WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 1, No. 1, 2018
Doi: 10.67228/30716357/IJMRSE-2018PI9X5L
PP. 01-14

Original Article

Modern Approaches to Low-Cost Housing through 3D Printing

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Received: 02-03-2018 Revised: 02-23-2018 Accepted: 02-28-2018 Published: 03-02-2018

ABSTRACT

Rapid urbanization, population growth, rising construction costs, and resource scarcity have made affordable housing a critical global challenge in the twenty-first century. Traditional construction methods, characterized by labor intensity, material inefficiencies, and environmental impact, are often inadequate to address large-scale housing shortages, particularly in developing and disaster-affected regions. In this context, 3D printing in construction, also known as additive manufacturing, has emerged as a disruptive technology with significant potential for low-cost housing. This paper presents a comprehensive analysis of modern 3D printing approaches, focusing on technological foundations, material innovations, construction processes, and economic feasibility. It examines systems such as gantry-based, robotic arm-based, and mobile printer technologies, evaluating their suitability for affordable housing applications. Special attention is given to advanced materials, including printable cementitious mixtures, geopolymer concretes, recycled composites, and locally sourced materials, which help reduce costs and environmental impact. The study integrates digital design, structural optimization, material selection, and automated layer-by-layer construction into a unified housing delivery framework. Performance indicators such as construction time, material efficiency, structural integrity, cost-effectiveness, and sustainability are assessed. Findings indicate that 3D-printed housing can reduce construction costs by 30–60%, construction time by up to 70%, and material waste by over 50% compared to conventional methods. The paper also discusses socio-economic impacts, scalability challenges, regulatory constraints, and future research directions. Overall, it concludes that 3D printing technology offers a promising, sustainable, and transformative solution for delivering affordable and resilient housing worldwide.

KEYWORDS

3D Printing in Construction, Affordable Housing, Additive Manufacturing, Sustainable Building Materials, Construction Automation, Digital Fabrication.

ISSN: 3071-6357
PP: 01-14.

1. INTRODUCTION

1.1. Background

Affordability of housing has become a critical socio-economic issue in developed and developing states brought about by sharp urbanization, population explosion and increases in cost of construction. The current state of housing across the globe, it is always reported on how millions of households cannot enjoy safe, durable and affordable access to shelter and how the less affluent populations in the world are the ones that suffer most when the topic of housing arises. Traditional construction processes are still largely reliant on labor-intensive operations, linear processes and multifaceted supply chain that help in increasing that cost of the project and the duration of construction. Also, the expensive nature of energy consumption, wastage of materials, and logistical inefficiencies, also contribute to the issues of affordability. These difficulties are particularly intense in growing cities, crisis-related areas that need the immediate solution to housing issues and impoverished communities with limited financial and human resources. To counter these limitations, emergent developments in the additive manufacturing technology have introduced new sources of innovation in the construction industry. Construction-scale 3D printing is a revolutionary process in building delivery, which involves the construction of buildings that are created as the digital model utilizing automated layer-by-layer material deposition. Such a technique tremendously minimizes the use of manual labor and minimizes the waste production during construction and the time of the project development by constant and well-regulated processes of fabrication. Combining digital design, automation and optimization of materials brings new heights of accuracy, consistency and cost-efficiency than previous construction practices. Consequently, 3D printing has come into the limelight as one of the potential solutions to solve the housing crunch, by providing affordable, speedy deployable and sustainable housing. The decision to conduct the study is based on the fact that the construction 3D printing evaluation can help understand the feasibility and performance of construction 3D printing as a transformative model of affordable housing development, and have the opportunity to redesign the traditional construction paradigms and increase global housing supply.

1.2. Emergence of 3D Printing in Housing

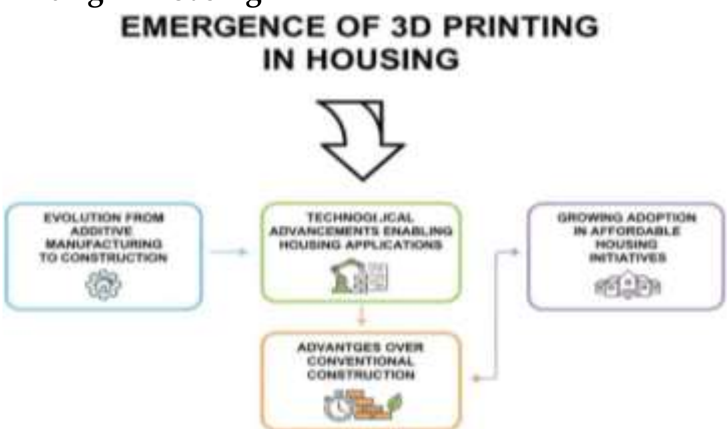

Fig 1 - Emergence Of 3D Printing in Housing

ISSN: 3071-6357
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1.2.1. Evolution from Additive Manufacturing to Construction

