P A P E R

How Could the Construction 3D Printing (C3DP) Technology Affect the Future of Material Use in Architectural Design?

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Paradigm shifts in architectural design often see their beginnings in the emergence of a new building material or technology. The development of reinforced concrete, for example, along with the possibilities offered by efficiently mass-produced materials and products, inspired Le Corbusier's early work. Among the ongoing developments of new building technology, the advancement of Construction 3D Printing (C3DP) employing additive manufacturing (AM) has most recently attracted architectural researchers and practitioners. Despite the expectation that this new technology will innovate architectural design and building construction, most studies on C3DP focus on construction or structural issues rather than architectural expression. In response to this literature gap, the present study seeks to identify the influence of C3DP technology on architectural material use and to discuss how this could reshape the future of architectural design. Through a systematic literature review, the paper identifies the mechanisms and characteristics of the technology and places them within a larger historical context. The study results indicated that the emergence of the C3DP technology brings the opportunity for a new set of architectural expressions and a reinterpretation of traditional materials encompassing the past, present, and future.

Paradigm shifts in architectural design often see their beginnings in the emergence of a new building material or technology. Among the ongoing developments of new building technology, the advancement of Construction 3D Printing (C3DP) employing additive manufacturing (AM) has most recently attracted architectural researchers and practitioners. With its potential for faster construction time and reduced labor cost, C3DP may be a promising solution for repairing communities following natural and manmade disasters. The unique construction process of C3DP, based on automation, also expands architectural expression and material use in a unique way. The present study aims to identify the influence of C3DP on the building design process and speculate how this emerging technology could bring changes in the future of architectural design. Through a systematic literature review, the paper identifies the mechanisms and characteristics of the technology and places them within a larger historical context.

3D-PRINTED BUILDING TECHNOLOGY

The definition of a 3D-printed building is a three-dimensional structure printed from a digital model (Hager, Golonka, and Putanowicz 2016), which can be achieved by various AM processes, such as extrusion printing, binder jetting, and 3D-printed formwork (Khan, Koç, and Al-Ghamdi 2021). The principle of AM is "the construction of layered structures" (Hager, Golonka, and Putanowicz 2016), while the construction processes and devices may vary depending on the method. Among various AM processes, Contour Crafting (CC), developed by Khoshnevis (Khoshnevis 2004; Khoshnevis and Dutton 1998), is the most widely used in 3D-printed construction (Souza et al. 2020). CC is one of the extrusion printing (EP) methods, in which an extruder nozzle sprays ready-mixed concrete for printing the digital model. This method employs a nozzle and a gantry crane for concrete printing and the key features are "trowels moving [along the] x, y, and z-axis" coupled with a robotic arm (Souza et al. 2020; Khan, Koç, and Al-Ghamdi 2021). With the advancement of 3D-printed building technology, its use in the industry has been expanding worldwide (Alhumayani et al. 2020) for various building programs, such as the El Cosmico Hotel in Texas, the 3D-printed house in Beckum, Germany, and the 3D-printed office in Dubai, UAE, often employing C3DP method. The technology is also considered an innovative solution for space habitats, such as NASA's proposed 3D-printed home projects on Mars (Yashar et al. 2022; Muthumanickam et al. 2023).

ADVANTAGES OF 3D-PRINTED BUILDING TECHNOLOGY

A well-known advantage of using C3DP is the significant reduction of construction time (Wu, Wang, and Wang 2016; Kothman and Faber 2016; Diggs-McGee et al. 2019). For example, Rouhana et al. (2014) reported that using 3D printing technology for the construction of a 200-m2 house was approximately three times faster than traditional methods. Also, Zhang et al. (2019) claimed that using C3DP may reduce about fifty to seventy percent of the construction time compared to traditional construction processes. The reasons for the reduced construction time include the automation of human labor and the elimination of formwork processes, which also reduce about thirty to sixty percent of construction waste and about fifty to eighty percent of labor costs (Zhang et al. 2019). This labor and time efficiency makes the technology competitive and promising in the building industry (Diggs-McGee et al. 2019; Kreiger, Kreiger, and Case 2019).

