Journal of Harbin Engineering University
ISSN: 1006-7043

Vol 44 No. 7
July 2023

Techno-Economic Analysis Of 3D Printing of Concrete for Industrialization: A Comparative Study

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Abstract-Additive manufacturing, or 3D printing, of concrete is a disruptive technology with potential to transform the construction industry. To understand its techno-economic feasibility for industrialization, a comprehensive comparative study is crucial. This paper presents a detailed techno-economic analysis and comparative study of 3D printing of concrete. It includes an overview of additive manufacturing in construction, comparative study of printing techniques, material compatibility, printing speed, accuracy, and resolution. Economic aspects such as material, labor, and equipment costs, energy consumption, and environmental impact are analyzed. Potential applications in building construction, infrastructure development, and customized component fabrication are explored, along with techno-economic benefits and challenges. The paper concludes with key insights and recommendations for researchers, practitioners, and decision-makers. This study provides valuable guidance for understanding the techno-economic feasibility of 3D printing of concrete, facilitating informed decision-making and promoting its adoption in the construction industry for industrial applications.

Keywords: The keywords for this paper are as follows: additive manufacturing, 3D printing, concrete, techno-economic analysis, comparative study, industrialization, construction industry, printing techniques, material compatibility, and economic aspects.

INTRODUCTION

The use of 3D printing in the construction industry has gained significant attention in recent years due to its potential for revolutionizing traditional construction practices. In particular, 3D printing of concrete has emerged as a promising technique for industrialization, offering improved efficiency, sustainability, and design freedom. However, to fully understand the techno-economic feasibility of 3D printing of concrete for industrial applications, a comprehensive analysis is required. This paper presents a comparative study that aims to investigate the techno-economic aspects of 3D printing of concrete for industrialization.

The paper begins with a brief overview of the current state of 3D printing in the construction industry, highlighting the growing interest and potential benefits of utilizing this technology for concrete-based applications. The advantages of 3D printing of concrete, including reduced material waste, increased construction speed, and enhanced design flexibility, are discussed in detail. The challenges and limitations associated with this technology, such as high initial investment costs, limited material properties, and lack of standardized guidelines, are also addressed

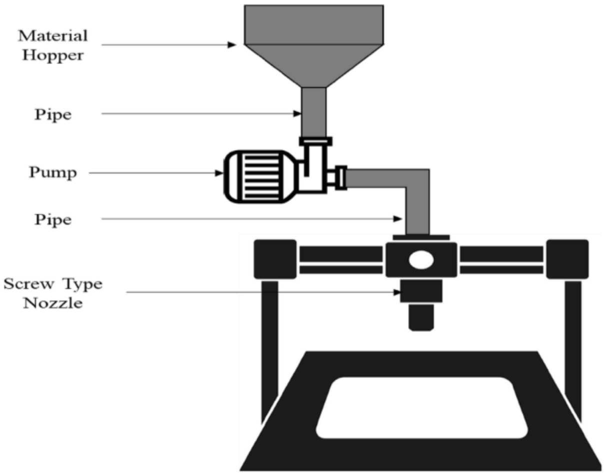

Figure 1: Components of 3d Printing

Next, the paper presents a detailed techno-economic analysis of 3D printing of concrete for industrialization, comparing it with conventional construction methods. The analysis includes various aspects, such as material costs, labor costs, equipment costs, energy consumption, and environmental impact. Different 3D printing techniques, such as extrusion-based, powder-based, and binder-jetting, are considered, and their advantages and disadvantages are evaluated in terms of techno-economic feasibility.

Furthermore, the paper discusses the potential applications of 3D printing of concrete in industrial settings, such as construction of buildings, bridges, and infrastructures, and analyzes the economic benefits and challenges associated with these applications. The potential for customization and mass production using 3D printing of concrete is also explored, along with the potential impact on the construction industry as a whole.

This paper presents a comprehensive comparative study on the techno-economic aspects of 3D printing of concrete for industrialization. The findings of this study can provide valuable insights for decision-makers, policymakers, and researchers interested in adopting and implementing 3D printing of concrete in industrial applications, contributing to the advancement of this promising technology in the construction industry.

