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Automated Construction of Structures using 3D Printing: A Review

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Abstract

The recent advances in 3D printing techniques from past one decade in terms of materials development, product evolvement methods, industry 4.0, technological up-gradations, manpower free constructions, customised production, waste minimization, freedom from designs at an affordable cost. 3D printing processes are extensively contributing in the field of structural industry. To meet the fast-growing demand of the humans there is a need to understand the concepts and in-depth knowhow of 3D printing processes. The technological developments of 3DP to infrastructure domain are still untouched zone worldwide. It is because of lesser projects successfully carried out since its inception. The article presents insights of additive manufacturing processes and its applicability to the construction industry. In the construction industry, 3D printing has not yet reached the point of commercial availability at global level. Fewer number of 3DP experiments for large-scale buildings can be discovered in the literature. A critical analysis of past and present literature studies is conducted worldwide and also investigated the potential benefits of additive manufacturing processes to construction industry. This article's unique contribution is its examination of the many uses for 3D printing in the construction industry, as well as the advances in technology that have made this possible.

Keywords: Additive manufacturing, 3D printing, construction industry, industry 4.0

1. Introduction

3D printing processes offer many benefits over traditional subtractive processes such as customised production, on demand manufacturing, high strength to weight ratio, waste minimization, ability to fabricate the complex assemblies, mass production, freedom from designs at an affordable cost. Three dimensional printing (3DP) is also termed as additive manufacturing (AM), which is an programmed techniques used for creating the 3D solid objects by successful addition of layer by layer [1].The first 3D printer was successfully commercialised in the year 1980 by Charles Hull [2]. It was well known technique similar to rapid prototyping technology. Later, it's wide used and application was observed everywhere. It enables to create unnumbered objects with abundant design flexibilities which cannot be produced by any other method. It is a controlled advanced manufacturing process with layer by layer deposition of thin film to fabricate the 3D solid object [3]. 3DP has its impact in major domains and have been rapidly evolving includes medical, telecommunications, aerospace, biomedical, renewable, microelectronic cooling devices, solar water heating, healthcare and infrastructure industry. 3DP automated and advanced progressions are also promising in construction industry. Successful deployment of innovative 3DP offers many opportunities for construction industry[4]–[9].

Infrastructure sector is one of the major domains consumes the considerable number of environmental resources. According to Koltz et al. [10] structural work in United States consumed 36% of the energy, 30% of the energy consumed by the raw material and approximately 12-13% consumed by portable water. The industry is being facing the problems of poor productivity. Nasir et al. [11] investigates in his study, compared the labor (manpower) productivity of 20 nations worldwide and reported that U.S. presented the worst results. The annual compound rate for productivity reported less than - 0.85%. The same issue of low productivity is also found in many developed countries including Singapore [12], U.K. [13] and Hong Kong [14].

3DP methods have huge potential and have made rapid progress in the last two decades in infrastructure industry. The global 3DP sector market value was approximately US$ 165 million in 2013. In 2018 it increases more than 21% per year and become US$ 420 million. It is expected to increase to US$ 3.18 billion at a progressing CAGR of 21.07%. by 2022-2023 [15]. They have exceptional abilities over other conventional processes. Recently, the capabilities of AM processes have been tailored by developing advancements in additive manufacturing processes. The AM processes capabilities such as high customized material properties, high end operational techniques, flexibility in processes, high strength to weight ratio, thermal insulating property as well conducting properties of the materials, affordability, printability are the key process parameters as shown in Figure 2.