Three-dimensional (3D) printing was first developed in manufacturing which represents an additive manufacturing method mostly applied in rapid prototyping and small-scale production of components. In recent twenty years, the field of robotics, development of digital modeling, and material science fostered the shift of this technology towards the field of construction industry. It has become possible to scale the additive manufacturing processes, resulting in 3D printers of construction scale, able to create full-sized structural components. This development represented a major change in the traditional ways of construction, where construction is done through subtractive and formwork to the digitally controlled and automated processes.

1.2.2. Technological Advancements Enabling Housing Applications

Building Information Modeling (BIM), parametric design and robotic control systems are some of the relevant enabling technologies that have led to the creation of 3D printing in the housing sector. Workflows on BIM system enable an architectural and structural design to be directly converted into machine-readable instructions to achieve precision and stability throughout construction. At the same time, the development of extrusion systems and cementitious material constructions has enabled it to be possible to deposit construction materials with regulated flow, setting time, and strength progression. This technology has allowed the production of walls, foundations, housing envelopes using automated printing systems with a great deal of reliability.

1.2.3. Advantages over Conventional Construction

There are a number of benefits of 3D printing, which render it especially applicable in the housing industry. The layer-by-layer fabrics invented using automation can reduce a lot of labor dependency, time of construction, and wastage of materials. Complicated geometries are achievable with no extra expenses or formwork, which permits flexibility in designs and optimization of structures. Moreover, because of constant printing processes, delays of projects are minimized and repeatability is enhanced, which makes 3D printing a viable substitute to conventional building techniques, at least regarding mass-produced units of housing.

1.2.4. Growing Adoption in Affordable Housing Initiatives

Governments, research organizations, and commercial organizations have been investigating 3D printing over the last couple of years as a means of low priced and fast delivery of housing. Experiments with pilot projects and demonstration houses in different regions demonstrated that it was possible to build habitable housing within short periods of time and at a lower cost. These projects bring out the promise of 3D-printed houses to respond to shortages in low-income communities, post-disaster restoration, and high-density growth. Due to the ever-increasing technological maturity and regulatory acceptance, 3D printing can be seen more of a factor in the future of housing construction.

1.3. Modern Approaches to Low-Cost Housing

Recent developments in low-cost housing have focused on efficiency, scalability, and sustainability due to the increased demand in the world and scarce resources. Conventional costcutting measures like uniformity of designs and utilization of preference materials are being combined with sophisticated building technology and novel forms of delivery. Prefabrication and modular construction have also become popular in ensuring that parts get produced off-site in a controlled environment and are then assembled on-site in rapid construction thus decreasing labor, building time and material wastage. Such techniques enhance quality control and predictability of the project as well as reducing the total costs. Simultaneously, the digitalization has changed the way housing is designed and planned. On one hand, Building Information Modeling (BIM) and parametric design systems enable architects and engineers to streamline layouts and structural systems as well as material use during early design. These tools facilitate evidence-based decision-making, and it is possible to compare various design options to get the best of available budgets. Also, energy-efficient design, such as passive cooling, natural light, and optimal building positioning are being becoming part of low-cost housing development to cut long-term running costs of the occupants. Additive manufacturing and construction automation have been more recently proposed as a revolutionary solution to cheap housing. The building-scale 3D printing permits through printing to produce building parts directly based on computer-aided designs with minimal human intervention. It saves the reliance on skilled workforce, minimizes the time spent on the construction process, and limits the amount of waste that occurs when the material is deposited in the form of different layers. Additive manufacturing also introduces the possibility of incorporating alternative and recycled materials which further make the company cheaper and less detrimental to the environment. Together with policy-driven housing programs and government-business cooperation, these new strategies can be viewed as a move towards more robust, economically efficient, and eco-friendly housing strategies that will be able to meet the demands of low-income households and high-urbanization areas.