LITERATURE REVIEW

P Krupík(2020) 3D printers as part of Construction 4.0 with a focus on transport constructions said that the 4th Industrial Revolution, also known as Industry 4.0, encompasses rapid advancements in digital and technical fields. This paper focuses on 3D printers as part of Construction 4.0, specifically in transportation infrastructure. A SWOT analysis is conducted to identify strengths, weaknesses, opportunities, and threats in this context. The current state of 3D printing technology is evaluated, acknowledging existing limitations and roadblocks. While 3D printing is still in the research and development stage, it is expected to play a significant role in Construction 4.0. However, achieving the ideal future scenario depicted in the diagram below will require further progress and time.

Zhu Jianchao (2017) 3D printing cement based ink, and it's application within the construction industry: This article discusses how 3D printing technology is the key driver of the third industrial revolution, following the advent of automation and mass production. The study focuses on cementitious-based materials for construction and employs a qualitative method using literature studies and in-house research findings. The article highlights the strategy for developing an optimal mix design that meets the requirements of the 3D printing process and overcomes current limitations. It emphasizes the need for further research to develop higher-strength printing materials for multi-story buildings without additional steel reinforcement. The study also suggests that SAC cement is more suitable for 3D printing mortar due to its quicker setting time and stronger early strength. The paper recommends the use of a combination of retarder and accelerator for comprehensive time setting control, with the type and quantity depending on various printing conditions.

METHODOLOGY

The research methodology is designed to provide a systematic and rigorous approach to conducting a comprehensive techno-economic analysis and comparative study of 3D printing of concrete for industrialization. It ensures that the research is based on sound principles and practices, and the findings are reliable and valid.

Selection of Comparative Study Framework: A comparative study framework is selected to evaluate and compare different 3D printing techniques for concrete. The framework is chosen based on its relevance to the research objective, and it may include factors such as working principle, advantages, disadvantages, potential applications, material compatibility, printing speed, accuracy, resolution, material costs, labor costs, equipment costs, energy consumption, environmental impact, and techno-economic benefits and challenges.

Data Collection: Data is collected from various sources, including research articles, technical reports, industry reports, and other relevant publications. The data may include technical specifications of 3D printing techniques, material properties, cost data, and other relevant parameters needed for the techno-economic analysis.

Data Analysis: The collected data is analyzed using appropriate statistical and analytical methods. Comparative analysis is performed to evaluate and compare the different 3D printing techniques based on the selected comparative study framework. The techno-economic aspects, including material costs, labor costs, equipment costs, energy consumption, and environmental impact, are quantitatively analyzed and compared.

Results and Findings: The findings of the data analysis are presented in a clear and concise manner, using tables, charts, and other visual aids. The results are interpreted and discussed in the context of the research objective and the existing literature.

Limitations: The limitations of the research methodology, such as the availability and accuracy of data, assumptions made in the techno-economic analysis, and other potential limitations, are acknowledged and discussed.

The global construction industry heavily relies on concrete as the primary building material, but it faces various challenges. One of the major challenges is the high cost of construction, with formwork alone accounting for over 75% of building expenses in cities like Sydney, according to a study by the Boral Innovation Factory. Another challenge is the significant amount of waste generated during construction, especially from shaped formwork that is eventually discarded, contributing to the construction industry's overall waste production. However, 3D printing technology is gaining popularity in the construction sector due to its potential to reduce various project-related aspects such as design, materials, costs, and time. The concept of 3D printing was first introduced by Charles Hull in 1984, and it involves creating physical objects layer by layer using numerical data in STL format. 3D printing allows for lighter objects with multiple functions as it uses minimal material. The construction industry is responsible for nearly 80% of the world's garbage, and traditional concrete casting into formwork can limit architects' design flexibility due to the cost and constraints of formwork. Additionally, the slow pace of construction, safety concerns, and sustainability issues in the current construction methods are also challenges. The use of 3D printing technology in concrete construction has been gaining momentum as it offers potential solutions to these challenges. Unlike traditional subtractive manufacturing methods, 3D printing is an additive manufacturing process that converts 3D models into material components layer by layer, which can revolutionize the construction industry.