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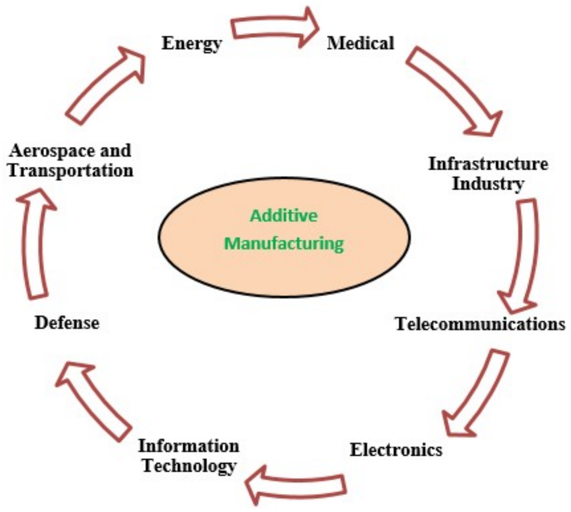

Figure 1: Potential application areas of additive manufacturing

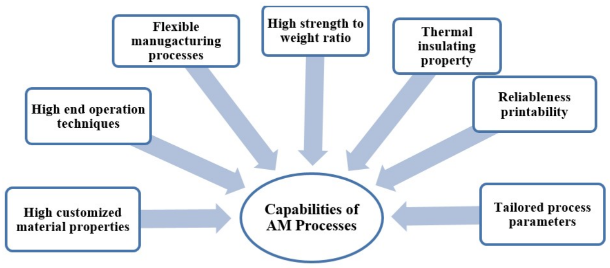

Figure 2: Potential abilities of additive manufacturing

1.1. Motivation:

Literature reveals that it is important to enhance process capability of 3DP. The importance of three-dimensional printing (3DP) processes for improving the methods and technology in infrastructural industry proven to be the boon to the entire structural engineering.

1.2. Specific Objectives:

Therefore, worldwide researchers have attracted and contributed a lot to the development of advanced potential benefits for 3DP. This review article has therefore been undertaken to study various AM processes adopted in infrastructure industry with their applications worldwide. The objectives of this present review contribution are:

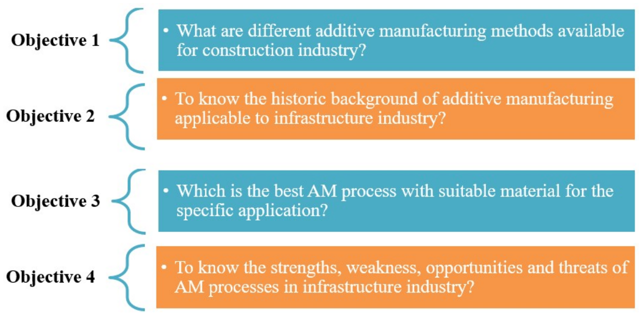

Figure 3: Specific objectives of a review article

This study would portray the answers to all relevant questions.

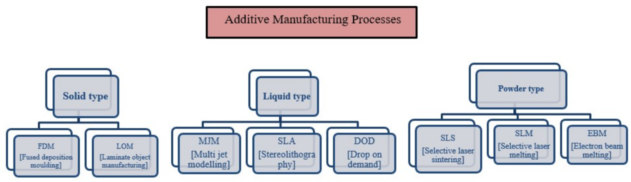

Figure 4: Three dimensional printing processes [16]

2. Types, methods and characteristics of 3D printing/AM processes applicable to construction industry

Figure 4 demonstrates the classification of AM processes which is a self-explanatory. According to Bouge et al. [17], three dimensional printing is based on AM processes. A 3D digital model is generated using Computer Aided Drafting (CAD) software. The model in the form of digital document is then transferred to the 3DP known as stereo lithography language (STL). Later, the (CAD) model is converted into films (layers) and sliced using slicing software. During fabrication of the part layer by layer the material deposits over the bed. The films are united together sequentially to form the 3D solid object. In year 2009, the very first commercial based 3DP was launched around the world.

2.1. Process flow diagram for additive manufacturing

The additive manufacturing process follows standard operating procedure (SOP) is shown in Figure 5 for 3DP. It illustrates the relationship between the initial concepts designing to actual part printing. It covers the major stages designing, generation, creation, exporting and part printing.