Another remarkable advantage of C3DP is the easy customization of building shapes, which allows freedom of design. This freedom is not only about aesthetics but also may allow more environmentally responsive building design. Unlike designing a vehicle meant for mass production, designing a successful building requires sensitivity to each project's unique site and context. There have been efforts to standardize and mass produce building design, such as modular or prefabricated systems, but these attempts have shown the limitations of the practice in addressing the specific needs of the inhabitants or climatic conditions. The application of C3DP to building design helps "mass customization of building elements" instead of "standard mass production" (Gramazio, Kohler, and Willmann 2014) and ultimately leads to more sustainable and environment-responsive building designs. In mass customization, the building form can be easily optimized to minimize the environmental impact and maximize the structural performance of the building, which may avoid using surplus material in structural design (De Schutter et al. 2018).

CHALLENGES OF 3D-PRINTED BUILDING TECHNOLOGY

As stated in the previous section, the literature widely claims that utilizing C3DP technology can reduce construction time along with material use and waste, thus making a cleaner construction process with increased safety of workers than conventional construction methods. Researchers also believe that C3DP would be more affordable in the future even though it is currently controversial (De Schutter et al. 2018; Labonnote et al. 2016; Wangler et al. 2016). While the elimination of formwork and the reduced construction time and labor may help lower the construction cost, the available information, such as a structured bill of quantities and pricing of materials, is insufficient for an accurate estimation of 3D-printed building construction costs (Yang et al. 2018). Also, Khan, Koç, and Al-Ghamdi (2021) pointed out that the cost of the 3D printer and the associated software packages should be counted together for the estimation and that more empirical studies are necessary to assess the financial performance of the new technology compared to other traditional processes. Despite this uncertainty, it is undeniable that the technology shows an opportunity to improve construction processes and be more effective and affordable in the industry (De Schutter et al. 2018; Souza et al. 2020).

Another challenge for the application of C3DP is the material, which needs to be fluid enough for pumping through the nozzle but stiff enough once the printhead does not support the material anymore and thus requires significant yield stress (De Schutter et al. 2018). These features are time sensitive since a long pause can make the material too stiff to be extruded or may create weak points in the inter-layer bonds (Cesaretti et al. 2014). As traditional concrete does not satisfy these rheological requirements for C3DP, many studies have been conducted to find an optimal property of cementitious material by testing different types of admixtures, aggregates, and reinforcements (Yin et al. 2018). However, all these studies are still in the early stages and the limited material palette is considered a major challenge in the advancement of 3D-printed building technology (Souza et al. 2020; De Schutter et al. 2018). The configuration of the printing, including the nozzle speed and flow rate (Souza et al. 2020), and the transportation of material and printing equipment to the printing location (Schuldt et al. 2021) are also primary challenges for successful construction. After the thorough exploration of the technology, developing policies, building codes, and specifications for the social adaptation of the new technology would be an additional future challenge (Khan, Koç, and Al-Ghamdi 2021).

HISTORY OF ARCHITECTURAL MATERIAL

When viewed within the context of the history of architectural materials and material production, the possibilities and current challenges of C3DP echo those of past technologies. If we link this all to the theme of the conference, we may, perhaps, see this history as one in the service of repair, which is to say, in answer to structural (or socio-economic, political, or ecological) failure, architects and engineers find new, more robust solutions. During the twentieth century, one of the most significant of these solutions was ferroconcrete. If we look at the history of stereotomic building, we find a variety of vernacular traditions employing adobe, rammed earth, and cob to which monolithic concrete structures in some ways owe their design. While concrete itself was successfully developed in ancient Rome, with builders adding a volcanic powder called pozzolana to the typical cement mixture of lime, water, and aggregate, the addition of metal, which began as early as 1774 with John Smeaton's Eddystone Lighthouse but did not become widely used until the late nineteenth century (Giedion 2009), would prove momentous in the architecture of the following decades.

From an architectural historical standpoint, the work of Francois Hennebique in the 1890s was of particular importance. Hennebique perfected a monolithic joint for reinforced concrete, hooking together bent cylindrical bars, which in turn allowed monolithic ferroconcrete frames. The Hennebique system in turn influenced a range of alternative methods of reinforced concrete construction and a similar range of architecture, from silos, granaries, and factories, to churches, such as Anatole de Baudot's Saint-Jean de Monmartre (1894) and housing, like Auguste Perret's 25 bis Rue Franklin (1903).