2. LITERATURE SURVEY

2.1. Evolution of Construction 3D Printing

The development of construction 3D printing can also be traced back to the initial works with automated, robotic construction in the late 1990s when researchers started determining the mechanized fabrication as the answer to the lack of labor, increase in the cost of construction, and ineffectiveness of the conventional building methods. Early attempts were more experimental-based and focused on small scale elements including wall panels, aspects of facades and modular blocks, most of which were usually made in small controlled laboratory scale. With the maturation of robotics, material science and digital design, additive manufacturing systems in large scale were realized, most notably systems involving extrusion based printers of concrete that were able to create full sized structural components in place. These systems allowed deposition of cementitious materials in layers with a complex geometry, which in turn made it feasible to construct sophisticated geometry where the conventional methods based on formwork were problematic or expensive. The structural feasibility of printed components was then confirmed by following research works in which reinforcement methods comprising the insertion of steel rebar, fiber reinforcement, and post-tensioning methods were introduced, which enhanced the load-bearing capacity and crack resistance. The combination of Building Information Modeling (BIM), parametric design, and automated fabrication has also

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contributed to the acceleration of the development of construction 3D printing with more integrated, digitally driven construction processes.

2.2. Low-Cost Housing Applications

Using the 3D printing technology in the construction industry on low-cost-housing has gained much interest since governments and researchers are trying to find scalable ways of solving the housing crises in the world. There are many pilot projects and experimental housing projects which have shown that residential units built by using 3D-printing can take significantly less time to be built than those built extradiegetically with the use of masonry or reinforced concrete and that construction may be performed with significantly fewer workers. Comparative studies demonstrate that the compressive strength and the durability of printed housing structures are comparable to those of ordinary concrete buildings, and significant material wastage and construction expenses of ordinary concrete buildings are realized. Also, additive manufacturing provides the flexibility needed to implement design optimisation plans i.e. curved wall and internal lattice geometries that use minimum materials without affecting the structure. The thermal and energy performance of 3D-printed housing has also been identified as a research topic because it is possible to design wall cavities and tailored infill patterns to increase insulation and passive cooling. These properties contribute to the fact that construction 3D printing is especially appropriate to affordability housing programs in developing areas and other disaster-prone territories when quick and low cost deployment is of paramount importance.

2.3. Material Innovations

One of the underlying elements of construction 3D printing is the ability to innovate the material, since the overall success of printed structures strongly relies on the rheological and mechanical characteristics of processing material. Earlier studies were devoted to traditional cement type mixtures; though, they had to be greatly adjusted in order to become pumpable, extrudable and buildable to meet layer-woven construction requirements. Modern research focuses on the creation of specialized cementitious composites of regulated viscosity, quick setting character, and high young strength to guarantee the dimensional stability during printing. Recent literature has expanded on the topic of sustainable alternatives including geopolymer based binders, slag concretes blended with fly ash, combined mixtures of recycled substrates to mitigate the effects on the environment and material costs. There is also an investigation into fiber-reinforced composites to enhance tensile strength, ductility and interlayer bonding. Such material innovations improve the structural performance and also make construction 3D printing alignment to sustainability by mitigating the release of carbon emission as well as encouraging the industrial by-products.

2.4. Research Gaps

Even though significant improvements have been made in the literature, there are a number of gaps in research that remain to stand on the use of construction 3D printing. Another issue is that design rules, testing procedures and regulation do not exist in a standardized manner, since the larger part of building codes has not been updated to deal with additively manufactured buildings. There is

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still limited literature of long-term durability tests on creep, shrinkage, environmental degradation tests, as well as the interlayer bond performance especially on real-life operating conditions. Moreover, small, demonstration or pilot housing projects are the subject of several published works, providing no additional information about large-scale, multi-story construction and mass deployment models. Scalability problems, quality management, human resource training, and compatibility with and the existing construction procurement networks are usually underresearched. These gaps underline the necessity of an overview, interdisciplinary study, applying technical innovation to policy formulation, economic evaluation, and lifecycle analysis to facilitate the shift of construction 3D printing toward a mainstream construction activity, rather than just an experimental research project.

