The 3D printing challenge in buildings

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Abstract. The rising awareness and usage of Building Information Modelling (BIM), a methodology that allows for better information management and communication amongst the several stakeholders of a building project, opened the construction sector's door to digital fabrication tools that for years have been applied in many highly productive industries. 3D printing (3DP), unlike the conventional construction process that showed no signs of progress over the past decades, has already proven to be an interesting technology for Architecture, Engineering and Construction (AEC), enabling important economic, environmental and constructability advantages, such as a reduction in building time and waste, mass customization and complex architectural shapes. Consequently, universities alongside companies worldwide, are now developing and applying 3DP to building construction. However, with the growing adoption of new technologies in AEC, new challenges arise that must be overcome in order to guarantee the buildings' correct performance. Therefore, this paper presents a literature review conducted to highlight new developments regarding the building physics and comfort of additively manufactured structures. The research revealed that the focus so far was guaranteeing printability, structural soundness, safety and durability, which means that there are still key requirements to be met, including fire resistance and adequate hygrothermal and acoustic behaviour.

1 Introduction

In the last decade, the economic context of the AEC sector has declined considerably. The 2008 economic crisis highlighted industry's fragilities in terms of its high fragmentation and heterogeneity, namely the wide variety of stakeholders, projects, materials and technologies as well as an industry hugely dominated by SMEs (Small and Medium-sized Enterprises).

A substantial amount of losses in the workflow take place between processes and sub-processes due to the lack of standardisation of information systems, which is why the construction sector is one of the least productive, with an average global growth in labour productivity of 1% a year over the past 20 years compared with a 3,6% growth in the case of manufacturing [1].

In addition, the changing demography is leading to a declining labour force with more people retiring than younger people interested in being a part of the workforce. This tendency follows the current negative perception associated with employment in the AEC sector, which is considered less prestigious than in other areas of engineering, due, among other reasons, to the crisis in the industry, its overall poor image and the unattractive conditions of entrance into the labour market [2, 3].

The international economic reality experienced in recent years has accentuated the strong restrictions on the activity of companies in the construction sector, due to either the reduction of investment or the financial situation of the entrepreneurial fabric.

With 9% of the EU GDP (Gross Domestic Product) and around 5% of European workers directly employed in

the sector, the construction industry is strongly exposed to the conjuncture and the economic cycles' oscillations. Thus, with the slowdown of the crisis in recent years, 2013 was a turning point for the industry at European level, with steady growth in terms of investment, production volume (Fig. 1), confidence index and employment.

Fig. 1. Evolution per year in the EU28 of the volume index of production in Construction (data source: [4]).

The construction industry is complex and multi-faceted, carrying upstream of its production chain the extractive industry, as the largest consumer of raw materials in the EU, and the manufacturing and distribution of construction products, and downstream of its production chain real estate activities [5, 6]. Consequently, it is considered one of the main drivers of

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the global economy, not only on account of their specific importance in creating wealth, but also because of its significant impact on employment worldwide (14.8 Million workers in EU28, see Fig. 2) [6].

Fig. 2. Impact factors for the future competitiveness of the architecture, engineering and construction (AEC) sector (data source: [5]).

However, investment on Innovation and Research & Development (R&D) in the AEC sector is rather low compared to the manufacturing industry in general, which is why it is mainly characterised by its resistance to adopt new technologies and modern management and operation processes. This reality is more pronounced for SMEs, where addressing labour-intensive requirements is the top priority of the investors, and companies are more interested in integrating available external technological advances into their activities than investing in developing their own [2].

Nevertheless, when construction firms make efforts in order to change its practices and innovate, difficulties such as a lack of skilled labour, the worker's demotivation, the limited cooperation that exists with the research community, a misalignment between businesses needs and university researches or difficulties in obtaining funding, often constitute setbacks to the desired technological development [2].

In the long run, the growth and sustainability of companies in the AEC sector will depend on their ability to diversify into new areas and adapt to technological developments [6]. Therefore, global technology trends point to a bet by construction players on integrating digitisation technologies, adopting new materials and processes as well as assuming a clear focus on energy efficiency [2, 6]. Hence, construction players must now strategically position themselves on the side of innovation in order to be competitive and benefit from the foreseen worldwide growth trend.

In order to consolidate a strategy for the future, Fig. 2 emphasizes the AEC sector relevance in EU28 and presents possible guidelines, such as the focus on technological maturity based on research, development and innovation, specialised qualification of human resources around the thought of digital change, financial sustainability and unification and promotion of territorial equality [6].

In this sense, to improve future approaches in the construction industry, new technologies such as 3DP are pointed out when planning the future. For this reason, the present paper analysed English-language literature from

the Scopus and Science Direct databases until 2019, intending to bring to light studies concerned with the comfort of occupants of 3D printed buildings. In this paper the different technologies that are being adapted for the AEC sector are identified, the 3DP concept and the advantages that may come from its use in building construction are mentioned, and questions related with the building physics of these structures are addressed, as well as what has been studied in this regard so far.