Of course, when examining the history of concrete in the twentieth century, one particular architect looms large: Le Corbusier. Historian Kenneth Frampton notes that in the work of Le Corbusier, "[concrete became] the primary expressive element of architectural language," for the first time. Le Corbusier's "Maison Dom-ino," proposed in 1915, introduced this extraordinary new approach to design, which harnessed the potential of ferroconcrete to provide an open floor plan, free façade, and independence between the building skeleton and walls. He then demonstrated these principles in buildings such as the Villa Savoye (1928-30), Maison La Roche (1923), and Maison Cook (1924), among others. His pioneering architecture, as well as that of architects of the Bauhaus School and De Stijl movement, which were compiled in the 1932 "International Style" exhibition at the Museum of Modern Art, charted the direction of architecture in the coming decades.

It should be noted that while most significant works of early Modernism were often private homes of ostensibly wealthy clients, Le Corbusier and other Modern architects from the beginning sought to harness the power of ferroconcrete to address post-World War I housing shortages affecting the general public. Le Corbusier, for example, developed the Maison Citrohan (1920) as an easily reproducible housing module and the Bauhaus School, under the directorship of Hannes Meyer, focused on socially responsible design, seeking to provide the masses with well-conceived products and housing.

In this mission is another example of how architectural materials and material production may be seen in the service of repair: architects at times also use their designs to confront social and environmental failures. In some ways, ferroconcrete has come to represent the failure of the Modernist utopian vision—austere, monotonous concrete housing projects, for example. In others, the building typologies enabled by the technology, such as soaring skyscrapers with glass curtain walls, have become symbols of capitalism and all of the social, economic, and environmental ills of post-WWII Western society. And yet, concrete also offers solutions to these problems.

In examining the history of concrete from this lens, one case study stands out—the Minimum Cost Housing Group's sulfur housing program of the 1970s. The Minimum Cost Housing Group (MCHG) was established in 1970, by Colombian architect Alvar Ortega. He was soon joined by a group of architects and recent McGill graduates, including Witold Rybczynski, Samir Ayad, Wajid Ali, and Arthur Acheson, who shared an interest in finding solutions to international housing problems. The MCHG, sought to undertake research that would address "the development of alternative uses for locally available building materials, particularly binding agents, in order to decrease the building cost, and increase the quality of construction in self-built housing" (Rybczynski et al. 1975, 20). One such binding agent was sulfur. Sulfur housing, on the one hand, responded to Western overdevelopment—exploiting the vast caches of Canadian solid-state sulfur, a consequence of the modern petroleum industry, to design buildings for Canadians—while on the other, looked toward the ways in which discoveries in Canada could be applied at an international scale. Elemental sulfur, the MCHG noted, existed naturally in many international regions but also was over-abundant, and thus inexpensive, in nations such as Canada (Figure 1) that had recently passed clean air legislation. Moreover, by their estimation, should sulfur prove a valuable building resource, nations experiencing housing shortages may also be enticed to recover sulfur from their refineries, instead of polluting the atmosphere—a potential opportunity for a building material to drive environmental legislation (Rybczynski, Ortega, and Ali 1974, 3).

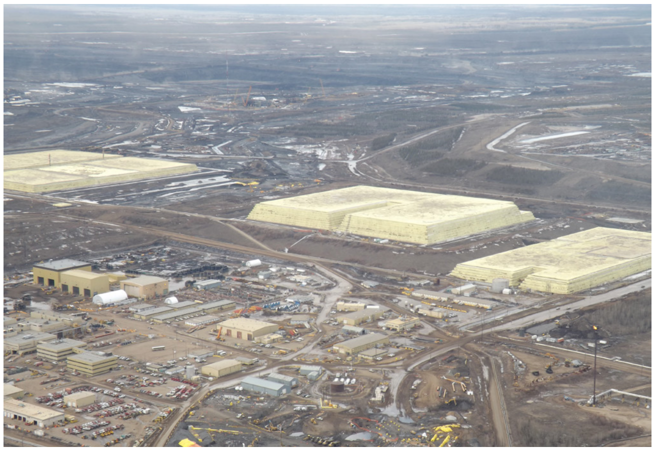

Figure 1. *Sulfur blocks at Syncrude base plant.* Jason Woodhead.