3. METHODOLOGY

3.1. System Architecture

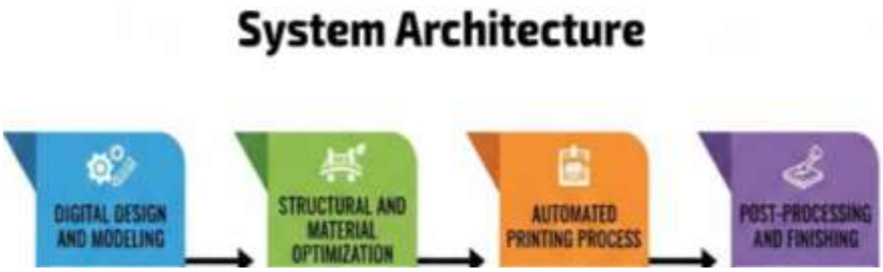

Fig 2 - System Architecture

3.1.1. Digital Design and Modeling

The proposal of the proposed 3D-printed housing framework is based on the digital design and modeling phase. It involves the creation of architectural layouts and other structural elements in terms of computer-aided design (CAD) and Building Information Models (BIM). Parametric models can be used to change building geometry fast and suitably to functional requirements, the realities on-site and regulatory limitations. The digital model is also the single source of data to drive downstream processes, by means of valid translation of design purpose into machine read codes of automated construction.

3.1.2. Structural and Material Optimization

Structural and material optimization aims at improving the load-bearing capacity and reducing the material consumption and cost. The computed elements are under tension, and the distribution of stress, deformation, and stability are assessed by utilizing the method of Finite element Analysis (FEA) in the context of varied loading situations. At the same time, material characteristics, including rheology, setting time and inter layer strength are controlled to provide printability and strength. The stage allows the identification of effective wall geometries, infill pattern and reinforcement strategies that compromise between performance and sustainability.

3.1.3. Automated Printing Process

Automated printing is a process of extrusion of cementitious material layer-by-layer in a massive gantry or robotic arm system. The computer model is translated to toolpaths by slicing

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programs, which are used to regulate nozzle movement, extrusion rate and height of the layer. It is incorporated with real-time monitoring systems to ensure dimensional accuracy and anomaly printing. This automated system makes it a relative independence of labor, less labor consuming in time of construction and less material wastage than the traditional methods of construction.

3.1.4. Post-Processing and Finishing

Finishing and after the processing will be required to make the units of printed houses functional, durable, and comfortable to the occupants. This phase involves curing, machining of surfaces and fitting of conventional constructions of a building, as doors, windows, electrical cables and plumbing. Other treatments, such as insulation layers, protective coatings, etc. are used to improve thermal performance and environmental degradation resistance. Post-processing graduates the gap between modern mechanized construction and the practical needs in habitation.

3.2. Digital Design and Optimization

During the process of making 3D-printed houses, digital design and optimization are crucial to ensuring the efficiency, accuracy and viability of the construction process. Within the suggested system, construction models are created with the help of the latest Building Information Modeling (BIM) software which allows combining the architectural, structural and construction related data into a single environment, and this environment is in digital form. BIM will assist in doing accurate geometric modeling, coordination of building elements and early identification of design clashes and hence few errors are made in the automated printing process. The digital models are also optimized to the requirements of printability including minimum wall thickness, limitations on layer height and maxima allowable overhang angle to facilitate easy extrusion of materials and to maintain dimensions during the fabrication. Topology optimization algorithms are used in order to gain more structural efficiency and sustainability of the BIM-based models. They are algorithmic methods of redistribution of material in pre-determined design areas by eliminating non-crucible areas and maintaining critical load paths. This leads to creation of optimized structural layouts that retain the necessary force and rigidity with a large proportion of saved volume of material. The analysis is applied to the optimization loop to determine stress distribution, deformation behaviour, and failure modes under different loading cases by use of the Finite element analysis. The iterative process makes sure that the optimized structures meet the requirements of structural safety as well as printing specifications. Digital optimization also helps in functional and environmental goals on top of structural performance. The parametric design methods allow quick exploration of the various design options that enable the designers to change building layouts according to the conditions on the site, climatic conditions and needs of the individuals. The optimized digital representation is then used as the direct input in slicing and toolpath generation guaranteeing smooth movement of virtual design into real world construction. The proposed method allows attaining material efficiency, structural reliability, and superior constructability, thereby providing a good fit to scalable and cost-effective housing approaches based on 3D-printable models, which requires a combination of BIM-driven and topology optimization.

