permitted 3D-printed affordable housing in the US that fulfils local building codes and standards is the low-cost 32 square meter house planned by the non-profit New Story and the company ICON, for the homeless persons in El Salvador, Bolivia, Mexico, Haiti, etc. [10], Fig. 4. This prototype house has a living room, a bathroom, a bedroom, and a porch that were 3D-printed out of concrete within 48 hours on the Vulcan printer, for the cost of approx. $10,000. The only elements of the construction that were not printed, but finished and installed by workers were the roof, windows, doors and installations. The Vulcan printer extrudes mortar out of a jet in a programmed configuration, building up layer by layer till completion of a basic house structure.

The last permitted model is planned to be built in late 2019 in El Salvador, and it is expected to introduce some improvements in terms of reduction of total printing time to 24 hours and lowering production costs to $4,000 [10]. The plan is to print, within the next three years, a total of 850 homes in Bolivia, Mexico, Haiti and El Salvador.

The outcome of a synthesis of computer generated design and robotic construction is a digitally fabricated house, consisting of composite bricks, presented within company Fastbrick Robotics.

Fig. 3. Project Milestone, Eindhoven University of Techology and Studio Houben & Van Mierlo Architecten, The first multi-storey 3D-printed house, The Netherlands, 2019–2021

Fig. 4. The New Story and ICON, The 3D-printed affordable housing, USA, 2016

This Perth based, Australian company has developed a construction robot – Hadrian X [11] that is expected to transform human/machine collaborative digital construction in the future, taking the benefits of fully automated machines onto the construction site. This robot is capable of constructing, without physical human input on construction site, an average sized house, under two days using robot automation, using modular unit of the masonry brick. Hadrian X robot is innovative in its mission to revolutionize the construction industry in general, and enable development of additional innovations, targeting other industries beyond bricklaying and construction.

IV. Conclusions

The housing of the future sets the vision that is related to overall sustainable development, socio-economic growth, fair distribution of wealth, rational land use, efficient energy use, reduction of waste production, and above all fulfilment of basic housing rights and safety, by the use of autonomous technology that enables housing production that is custom-made, efficient and affordable to the widest range of population. The fourth industrial revolution in technology and manufacturing processes, applied to housing design and production, replaces standard mass-produced housing models with mass-customized ones, thus creating new possibilities for high quality, reliable and efficient customized housing solutions, at affordable cost. This allows solving of the housing shortages and providing access to housing for wider groups of population, by using 3D-printing automation technology that significantly reduces construction time and waste, energy and material use, labour costs, etc., making housing production more durable, resilient, and energy-efficient.

The novel digital technologies and recent progresses have introduced the inevitable paradigm shifts in housing design, displacing many of the deep-rooted conventions towards digital ones. These digital technologies introduce new approaches to housing design by incorporating housing research, design, process of construction and assembling of buildings. This novel technological approach is seldom used as a tool to augment the sustainability of housing design, structure and materials, as showed in this paper. Innovative materials and structures following this technological paradigm shift, are fundamentally changing the whole process of housing design and production. There is unlimited prospective for research progress in these fields.

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