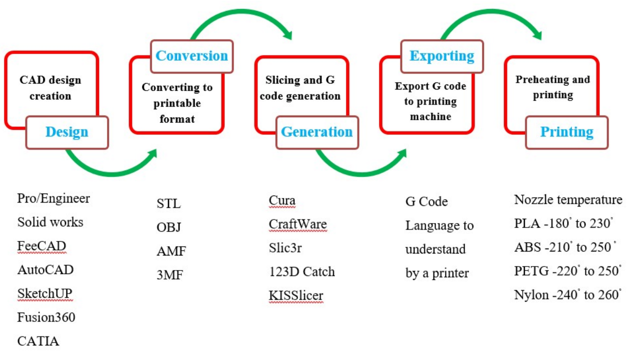

Figure 5: Process flow diagram

2.2. Additive manufacturing processes used in construction industry:

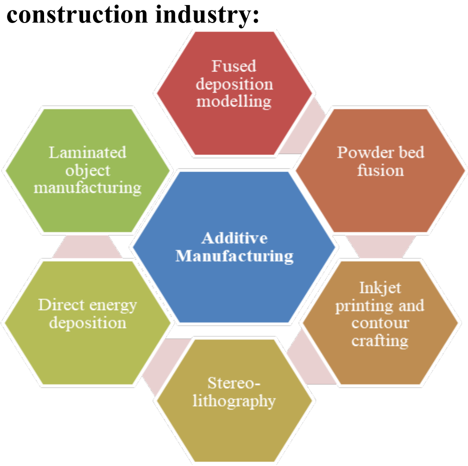

Figure 6: Additive manufacturing processes

2.3. Summary of materials and application of additive manufacturing.

Method	Material	Application	Ref. no.
Fused deposition modelling	Filaments prepared from thermoplastics polymers (Continuous fiber-reinforced)	Small composite 3D objects	[18]
Stereolithography	Monomers (Composites polymer blended ceramics)	Small structures	[19]
Direct energy deposition	Alloys and metals in the form of powder or filament (Ceramics and polymers)	Structural components	[20]
Laminated object manufacturing	Composites paper made up of ceramics, metals and polymers	Small electronic components	[21]
Powder bed fusion	Fine powders (Compact made up ceramics, metals and polymers) Printer: SLS and SLM Metals, alloys and limited ceramic and polymers (3DP) polymers (SLS or SLM)	Lightweight structures	[22]
Inkjet printing and contour crafting	Concentrated dispersion of particles in a liquid (ceramics, metals and polymers - Semisolid gel or ink)	Infrastructure objects Buildings Large structures	[23]

2.4. Potential execution of 3D printing in construction industry

3D Printing technology	Application	Ref. no.
Direct energy deposition	Constructional building parts (Polymer, ceramics and metal based)	[24]
Laminated object manufacturing	Plaster model	[25]
Fused Deposition Modelling (FDM) (SLS) (Kamer Marker)	Constructional building parts (Polymer, ceramics and metal based)	[26]
Fused deposition modelling	Complete house	[27]
Powder bed fusion	Lightweight structures sheets (Geo-polymers)	[28]

3. Parameters affecting capability of 3D printing in construction industry

There are three primary characteristics that must be carefully addressed in order for AM to be successfully implemented in large-scale construction:

3.1. Printable feedstocks: Core innovations in feedstock depend on a number of factors, including source and configuration, mix design with various fillers, and element size. The optimal blending of feedstocks ensures that the nozzle can receive material continuously during the extrusion process by providing the right amount of open time and setting time [29].

3.2. Geometry: Full-scale constructional objects with intelligent self-reinforcing geometry can be customized. The strength depends upon the stability of the filaments deposited during printing process. Also some infrastructural shapes like trusses may improve both strength as well as rigidity [30].

3.3. 3D printing setup: It is imperative to study the geometry as well as the size of manufacturing in the construction industry to have a printer that is combined with a pump. As a result, it is necessary to conduct research on the pressure and flow rate in agreement with the various combine designs. The speed of the printer and the size of the printer setup are other important factors in determining whether or not a satisfactory print quality, as measured by a smooth surface, square edges, and consistent dimensions, is achieved [31] Multiple interconnected parameters determine the print quality and structural integrity of 3D printing constructional components.