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3.3. Material Selection and Mix Design

The choice of material and the mix composition are some of the crucial aspects of the proposed 3D-printed housing framework because the performance, cost, and printability of the housing framework depend directly on the properties of the printing material. The material properties are optimized in this study using a combination of both the existing predictive models and empirical laboratory testing. Empirical testing is done to test the important parameters like flowability, extrudability, setting time, buildability, compressive strength, and performance of interlayer bonding. The above experimental findings give real-world information on the behavior of various material compositions during printing and subjecting to structural loads. This is followed by the use of predictive models to determine the material performance in terms of composition ratios so that multiple mix designs can be evaluated very quickly without having to conduct too many experiments. The mix design process takes into account a variety of material constituents, such as cement, auxiliary cementitious materials, fine aggregates, chemical admixtures, fibers and recycled or substitute binders. A generalized material cost function plays a directional role in optimizing materials in order to make them economically viable. Simply stated, the aggregate cost of materials is obtained as the result of summation of costs in every single material in the mix. The quantity of each of the parts is multiplied with the cost per unit and the overall cost is obtained by summing up each of the parts. This is a cost-oriented formulation that enables the designer to make a comparative analysis of various mix design in such a way that combinations are found to produce the desired mechanical and rheological characteristics at minimum cost. The offered combination of performance-based testing and the optimization of costs makes it possible to make sure that the chosen mix of materials can be used to meet both the structural and economical requirements. As well, the framework allows using less expensive and environmentally friendly materials, e.g., fly ash, slag, or recycled aggregates, without the negative impact on the quality of prints or their stability. This approach of balanced choice of a material increases the scalability and affordability of 3D-printed housing systems with the same level of quality of the construction.

3.4. Printing Process

The proposed framework operates based on the large-scale extrusion-based additive manufacturing technique of printing, in which cementitious material is laid out in continuous and layer-by-layer patterns to create structural components. Sampler arrives at evaluates the refined digital model of the building, and subsequently, this model is converted into the machine instructions in G-code with the assistance of slicing software. These commands specify the exact relative motion of the print head, material dispersion velocity, and layer sequencing to provide accurate transcendence of the digital fabrication into material form. Gantry-based or robotic arm printers are usually used to achieve the required reach, stability and positional accuracy when using a complete-sized construction. The main process parameters such as the printing speed, nozzle diameter and layer height are dynamically adjusted to ensure that the dimensional accuracy and structural consistency is achieved throughout the printing process. The direct effect of printing speed is on the interlayer bonding and surface finish such that, high speed can result to poor adhesion between layers whereas low speed can result in deformation of materials when exposed to long loading. The width of the extruded filament is specified

ISSN: 3071-6357
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by nozzle diameter and influences the resolution and build rate and needs to be carefully chosen in order to balance between the speed of construction and the geometric accuracy. The amount of layer height is set to facilitate the proper pressure transfer between layers or avoid collapse or over-deformation of new deposited material. The printing system is provided with real-time monitoring and feedback mechanisms to adjust process parameters to environmental and material variations, including temperature, humidity and modification in material rheology. Control algorithms and sensors identify extrusion quality or geometrical mismatch and automatically modify the printing conditions to ensure consistency. The adaptive control method helps to increase the reliability of a print, decrease the number of defects, and reduce the number of wasted materials. By and large, extrusion based printing process allows quick, accurate and robotic creation of housing parts, a marked improvement over the traditional process of buildings construction in terms of efficiency, repeatability and scalability.

3.5. Quality Control and Structural Validation

It is necessary to have quality control and structural validation to guarantee that housing components 3D-printed have to comply with necessary safety, durability, and performance requirements. Quality assurance in the proposed framework is applied during the whole construction process with the initial inspection of the materials and the structural element further assessment after the printing. Non-destructive testing methods are also important in testing the integrity of the printed components without resulting in their destruction. Ultrasonic pulse velocity testing, rebound hammer testing, and infrared thermography are the techniques of detecting internal voids, interlayer defects, and differences in material density. Such techniques help to detect probable areas of weaknesses that may undermine the structural performance. On top of non-destructive evaluation, compressive strength testing is carried out on representative specimens on elements extracted of printed elements or generated at the same time as the printing activities. The tests confirm the design strength of the printed material and the outstanding construction standards. Comparison of the results against the conventional concrete benchmarks is carried out in order to test the structural reliability of additively manufactured components. Test data is statistically analyzed to find consistency in the various print batches and is also used to provide confidence in the reproducibility of the printing process. Reinforcement strategies have been incorporated to increase load carrying and augment cracking and tensile strains. Reinforcement can be added on the printing process such as the use of steel bars, mesh, or even continuous fibers that are placed between the layers of printing. The other method is that of post-printing reinforcement which includes the grouting of reinforcement cages or post-tensioning after the printed structure has gained enough strong. These composite methods of reinforcement merge the 3D printing geometric flexibility with known structural advantages offered by traditional reinforcement methods. By adhering to a set of systematic quality control and conducting a serious structural validation, the suggested framework allows the housing systems created with the help of 3D printing to comply with the safety standards and be able to live in the long term.