Mechanisms of 3D printing:

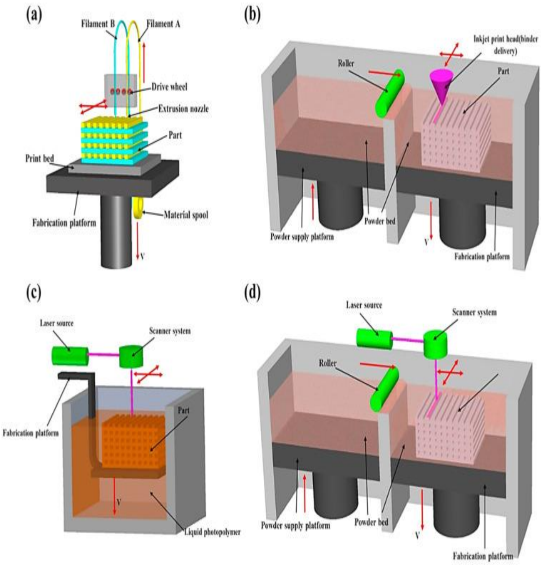

Figure 2: 3d printing concrete

Motion Management

A Cartesian Fused Deposition Modeling (FDM) 3D printer, utilizing Cartesian or cylindrical coordinates, was chosen for its practicality and ease of management. The printer's nozzle is mounted on the Z-axis, which moves along the X and Y axes to print concrete structures. Linear motion control with servo motors ensures precise movement, and frames can be used to increase the printing area. CNC software controls the movement of the nozzle using G-code, similar to CNC milling, and adjustments can be made on the GUI panel of the program.

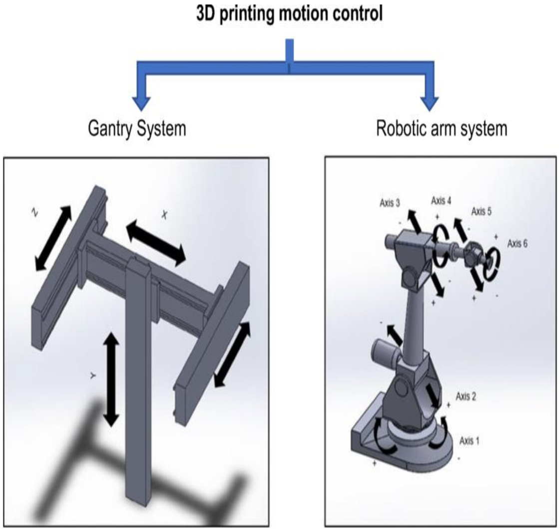

Figure 3: Motion Controller In 3d Printer

Dispensing System

The dispensing system is crucial for 3D printers to ensure adequate and consistent material extrusion. Screw and pump feeding types were tested, and the screw type nozzle provided better material control and constant extrusion, while the pump feeding type had difficulties with layering. The developed screw has specific characteristics such as length, pitch, diameter, and blade angle. Different pitch-to-diameter ratios were also tested, with a ratio of about 0.96 showing sufficient pressure for extruding ordinary mortar. The rotating speed of the screw is intricately linked to material extrusion control for uniform layer construction.

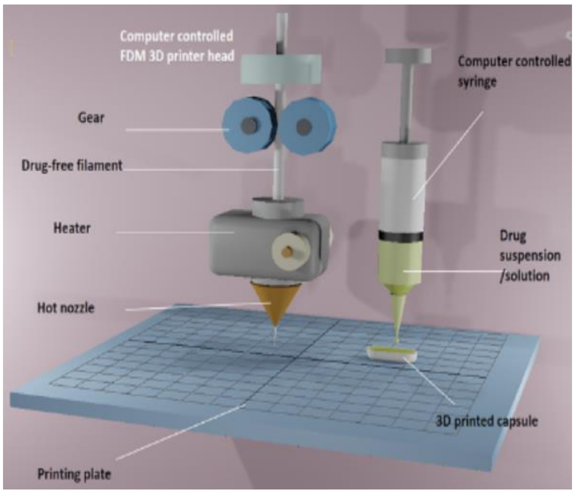

Figure 4: Dispensing system

RESULT AND DISCUSSION

The 3D concrete printing technique allows for predesigned structures to be constructed layer by layer without the need for vibration or formwork. Contour crafting (CC) is a promising concrete printing technology that uses robotic arms or mechanical instruments to build items layer by layer. Components are created as volumetric instruments using 3D modeling software, sliced into 2D layers, and then printed using a cementitious material. The material must possess adequate extrudability, build-ability properties, and high strength (around 80 MPa) to create strong connections between layers. The printer typically has specific dimensions and requires software expertise to operate. Solidworks and Inventor are commonly used software for designing printed concrete, and an open-source slicer program is used to transform stereolithography files into G-code instructions. Hardware improvements, such as a new nozzle with trowels for easier concrete flow and ability to print angled walls without contact with the concrete paste, are needed to enhance contour crafting.