The most frequent form of 3DP material found in structures is mortar. It is primarily composed of Portland cement and plasticizing agents, with additional additives added to increase its workability, durability, water holding capacity, and setting speed. Three steps make up the 3DP process for cementitious materials: mixing the material, delivering the

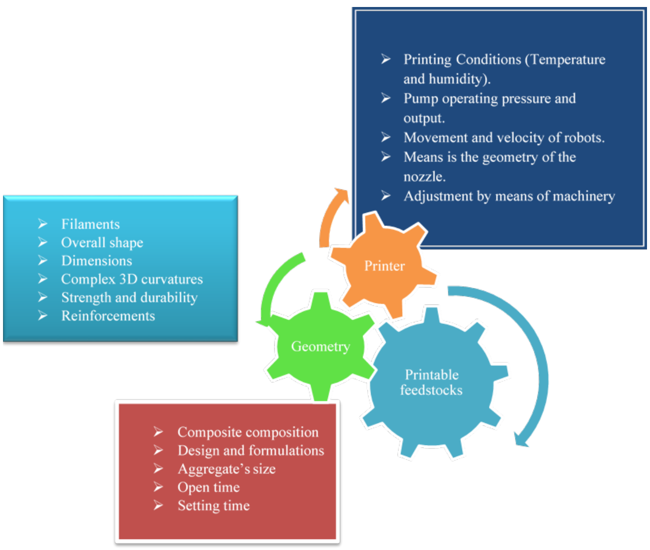

Figure 7: Relation of key parameters for affecting 3D printing in construction industry

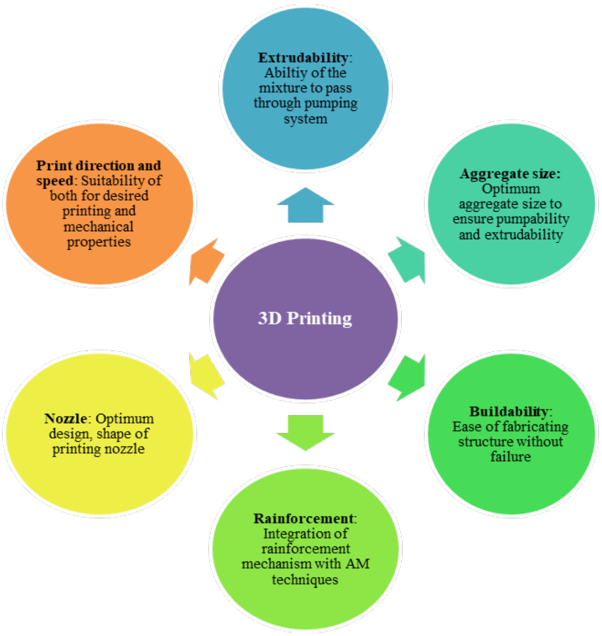

Figure 8: Process parameters of 3D printing in construction industry

material, and extruding the material. During the delivery phase, a well-mixed material should flow or extrude easily, but it also needs to settle quickly after extrusion so that it can support stresses in layers that come after it. It is possible to link these two separate times to the thixotropy. In order to advance the development of concrete printing technologies, researchers have defined the parameters of extrusion materials. The most crucial factors to think about when printing residential structures, homes, and offices are the material's workability, extrudability, flowability, buildability, pumpability, and open time [38, 39]

4. Pillars of 3D printing in construction industry

4.1. Advancement in Materials:

The materials used in 3D printing need to be compatible with the said technique. The material commonly used involves metallic, polymeric as well as cementations materials. Polymers are generally melted in fused deposition modeling (FDM) or fused filament fabrication (FFF) techniques and other related techniques [32]. They are