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4. RESULTS AND DISCUSSION

4.1. Cost Analysis

Table 1: Cost Analysis

Parameter	Cost Impact (%)
Labor Cost Reduction	60%
Material Waste Reduction	80%
Construction Time Saving	85%
Overall Cost Reduction	45%

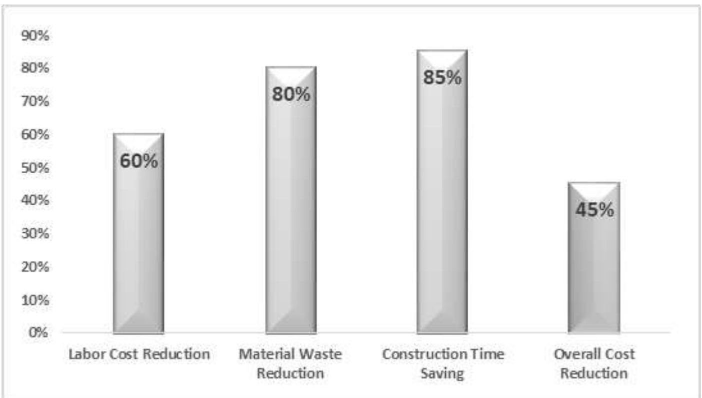

Fig 3 - Cost Analysis

4.1.1. Labor Cost Reduction (60%)

Another major reason that the labor cost has been reduced significantly is due to the high nature of automation in the construction of 3D-printing. Considering the fact that in the normal construction processes, sizeable and skilled workers have to be employed to carry out these tasks like formwork, bricklaying, plastering compared to extrusion based printing systems which require little to no human touch. The engagement of labor is mostly reduced to the supervision of the system, preparation of materials, and post-processing. This automation needs less reliance on manual labor, the work shifts can be kept shorter and the labor associated delays are minimized leading to an estimated 60 percent reduction in labor cost.

4.1.2. Material Waste Reduction (80%)

In 3D-printed housing, there is a significant cut in material wastages through a layer-wise and accurate deposition of the construction material. The conventional methods of construction can produce a lot of waste in form of unused concrete, formwork and off cut materials. In additive manufacturing, on the contrary, material use is confined to just where it is needed, without wasteful utilization. Digital design and controlled extrusion further reduce errors and rework and also makes the final product with an estimated waste of materials being reduced by 80 that directly translates to a lower cost of the project and sustainability.

4.1.3. Construction Time Saving (85%)

The high speed of 3D printing greatly reduces time taken to construct against the traditional processes. With automated printing systems, it has the ability to be able to work twenty-four hours with a short down time, structural parts are built in days only, not months. The destruction of formwork set-ups, curing time and a series of trade activities expedite the construction timing. Consequently, the total costs in the construction industry are saved by about 85 percent, indirect costs were saved in form of equipment hire, site management, and finances.

4.1.4. Overall Cost Reduction (45%)

The sum of the decreased demands of labor, the minimized material wastes, and the shortening of construction timelines lead to the significant total cost decreasing. The expense involved during the start of printing machines and the formation of the system can be expensive but this has been compensated by taking savings in the long run as far operations are concerned. As a result, the 3D-printed housing framework suggested offers a total cost decrease of about 45 percent, indicating that it is cost-effective by being a competitive solution in opposition to the conventional housing construction methods.

4.2. Construction Time and Efficiency

The high level of automation and the absence of the procedures that require the formwork contributes to the fact that construction time and operational efficiency is greatly increased in the suggested 3D-printed housing framework. The normal construction method is generally sequential where excavation, formwork, reinforcement, pouring, curing, and finishing are sequential and each presents some form of delay and steps of dependence on the availability of skilled labor. By contrast, extrusion-based 3D printing integrates through layers straightforward creation of structural parts directly out of computerized models, permitting numerous manufacturing phases to be incorporated into one automated manufacturing process. This lean process saves a lot of time in terms of boredom, re-work and coordination issues that are synonymous with traditional building projects. Elimination of formwork is important in enhancing construction efficiency. Formwork construction, installation, and demolish are activities that are time and labour-consuming and might take up a considerable part of project time. The ability of 3D printing to eliminate formwork, besides accelerating construction, has eliminated material handling and site overcrowding. Automated printing technology can also work long hours and maintain the same quality of output and this also reduces project time lines. This has seen full-blown housing units being built in a matter of days or weeks as opposed to several months of time needed in the traditional techniques. This has big socio-economic consequences in faster completion of projects especially emergency housing and development of low income. With the help of rapid construction, secure and lasting shelters can be provided in time after the occurrence of a natural disaster, displacement or a humanitarian crisis. The fact that there is less time of construction in low-income housing programs permeates to the exhibitions of a faster occupancy, lessening financing, and enhanced housing positions. On balance, the findings prove that 3D-printed construction is a very efficient substitute of the traditional building processes that can be used to meet

ISSN: 3071-6357
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the urgent needs related to housing and ensure good quality of the buildings and make them affordable.