2 The next industrial revolution

2.1 Industry 4.0

With European citizens spending on average over 90% of their time indoors, with 40% of Europe's energy consumption coming from buildings and with buildings alone generating 36% of greenhouse gas emissions in the EU, the direct link between people's well-being and the methods and materials used to build, maintain and renovate civil engineering structures becomes clear [5]. Therefore, the adoption of innovative methods able to automate processes, minimise waste and increase productivity is the transition that the AEC sector needs.

Progress towards the next industrial revolution, also known as industry 4.0, will not only provide inherent environmental benefits, but also have a positive impact on quality, reducing project delays and safety in the construction process [5].

While the first industrial revolution was connected with mechanization, water and steam power, the second characterized by the beginning of mass production with electricity and the assembly line creation, and the third related with the introduction of computer technology and automation in processes, the fourth industrial revolution will be based on the usage of Cyber-Physical Systems (CPS) [7, 8].

CPS are systems whose operations in the physical world are controlled, coordinated, and monitored by computer-based algorithms, which are integrated with the internet. Thereby, real on-site data can be acquired via sensing and automatically linked with virtual models, which allows for the collaboration of assigned parties throughout the value chain [9-11].

Niemelä *et al.* [12] refer additive manufacturing (AM) as "one of the core technological advances in the paradigm shift to Industry 4.0".

2.2 New technologies in the construction industry

Notwithstanding the construction industry resistance to change its practices, the latest building market downturn has currently offered an opportunity for a new perspective that can move the construction industry into a brighter future.

Thus, at the moment, construction companies must, while retaining the know-how acquired so far, keep up with the technological transformation that recently emerged with the introduction of BIM in the AEC sector. BIM is essentially a set of processes of information

exchange based on a parametrically designed 3D digital model (4D when considering the schedule and 5D the costs) that represents different building components and their relationships [10].

Accordingly, BIM provides a great advantage over conventional processes, as it facilitates cooperation among all stakeholders throughout the construction life cycle. In addition, when used in coordination with other technologies, as for instance, Virtual Reality (VR), which enables the simulation of close-to-reality settings in the early design and engineering phases, helps detecting clashes, therefore avoiding costly mistakes [10, 13, 14].

The introduction of BIM played a central role in the promotion of digitisation, and consequently, in recent years Industry 4.0 technologies have been increasingly considered for the AEC sector [10].

An example of a new trend with great application prospects is Internet of Things (IoT), which concept is based on the integration of sensing equipment such as radio frequency identification (RFID), infrared sensors and global positioning devices in equipment, material and workers, in order to make them connected to the internet and enable information exchange in real-time, which directly ensures safety on construction sites [15-17]. According to Garyaev *et al.* [17] IoT has been successfully applied in numerous industries, from logistics and transportation to agriculture, energy and smart buildings.

Another digital tool being adapted to the construction sector is Artificial Intelligence (AI), which refers to the machines' ability to undertake tasks as if they had human intellectual skills, suchlike learning, planning, self-correcting and reasoning.

Just as AI and IoT, among other technologies, are encouraging information complexity through new forms and data sources, another trend in digital modernization is Big Data Analytics (BDA). While Big Data (BD) characterises information which current technological tools cannot save, control and process given its high velocity (data processing speed), volume (amount of data) or variety (data range), BDA is the structure created to analyse information considered Big Data, with the purpose of recognising patterns and new opportunities

[18, 19]. Ram *et al.* [20] state that BD stored across the whole lifecycle can be used for improving BIM's output, thus improving BIM's efficiency.

The combination of digital trends such as IoT, AI and BDA can transform the industry by enabling asset management, predictive maintenance, construction site monitoring, remote monitoring and safe construction.

Another powerful way for innovation lies in construction materials, which solutions can vary from the progressive innovation of mainstream materials and current characteristics to completely breakthrough materials with entirely new or improved properties [14].

However, as the use of cloud-based technologies grows and connectivity advances the exposure to potential cyberattacks increases, which raises major concerns. Cybersecurity, which is presumably going to be a major challenge of the future, refers to answering these digital security vulnerabilities by protecting computer systems and networks from cyber threats [21, 22].

To sum up, BIM is acting as a key enabler of the adoption of many technologies in the AEC sector. Yet, Correa [10] mentioned that in spite of BIM's large application on the conception, design, and planning phases of the building lifecycle, there is a lack of integration of BIM in the construction phase, on account of the still wide reliance of the construction site on human labour.

To address this issue, several research groups are focusing on processes' automation by combining robotics and additive manufacturing, commonly known as 3DP [23-29].