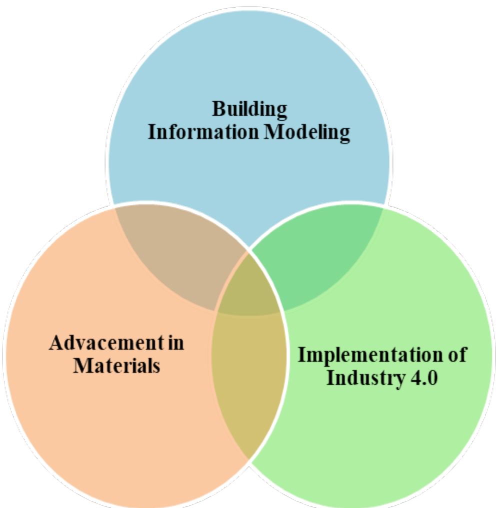

Figure 9: Pillars of 3D printing in construction industry

usually employed for aesthetic applications on account of its poor structural strength. Such material provides minimum risk option for adopting AM in civil as well as mechanical construction works [33]. The thermoplastic polymers e.g., ABS and PLA, melting down at higher temperature ranges and solidifies after cooling, are the well-known polymeric materials. On account of biodegradable quality, PLA is treated as more durable than ABS. In concrete printing and civil contour crafting, the commonly used material involves high performance cementations materials e.g. concrete. Such materials can be evolved for building structural and architectural objects with no formworks [32].

In addition to this, for printing structures, the materials should have properties like pumpability (able to pump), extrudability (to extrude through fine nozzle of printing equipment), buildability (deformation resistance of the printed material), and open time period (period for which above three properties are within workable range) [32], [34].

4.2. Design module (Building Information Modeling)

As was stated previously that in order to print anything with a 3D printer there is a requirement of a CAD model of the object in digital document format. Building Information Modeling (BIM) is the software platform that is utilized most frequently in the construction industry. The BIM module uses information and communication technologies to streamline the procedures that involved project in order to make the project safe (reliable), more creative, and more effective [35].

An efficient project plan is created when the building has been developed on the BIM module and the associated expenses and materials have been entered. The software has been widely adopted and is being used for design of traditional construction projects in construction industry [36]. The BIM software's output of CAD files should be translated into machine language. Most 3D models are saved in STL, which stands for "stereolithography," the first method of 3D printing. For a greener infrastructure to be built, BIM can provide the necessary value judgments. Sustainable design is a tool for fostering environmental friendliness in the construction industry. Sustainable design is an approach to architecture, landscaping, and urban planning that seeks to lessen humankind's ecological footprint without sacrificing aesthetic quality [35], [37].

Figure shows the action research continuity for the implementation of building Information modeling process in constructional industry. It is planned in four stages for its effective implementation and for obtaining the precise results.