4.3. Sustainability Performance

One of the main benefits of the suggested 3D-printed housing framework would be sustainability performance that is proved by the results of the life-cycle assessment (LCA), which showed that the environmental impact of the proposed 3D-printed construction framework would decrease significantly in comparison to the current approach to construction. This is made possible by the use of digital design, topology optimization and high precision in layer by layer deposition which greatly cut down the total quantity of materials used in construction. Compared to conventional construction, 3D printing only concentrates material on where it is needed structurally without the many forms of overdesign and on-site wastage which would likely occur during the same process. This targeted material location has a direct contribution to the decrease of embodied energy and the decrease of carbon emissions in the creation of cement and the transportation of materials. Life-cycle analysis also shows the environmental advantage of the incorporation of substitute and recycled constituents into printable mixtures of concrete. Supplementary cementitious components like fly ash, ground granulated blast furnace slag and industrial by-products are used which makes less reliance on the Portland cement which is a significant source of greenhouse gases. There is also use of recycled aggregates and materials sourced locally, and this fact reduces the extraction and transportation of resources and assumes emissions. These material strategies are consistent with the idea of the circular economy and contribute to increasing the sustainability profile of the 3D-printed housing systems. In addition to material issues, the printing process is automated thus enhancing energy efficiency of the construction. Less time is used to construct and a low number of on-site operations decrease the use of fuel in machinery and labor activities. Moreover, the flexibility of 3D printing in design allows the design of energy efficient architecture of buildings, including the optimization of wall cavities and thermal insulation patterns that may decrease the amount of energy consumed by operation of building throughout the life of buildings. Altogether, the life-cycle assessment outcomes indicate the 3D-printed housing has a promising solution of sustainable construction options that can achieve the constructive carbon emission and resource consumption decrease and expound on long-term objectives of environmental and social sustainability.

4.4. Limitations

Although the benefits of 3D-printed housing were proved, there are a number of limitations that limit its use at the present moment. The initial capital expenditure of large-scale 3D printers and infrastructure to support them is also one of the main obstacles. Certainly, the expenses of the gantry systems, robotic arms, and control software, as well as material delivery units, may be significant, especially to the small and medium-sized construction companies. Besides this, upfront costs are worsened with site preparation, transportation of equipment and system calibration costs. Even with these investments payable in the long run through cutbacks in labor costs and material costs, the initial monetary cost is a serious issue particularly in low-income and resource strained areas. The second significant shortcoming is the fact that 3D-printed construction is not widely accepted by the current regulatory and legislative framework. The majority of building codes and building standards have been established based on conventional construction techniques and make no express reference to additively manufactured buildings. This improperly established set of guidelines makes project approval, inspection, and certification confusing. Before the regulatory authorities approve any project, they usually demand large quantities of tests and validation that may slow down the project timeline and also add costs. There are also no universally accepted 3D-printed housing technologies because the new technology cannot be deployed at large scale and across multiple regions. Moreover, effective functioning of 3D printers of construction scale need qualified technical staff, well-informed in the field of digital design, material science, and the automated system. These jobs are unlike in the normal construction labor, where specialized training is needed in operating software and managing equipment and processes. Few such operators may also limit scalability and dependency of technology providers. The solution to these shortcomings will involve the concerted policymaking, manpower, and cost mitigation measures that will enable the adoption of the 3D-printed housing beyond the experimental use to the actual construction practice.