Figure 5: Contour crafting

Software:

Contour crafting requires G-Code for implementation, which is generated from CAD models using software like Slic3r or Solid works. The software controls the nozzle angle and requires revising the concrete mixture for extrudability, buildability, and formability. 3D printing of concrete can be faster, more cost-effective, and accurate compared to conventional methods. Proper use of admixtures and adjustments to the mixture recipe may be needed based on geographical factors. Expertise from multiple disciplines is required for successful implementation of contour crafting, but it can result in streamlined construction processes and potential challenges.

Materials:

Design Mix: The concrete mix for 3D printing must meet specific requirements related to the printing process, and target goals for the mix properties are defined. These goals may sometimes be conflicting, such as the balance between water-cement ratio and compressive strength. The mix needs to be pourable, buildable, and set at the right speed for proper bonding between layers. Extrudability, flowability, buildability, compressive strength, and open time are crucial properties examined. Aggregates, cement, superplasticizer, accelerator, and retarder are added to the mix in precise amounts determined through trials to achieve the desired balance. Excessive amounts of superplasticizer can have negative effects on the mix.

MECHANICS:

Machine Design

The success of the concept depends on the design of the proper machine that would serve as a 3D printer for the concrete mixture. When designing the machine, a number of parameters had to be taken into account in order to account for both the qualities of the previously mentioned fresh and printed concrete. The concrete tank and pumping mechanism, the printing nozzle, and the motion control system make up the machine's fundamental three parts.

The concrete is manually pumped from the tank to the nozzle, where it is supposed to be poured, where it begins its trip. To print a three-dimensional element, the machine is built to move on an x-y-z triaxial plane. Along the Axes Movement The printer was created primarily to print a structural wall measuring 77 cm by 10 cm, with the goal of eventually printing bigger pieces as the experiments progressed.

Two parallel lines, each measuring 77 cm in length and 2 cm in width, were printed on the wall, spaced 10 cm apart. In order to print two lines parallel to each other, the nozzle must be able to print one line on the longitudinal axis (x-axis) and then move along the perpendicular axis (y-axis) to position itself for the second line to be printed. In order to print layers on top of layers and finish the 3D design, it must also be able to move along the z-axis. Each layer is intended to be 2 cm tall, hence the machine is built to advance in 2 cm increments. The major component of the device is a vertical component that holds the portable tank and nozzle in place. This component, which controls motion along the z-axis, may be turned on and off manually or hydraulically. The piece moves over a threaded horizontal bar and was created to roll along a predetermined track along the x-axis. The x-axis motion is managed by a revolving drill with variable speed. The nozzle held by this element can also change locations on the y-axis and move in a direction perpendicular to the action of the machine.

Nozzle Design:

The nozzle is another important component that significantly affects the qualities of extruded concrete. In particular, the flowability of the concrete mix is directly correlated with the nozzle diameter. To compensate for decreasing diameter size, the mix's flowability should be raised, and vice versa. The nozzle also includes two trowels—a top trowel and a side trowel—that trail behind it. As the nozzle goes past, the side trowel on the outside helps to straighten the concrete being poured.

To achieve optimum buildability, the top trowel is used to level the concrete layer's upper surface. The team tested with syringes with opening sizes ranging from 1 cm to 2 cm before creating the nozzle. This was done in order to establish the ideal nozzle diameter. The 2 cm diameter size turned out to be the best one for the nozzle function. When the diameter was less than 2 cm, the concrete components tended to segregate, which had difficulties with buildability since the layer couldn't support itself.