Altogether, after decades of no significant differences in the technologies and processes used in building construction, the current adoption of new technologies around the concept of digital transformation in the AEC sector, which can be divided in three different groups under the name of digital technologies and processes, materials science and robotics and automation (see Fig. 3), is now starting to close the gap between the level of innovation and automation characteristic of other industries compared to the lack of progress seen in construction.

Fig. 3. Key emergent technologies for the industrialisation of the construction sector towards Industry 4.0.

2.3 The adoption of new technologies by AEC companies

PTPC (Portuguese Construction Technology Platform), which is a Portuguese association member of the ECTP (European Construction Technology Platform) Steering Committee, conducted a survey on technological maturity and digital transformation in construction companies in the northern region of Portugal. According to this survey, it is clear that there is still no clear guidance from construction firms for the definition and establishment of an objective strategy for the adoption of new technologies [2].

In general, there is a low level of technological maturity of SMEs in the AEC sector, with most companies in the industry using management software over software specialized in core engineering and construction activities (see Fig. 4).

Fig. 4. Informatic tools used in companies from the northern of Portugal based on a survey (data source: [2]).

The study also found that most of the companies do not account for R&D investment, almost half of them do not use BIM and about 1/3 claim to be unaware of the technology. By and large, these companies identified budget constraints as the main obstacle for the adoption of modern technologies in the sector [2].

As the most productive industries are those with a high level of digitisation and change usually starts with stakeholders, digital transformation will only be possible when companies shift their mindset and start investing in digital innovation-driven development.

However, the adoption of digital technologies in construction is affected not only by the market structure but also by companies' size. For that reason, digital implementation is often led by large companies that have more capacity as well as more human and economic resources to support innovation [30].

On the other hand, with the growing awareness around digital processes, this development can also be demanded from project's owners. In fact, in the United Kingdom, the government has shown itself to be a key driver of the use of BIM processes by mandating the use of BIM on all public funded projects from April 2016 onwards.

Thereby, across the construction industry of the United Kingdom, the overall BIM awareness and adoption has grown from around 10% in 2011 to about 70% in 2019 [31].

Currently, BIM is a frontrunner innovation in the construction industry and, although progress in digitalisation has been different from country to country, its use in the European context is present in 29% of the existent construction companies [30].

On the whole, despite the overall slow adoption of technological tools by the construction industry, consistent and constructive progress is being made and according to the Boston Consulting Group [32] by 2025 the global digital transformation in the engineering and construction sector will lead to potential cost savings of 13% to 21% in the design and construction phases and an additional savings of 10% to 17% in the operational phase.

3 Additive manufacturing

3.1 Concept

Additive manufacturing, originally referred to as rapid prototyping and commonly known as 3D printing, is the process of additively producing objects, initially modelled using a three-dimensional digital system, by depositing successive layers of material [33-35].

In accordance with ISO/ASTM 52900-15 [36], there are seven different AM categories, namely binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. These different process categories have specific operating principles and therefore distinct levels of complexity, which not only influence the quality and structural properties of the printed component, but also the productivity of the printing process and the cost of the final elements [37-39].

For a visual representation, Fig. 5 presents an illustration of the workflow regarding the material extrusion process, which of the seven AM categories is the one most commonly associated with 3DP. First, an object is three-dimensionally modelled with a modelling computer program, then the 3D digital design is analysed and split into a series of cross-sectional layers whose are converted into a print path and deposited one over the other from the bottom up [25].

Fig. 5. Material extrusion process.

3.2 General applications

Over the past two decades the AM technology matured considerably, rapidly changing the traditional production methods in a number of markets [34, 35]. Beside enabling mass customisation, which unlocks new possibilities in terms of production patterns in multiple sectors, with 3DP, objects can be built in places as remote as space, which is why AM is currently a multi-billion dollar industry [40].

This revolutionary technology is considered for the construction of human colonies in extra-terrestrial environments, such as Martian or Lunar land [41, 42] and is popular in the aerospace field as it can easily produce lightweight and durable components [34, 35, 43].

Furthermore, AM has showed potentialities in the sports industry, from the production of accessories with complex geometries to the creation of adjusted protective equipment [40]. Likewise, the automotive industry has also benefited from the faster way to bring products to market, thus saving on overall vehicle development [44] and the medical field greatly implemented AM from orthopaedics to plastic surgery, with exact applications such as human organs prosthetics [34, 35, 45].

On balance, the unlimited capabilities of 3DP enable its application in numerous areas. Thus, having in mind the productivity problem of the AEC sector as well as the high costs associated with building complex shapes using traditional construction processes and the increasing demand of housing all over the world, the application of AM in the construction industry may be the solution that the sector needed.