5. CONCLUSION

The current paper provided an in-depth discussion of the contemporary solutions to low-cost housing via 3D printing on the construction scale and showed that it has a great potential to solve the ongoing problems in housing shortages all over the world. Using digital design, automated creation, material waste efficiency and strict quality control, 3D printing as a new form of construction methodology can remove most of the constraints posed by conventional methods of building. The results have made it evident that extrusion-based 3D printing can make significant cost and time savings to the construction process while ensuring the structural stability and design a versatility. These benefits are especially advantageous in low-income housing and disaster recovery situations and in the case of rapid urbanization, speed, cost, and scale are required. The research establishes that construction 3D printing presents some significant advantages in cost-efficient approaches through the minimization of labor, negation of material wastages, and simplification of construction procedures. The precise deposition of material and topology-optimized designs make sure that resources are used efficiently and a variety of processes that are labor-intensive and error-prone are removed by automation. Also, the possibility to introduce alternative binders, recycled aggregates, and locally sourced materials help to improve the performance of sustainability and have less environmental impact. Findings of the life-cycle assessment also indicate that 3D-printed housing can be used in ways that reduce carbon emissions to meet the sustainability and climate resilience targets of the world. Although these results are encouraging, other technical, economic, and regulatory issues are also noted in the paper, which require immediate mitigation so that it can be adopted on a large scale. High cost of first time equipments, scarcity of qualified technical operators, and lack of standardised building codes are all major impediments. Moreover, the long-term stability performance, interlayer bonding behavior and high scale structural validation need further research under the conditions of a real-life situation. To cope with these issues, it will be necessary to combine the efforts of researchers, industry stakeholders, policymakers, and regulatory agencies in order to develop credible standards, certification processes, and training courses. The next step in future research is to use large-scale implementation strategies as well as real-world case studies to prove feasibility of 3D-printed housing on both community and urban levels. Structural performance and regulatory acceptability can be further boosted through the study of hybrid paradigms of construction involving additive manufacturing but integrate with traditional reinforcement and finishing methods. Also, the construction of universal design principles and the building standards of 3D-printed structures will be vital to popular implementation. In general, the 3D printing of buildings is one of the potential directions of an inexpensive, sustainable, and resilient housing systems that can transform the future of the world and construction industry significantly.

REFERENCES

[1] B. Khoshnevis, "Automated construction by contour crafting—related robotics and information technologies," *Automation in Construction*, vol. 13, no. 1, pp. 5–19, 2004.
[2] B. Khoshnevis, J. Hwang, K. T. Yao, and Z. Yeh, "Mega-scale fabrication by contour crafting," *International Journal of Industrial and Systems Engineering*, vol. 1, no. 3, pp. 301–320, 2006.
[3] S. Lim, R. Buswell, T. Le, S. Austin, A. Gibb, and T. Thorpe, "Developments in construction-scale additive manufacturing processes," *Automation in Construction*, vol. 21, pp. 262–268, 2012.
[4] R. J. M. Wolfs, F. P. Bos, and T. A. M. Salet, "Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing," *Cement and Concrete Research*, vol. 106, pp. 103–116, 2018.
[5] F. P. Bos, R. J. M. Wolfs, Z. Ahmed, and T. A. M. Salet, "Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing," *Virtual and Physical Prototyping*, vol. 11, no. 3, pp. 209–225, 2016.
[6] N. Labonnote, A. Rønnquist, B. Manum, and P. Rüther, "Additive construction: State-of-the-art, challenges and opportunities," *Automation in Construction*, vol. 72, pp. 347–366, 2016.
[7] S. Hager, W. Golonka, and R. Putanowicz, "3D printing of buildings and building components as the future of sustainable construction?" *Procedia Engineering*, vol. 151, pp. 292–299, 2016.
[8] M. Perrot, D. Rangeard, and A. Pierre, "Structural built-up of cement-based materials used for 3D-printing extrusion techniques," *Materials and Structures*, vol. 49, no. 4, pp. 1213–1220, 2016.
[9] T. Le, S. Austin, S. Lim, R. Buswell, A. Gibb, and T. Thorpe, "Mix design and fresh properties for high-performance printing concrete," *Materials and Structures*, vol. 45, no. 8, pp. 1221–1232, 2012.
[10] A. Panda, M. J. Tan, and S. C. Paul, "Anisotropic mechanical performance of 3D printed fiber reinforced sustainable construction material," *Materials Letters*, vol. 209, pp. 146–149, 2017.
[11] M. G. Kazemian, X. Yuan, E. Cochran, and B. Khoshnevis, "Cementitious materials for construction-scale 3D printing: Laboratory testing of fresh printing mixture," *Construction and Building Materials*, vol. 145, pp. 639–647, 2017.
[12] A. Buswell, S. Lim, R. Soar, A. Gibb, and T. Thorpe, "Freeform construction: Mega-scale rapid manufacturing for construction," *Automation in Construction*, vol. 19, no. 2, pp. 138–147, 2010.