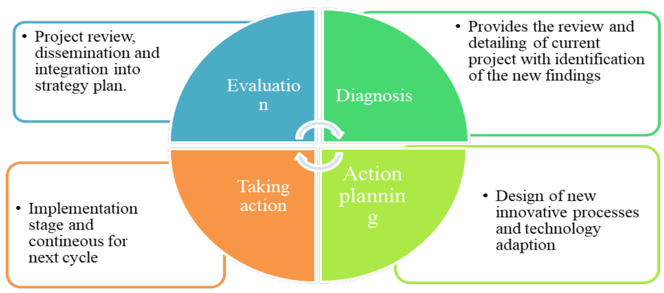

Figure 10: Action research process adopted for **BIM** module

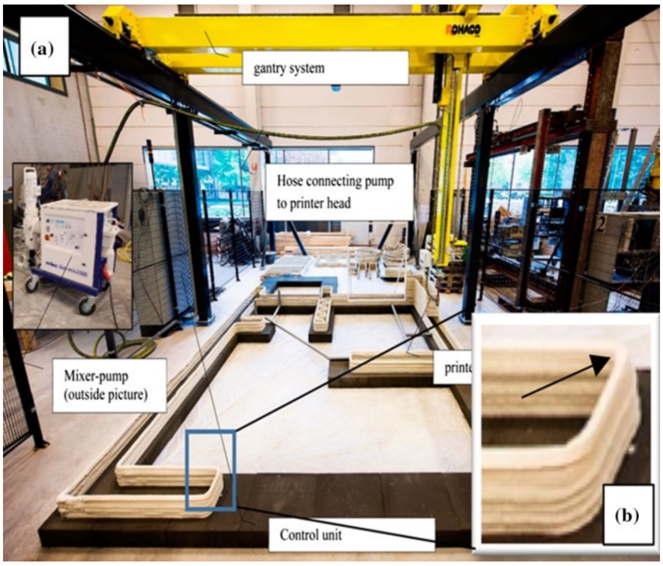

Figure 11: Advanced 3D printing robotic model (Gantry type) (a) 3D printing for large scale construction (b) 3D printing for smooth corners and counters

Figure 12: Advanced 3D printing robotic model (Articulated type)

4.3. Robotic Modules:

The development of large-scale 3D printers has made great strides in recent years, allowing for a wider workspace and the manufacturing of industrial-scale 3D buildings. The commonly used 3D printing robotic models are gantry robotic system (Shown in figure 11) and articulated robotic system (as shown in Figure 12)

Cartesian coordinate system is used for the nozzle of a printer on a gantry robotic system can be moved in all three directions along X, Y, as well as Z planes. For a print area measuring (9 m by 4.5 m by 2.8 m), as depicted in Fig. X, a gantry robot is the best option. When the head's motion is no longer in a straight line, this additional plane is used to rotate the nozzle. This assists the 3D printing to make more critical and complex geometries to print.

5. SWOT analyses of additive manufacturing in constructional industry:

The examination and evaluation of numerous strengths (S), weaknesses (W), opportunities (O), and threats (T), as well as other associated criteria, that may influence particular parts of interest under planning or require reevaluation and changes is what is meant by the term "SWOT analysis." The exact same strategy is used for additive manufacturing in order to ensure that it is successfully used in the construction business.

5.1. Strengths of 3D printing in construction industry

Strengths of AM in Infrastructural and mechanical erection structural sectors

1. AM reduces the construction time as compared to conventional construction techniques. It helps initiating subsequent phases early. It reduces overhead cost, and helps yielding resources. Using these techniques civil structures having geometrical complexity can also be mass produced. [40]
2. The construction, storage and transportation costs can be minimizing by preferring AM. It also reduces supervisory and labor costs. [41]
3. Geometrically complex designs can be easily printed using AM. [42,17]
4. It shortens the supply chain process by eliminating lead times and increasing productivity. [43]
5. It minimizes challenges generally faced during conventional construction methods.
6. These techniques produce eco-friendly structures by reducing wastes that take place in traditional methods. [44]
7. The waste generated during conventional construction techniques could be minimized using AM. [45]
8. It does not require molding as well as supporting structures since objects can be directly printed on site without the need of formwork. [46]
9. It ensures safety of the individuals, societies and the organizations involved.
10. It prefers social equality among the manpower involved on construction sites.

5.2. Weaknesses of 3D printing in construction industry

The difficulties encountered in AM in construction industries comprises

1. Material related challenges (e.g., printability, open time and buildability)
2. Scalability and AM has certain directional as well as geometrical constraints [47]
3. It poses hacking threat.
4. It is to ensure that the multidisciplinary works to be executed efficiently in a group, which is a challenge to synchronize multidisciplinary tasks [48]
5. AM is a fully automated one and does not intervene human involvement, which consumes lot of time in creating digital models.
6. It is difficult to maintain structural integrity. Specifically in plumbing, door and window fitting and electrical works [49]

2.

3. **Figure 13**: Major strengths of 3D printing in construction industry

7. It demands change / modification in the architectural and engineering designing methods.
8. Cost estimation, establishing controlled environment, scheduling at construction sites, unavailability of codes and regulations, liability issues, skepticism, requirement of skilled workers are some of the challenges to be faced [50].