3.3 Construction industry applications

With endless potentials, everyday new 3DP applications emerge. However, although different AM processes have been positively applied in a wide range of industries, its introduction in the construction industry it is still in the beginning [46].

Benefits of its application in the sector include a reduction in building time and waste and higher flexibility inherent to the manufacturing process to produce complex shapes, all of which will lead to a significant cost reduction [14, 47]. Furthermore, automation of building processes will result in a reduction of the manual labour and the better control of the construction site, therefore increasing its safety [48].

Whereas Labonnote *et al.* [49] underline the unparalleled design opportunities that the AM technology unveils, García de Soto *et al.* [47] go a step further highlighting the AM potential to move construction into the digital era.

Many researchers and companies believe that 3D printing can indeed change the construction industry in a positive way and some large-scale structures have already been manufactured by addition as can be seen in the example of Fig. 6.

Indeed, it can be concluded by the increasing number of studies and projects in this subject that recently there has been a big bet from the different AEC stakeholders on this rising technology.

Fig. 6. 3D printed building in Dubai by Apis Cor (photographs source: [50]).

4 Building physics

As mentioned previously, nowadays a number of projects by companies and universities are being performed on the implementation of AM in building construction, namely Contour Crafting by the University of Southern California [51, 52], the D-Shape technology by the construction company Monolite UK [53], Concrete Printing by the Loughborough University [54], 3D Concrete Printing by the Eindhoven University of Technology [29] and the Digital Construction Platform by the Massachusetts Institute of Technology's Media Lab [55], among others.

Since the material used for 3DP must be compatible with the 3D printer, research teams started by developing large-scale 3D printers capable of manufacturing prototypes of building elements. Meanwhile, mainly cement-based mixtures were developed, and most projects designed their specific mixture's compositions in conformity with their printer's specificities.

The design of cementitious mixtures for three-dimensional printing with the necessity of extrusion must fulfil basic requirements regarding workability and open time. Therefore, their composition, which primarily consists of aggregates, cement and water, also includes additives and admixtures to improve the mixture's fresh or hardened properties, as performance assumptions require [48, 56]. In addition, given the global environmental circumstances, the selection of raw materials should take into consideration the need to move towards the concept of sustainable development, which implies that preference be given to the use of renewable resources, conducting to a circular economy [48].

As has been noted, up until now the focus of research projects has been on answering questions related with the 3D printer, material's composition and its structural properties as well as the placement of reinforcement. However, there are still a great deal of improvements to be made and issues to be addressed, as can be seen from the representation in Fig. 7.

Building physics comprises several different disciplines related to building performance, being responsible for providing comfortable indoor environments to the built structures.

With the increasing application of large-scale 3D printers to additively manufacture buildings, more and more challenges will inevitably arise, as pointed out by Liu *et al.* [56]. Accordingly, current mandatory standards, such as earthquake and seismic safety or fire resistance regulations in residential buildings cannot be withstood.

Fig. 7. Evolution of the 3D printing integration in the construction industry.

Similarly, areas of building physics such as air and rain tightness, ventilation, moistures' control (surface and interior condensation), hygrothermal performance (heat transmission mechanisms such as conduction, convection and radiation, linear thermal losses, thermal bridges and solar gains), and acoustic insulation (sound absorption and reverberation time) will become the focus of future research projects.

Furthermore, over the coming years, questions related to the context of the printing site, such as climatic conditions (external and internal forces of wind, rain, snow or solar radiation) must be experimentally tested out as it will affect the characteristics of the mixture [48].

Besides, up until now, most large-scale AM applications are previously printed and then assembled together on site [56]. This assembling task will possibly continue to happen in the future for tall buildings or even high-rise buildings, consequently, in these cases, the type of fitting between the different building elements will influence the building physics as well and must be further considered.

5 Conclusion

Opposite to other industries, in Civil Engineering, every project has its unique specifications, geometry and players throughout the lifecycle of the structure. The fragmentation seen in the sector, coupled with a lack of innovation, is translated in its current low productivity.

The introduction of additive manufacturing in the construction industry enables a large technological jump, as allows for processes automation. This literature review showed that there are numerous new technologies being applied in construction; however, it is up to the companies to identify which innovations are relevant for them and then invest in their further development. Going forward, 3DP provides the opportunity to print multiple materials at the same time through different extrusion nozzles while automatically adding reinforcements.

Overall, although the current adoption of AM remains slow mainly due to the technology not being yet broadly developed, with studies, presently on the experimental and development stage, predominantly focusing on guaranteeing printability, structural soundness, safety and durability, it is safe to say that it has the potential to make a positive change in the industry.

To conclude, in line with the increasing number of emerging studies on AM adoption in the AEC sector, advancements in the field of building physics are vital for the optimum performance of the building and, therefore, to the introduction of this technology in the construction market.

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