Tank and Pump Design:

The pump used in the concrete printing system must be capable of handling the specific mix requirements, including aggregate size and water-to-cement ratio. A piston-pump was developed as there was no suitable pump available for the small size of the project. The cement screw pump was not appropriate due to high pressures and air spraying. The final pumping device is directly integrated with the movable tank and operates by pressing down on the piston. The pump pressure directly impacts the concrete pouring speed. Early trial tests focus on extrudability, influenced by the amounts and distributions of dry components in the mix. The mix proportions are calculated based on slip-form concrete design principles. Further experiments are conducted to meet the remaining requirements, and the role of additives becomes prominent.

Extrudability:

It refers to the capacity of the concrete to be extruded out of the nozzle. This is assessed on the basis of the distance over which the paste can be printed without blocking the nozzle. Also, the printed paste should be clear of cracks separations.

Compressive strength:

The concrete's target strength is calculated using 5x5 concrete cubes and BS 1881-116:1983. Since the structure is printed in layers rather than in its whole, strength is very crucial. The desired strength and strength growth should be high since the printing process just takes a few minutes and setting time should be taken to be immediate.

Flowability:

The slump flow test is a method for determining flowability. An upside-down cone is used to disperse the concrete. The amount of time needed for the mixture to spread by a particular diameter is measured, and the rate of flow may then be calculated. Greater flowability and workability are correlated with a readily expanding mixture.

Buildability:

Concrete's buildability is its capacity to solidify before a further layer of concrete is poured over the previously applied layer. The number of layers that might be built without the lower levels significantly distorting allows for an evaluation of the buildability. Each print session should produce an object with at least 20 layers.

Open time:

In essence, the amount of time that has occurred since the water was added to the combination is its open time. The concrete shouldn't quickly solidify while printing because it would clog the nozzle and stop the operation in its tracks. The printing process therefore relies heavily on the concrete's open time.

Experimentation and Designing

Using a 3D printer supplied by a digital file that explains the specifics of the thing, three-dimensional (3D) printing is a cutting-edge approach for creating objects. It is also known as rapid prototyping (RP), layer manufacturing, additive manufacturing (AM), additive fabrication, additive processes, direct digital manufacturing, and solid freeform fabrication. Materials including plastics, metals, concrete, sand, or resins are used in this printer.

Researchers explored various 3D printer designs, building techniques, and materials in order to advance this technology for the fabrication of structural elements and/or complete structures.

In this study, the most recent advancements in 3D printing techniques are reviewed. By contrasting the price of concrete for a Multipurpose Hall that was constructed conventionally with the price if it had been constructed using 3D printing, the impact of 3D printing is examined. Software called Revit is used to create the model. A modern analysis of advancements in 3D printing techniques is presented in this research. A comparison of the concrete cost of a Multipurpose Hall that was constructed traditionally with the cost if it had been constructed using 3D printing is used to examine the effects of 3D printing. Revit software is used to create the model.

Selected Case Study:

The conventional construction of a Multipurpose Hall is analyzed, including examination of architectural and structural designs from Greater Amman Municipality for material costs comparison with 3D printing. The hall is a one-story structure made of concrete and stone, with a traditional shape and a total area of 350 square meters (m2). The aim of applying 3D printing in this public building is to achieve cost savings and shorter construction time. The Revit modelling programme is used to represent each zone of the building based on its function, including concrete works, interior walls, and exterior walls above ground level, with determination of materials and estimated costs.

Concrete Works:

For the external walls behind the stone, 20 MPa concrete compressive strength is employed. With a concrete compressive strength of 25 MPa, reinforced concrete (RC) is utilised for slabs on grade and stairways. Columns, slabs, beams, and stairs are all made of RC components with a concrete strength of 30 MPa.

External Walls:

The outside wall of Multipurpose Hall is a typical wall made up of a 17 cm layer of concrete, a 10 cm plastered hollow cement block wall, 3 cm of extruded polystyrene insulation, and 5 cm of stone cladding. The outside wall of Multipurpose Hall is a typical wall made up of a 17 cm layer of concrete, a 10 cm plastered hollow cement block wall, 3 cm of extruded polystyrene insulation, and 5 cm of stone cladding.

Figure 6: Multipurpose hall exterior.

Table 1: Basic data of multipurpose hall.