5.3. Opportunities of 3D printing in construction industry

Structures building manufacturing using additive manufacturing processes are promising in nature, the quality of constructions can be improved using 3 D printing technique, further opportunities involve employment of cable robots, mobile robots as 3 D printing development systems [51, 52].

5.4. Threats of 3D printing in construction industry

It comprises printing material risk (specific-material requirement, costly material, printing equipment (special duty equipment) risk, site and environment risk, management risk due to unfamiliarity with the new technology, stakeholder's risk (due to actions or decisions made by owner, designer, workers, suppliers, and others), Regulatory risks, cyber securities risk. [53 – 58]

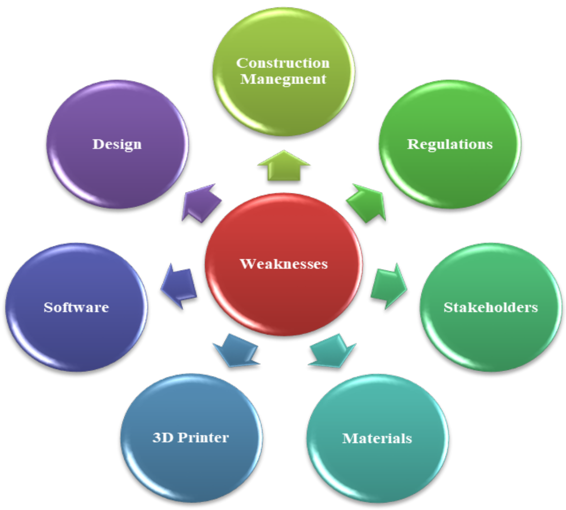

Figure 14: Major weakness of 3D printing in construction industry

Figure 15: Major threats of 3D printing in construction industry

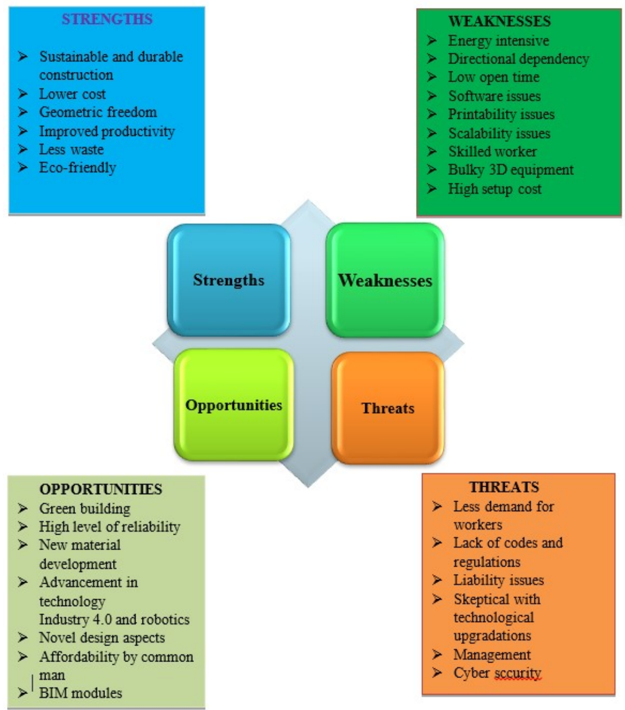

Figure 16: SWOT analysis of 3D printing in construction industry

6. Applications of 3D printing in construction industries at global level

The use of 3D printing has been expanding into several fields. The main fields that employ 3DP for producing prototypes and real printing applications are architectural modeling, civil construction, and the infrastructure business. Warszawski and Navon [59] identified a number of difficulties facing the construction industry. Inadequate workmanship, a high accident rate, a lack of experienced workers, and inadequate management oversight are a few of them. Hope for a resolution to these problems is offered by the development of 3D printing technologies. The use of 3D printing technology to automate the building industry is a topic that has received more and more attention in recent years. It has the ability to completely change the way buildings are made [60]. The traditional techniques used in

Figure 17: 3D printed house by Dus Architects [61]

the construction industry are casting, molding, and extrusion. In the construction industry, 3D printing has the potential to solve problems like hollow buildings and geometric complexity. As a result, its dependability results from the fact that it can be manufactured with great accuracy, enabling a variety of design options. In 2014, the first 3D printed residential structure was constructed in Amsterdam using the FDM process (Figure 16). The project was driven by architects from Dus Architects, who intended to show the printer's portability with low material waste and shipping expenses [61].

4. In 2014, WinSun, a Chinese architecture firm, mass-printed homes in Shanghai in less than 24 hours, as shown in figure 17. The size of traditional 3D printers made it difficult for home builders to use this technology in a variety of ways. However, a 150 m long, 10 m wide, and 6.6 m high cement and glass fibre as raw materials were utilized during printing of this project. During the project, WinSun had trouble with things like brittleness with wall surfaces, integrating building services [62].

In September 2015, Andrey Rudenko printed the inside of a hotel room in the Philippines, measuring (12.5 10.5 4) m, making it the first commercially viable building to be produced using 3D printing technology as shown in figure 18. It required 100 hours of print time to finish the job. Although it was not a continual process. It was discovered that the printed materials, a combination of sand and local volcanic ash, were particularly challenging to extrude. A trustworthy technique was created, with sturdy walls and effective layer-to-layer bonding, despite the lack of a detailed quantitative characterization report [63].

Figure 18: 3D printed house by WinSun [62]

Figure 19: The interior structure of the hotel with 3D printing in Philippines [63]

7. Future prospects of Additive manufacturing in construction industry

- The key to AM's impact realization and successful deployment as innovative ideas in construction is a collaborative and multidisciplinary approach to research. Eco-efficient design can be realized with the help of AM techniques with numerous scientific fields and technological advancements.
- The most difficult tasks of 3D printing for buildings and construction are the design, the process constraints, the process parameters, the behavior of the materials, and the creation of analysis tools that can take all of these things into account and make accurate predictions that allow for more design flexibility.
- Numerical simulation techniques might help designers to understand the design context as a whole, which would let them use strategies like topological optimization and functionally graded materials to make more sustainable buildings.
- Development, optimization, and demonstration from research laboratory to the competitive market large pilot scales are required for everything from printable feedstocks and formulations to printing technology configurations like robotically assisted machinery, printing resolution, and nozzles of varying shapes and sizes.
- There is a need to conduct extensive research into performance assets like mechanical actuators and carriers for loadbearing capacity and smart self-reliance geometries to accomplish. The 3D printing techniques has the prospects to significantly improve the construction sector in coming years.

8. Concluding remarks:

Research prospects of additive manufacturing in the construction industry are very promising as it can be seen from the high number of articles cited for 3DP. This article offers a comprehensive review of in-depth knowhow of strength, weakness, opportunities and threats of AM in construction industry.

It fulfils the research gap in the literature and addresses the major applications. It covers the applications of 3DP in construction industry applied to home, offices, residential buildings etc. Moreover, the paper discusses and evaluates the different methods of 3DP applied to construction industry. The highlights of this review are presented as follows.

- 3D printing with adaption of industry 4.0 has revolutionized the infrastructure sector globally. This leads to more competent and maintainable construction.
- The advances of 3D printing technology with its wide spread continuous at exponential rate globally as witnessed in the literature, but the applications are rare

and success stories are limited. There is a journey for it to travel to highest potential and implementation.

- There are some practical difficulties during adaption of robotic systems to sites such as villas
- Additive manufacturing techniques integrated with BIM modules is a game changer in construction industry.
- There are still limits on how 3D printing can be used for large-scale projects, even though the technology may lead to more durable goods that can be made faster.
- It is important to promote the set-up and study the standardization of 3D printing for construction, even if certain research has reached milestones in creating large-scale building components by undertaking lab-scale testing or prototype fabrication.

Disclosures

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