Floor area	350 m^2
Construction type	Concrete construction
Cladding material	Stone
Exterior wall area	477 m^2
Total concrete volume	438 m3
Total cost	Rs.2,40,716

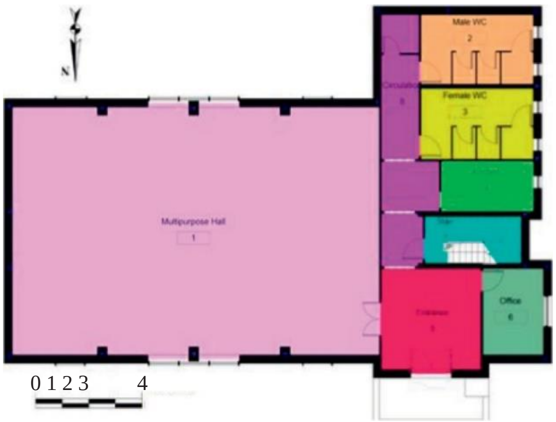

Figure 7: Ground Floor Plan For Multipurpose

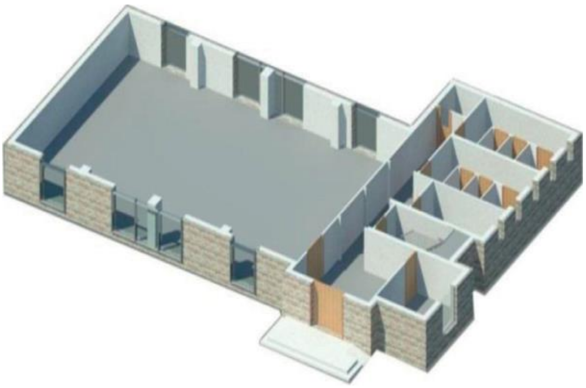

Figure 8: Perspective plan of multipurpose

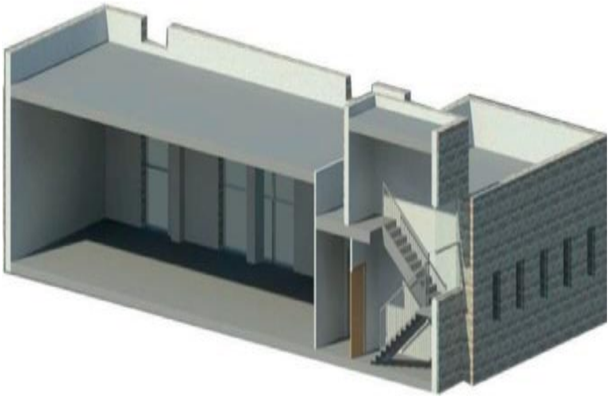

Figure 9: perspective section of multipurpose hall.

Table 2: Cost of construction works above ground level by conventional construction.

Work description Unit Quantity	Cost\unit (Rs)	Total cost (Rs)
Stone attached to concrete 20 MPa for external walls (stone height = 50 cm) m^2 32	85	2720
Stone attached to concrete 20 MPa for external walls (stone height = 25 cm) m^2 430	60	25800
Extruded polystyrene (thickness =3 cm) for external walls m^2 230	8	1840
Hollow cement block (thickness =10 cm) for external and internal walls m^2 207	15	3105
Hollow cement block (thickness =15 cm) for external walls m^2 220	14	3080
Hollow cement block (thickness = 20 cm) for internal walls m^2 17	20	340
RC 25 MPa for stairs m^3 5	95	475
RC 25 MPa for slab on grade (thickness = 20 cm) m^2 216	18	3888
RC 25 MPa for slab on grade (thickness = 12 cm) m^2 225	15	3375
RC 30 MPa for columns m^3 25	200	5000
RC 30 MPa for slab and beams m^3 117	200	23400
RC 30 MPa for stairs m^3 3	200	600
Total		73,623

CONCLUSION

As a result, 3D printing reduces 65% of the conventional construction cost of material if it is applied in Jordan. The equipments' cost, construction time, and labor costs were not calculated herein since they depend on the required size and speed of printer for the project. The research concludes with a summary of the findings and their implications for the techno-economic feasibility of 3D printing of concrete for industrialization. Recommendations are provided for future research, and practical implications for researchers, practitioners, and decision-makers interested in the techno-economic analysis of 3D printing of concrete for industrial applications are discussed.

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