In 1971, the group designed their first "waste-material, low-energy, quick-fix, easy-assemble, universal building block" made of sulfur. By 1975, the MCHG had constructed three demonstration projects using sulfur building technology: Ecol, a demonstration home in Ste-Anne-de-Bellevue, Quebec (1972); Round House, a community building in Saddle Lake, Alberta (1973); and Maison Lessard, an orphanage in Saint-François-du-Lac, Quebec (1974–1975) (Rybczynski et al. 1975, 724) . Although the sulfur housing program at McGill concluded just under fifty years ago, it, combined with the social-housing schemes of Le Corbusier, Hannes Meyer, Team X, and others, offers an interesting lens by which we might examine contemporary concrete technologies. While sulfur and traditional concrete technologies pose challenges for current 3DCP methodologies, for the reasons mentioned previously, studying the motivations and research methodologies of historical actors may offer new solutions. For example, the MCHG attempted to address ecological and social ills while at the same time solving a technological problem. Might widening our perspective of the technological problem of C3DP to include ecological and social needs in fact uncover innovative solutions? Meanwhile, vernacular earthen case studies could influence the formal elements of C3DP buildings. Further, both historical examples relate to the potential for C3DP structures to be sustainable solutions to housing in the twenty-first century.

MATERIAL USE IN CONSTRUCTION 3D PRINTING

While sulfur has been a challenge for Earth-bound architectural efforts, it has been implemented in extraterrestrial design. Sulfur is particularly well-suited for planetary robotic construction, such as the Mars or the Lunar habitats (Figure 2). Sulfur is an accessible material on Mars and the Moon as a form of sulfides and sulfates, and waterless construction can be achieved if sulfur is mixed with regolith (Shahsavari et al. 2022). Printed sulfur concrete is reported to have a higher performance in vacuum conditions with a high temperature and cures faster than the typical printed plain cement concrete (Giwa et al. 2024). Therefore, sulfur concrete is considered an effective material for 3D printing in the harsh climatic conditions of space, and there has been ongoing research to identify the material's behavior under extraterrestrial conditions. Experiments have examined the performance of sulfur concrete in relation to extreme temperatures, vacuum, chemical reactions, and low gravity (Shahsavari et al. 2022; Giwa et al. 2024; Wang and Snoeck 2023).

In addition to the revival of sulfur concrete through C3DP, the utilization of earth for 3D-printed buildings also has been a notable material expansion. Although the earth has been considered a sustainable material and consistently used throughout the history of architecture (Figure 3), as mentioned previously, the labor-intensive construction process has been a barrier to the further dissemination of material in contemporary architecture. The automated process of C3DP may overcome this barrier, and also, enrich the architectural expression of the material through the unique sequence of printing. This maximizes the potential of the earth as a building material, which can be shown in the following two projects, El Cosmico Campground Hotel in Marfa, Texas, USA, and Tecla Eco-Housing in Massa Lombarda, Italy.

The El Cosmico project (Figure 4) was designed by Bjarke Ingels Group and is currently in the process of construction by ICON. Tecla Eco-Housing (Figure 5) was designed by Mario Cucinella Architects and constructed by WASP. In both of these projects, the primary printing material was local raw earth, and the design showcased the freedom of C3DP technology by employing curved surfaces, including domes, vaults, and parabolic forms. The horizontal earth layers exposed on the wall, similar to rammed earth wall layers, celebrate the in-situ printing process and provide the building users with an experience that encompasses novel technology and ancient material. Testing the design and construction process with these experimental projects, the teams attempt to expand the work to vulnerable communities and propose a solution to the housing crisis in the US and other nations.

RESULTS AND DISCUSSIONS

Through a review of the literature and a brief historical vignette of stereotomic material production, this paper suggests that the emergence of C3DP technology offers a pathway to a fundamental shift in contemporary design and construction processes. The advancement of C3DP enriches and reshapes architectural design by reinterpreting traditional architectural materials with a new automated construction process, ultimately contributing to the innovative use of local materials and low-carbon design and construction. On the one hand, it allows a different sort of architectural expression, one that revives a more ancient design language of monolithic materials and supports rounded corners and horizontal surface patterns without prohibitive costs; on the other, C3DP addresses the present housing crisis and future planetary habitat preparation. This reciprocal relationship across the past, present, and future indicates that the efforts to advance the C3DP technology and its application today may offer solutions beyond technological innovation for its own sake; if architects and engineers take note of past methodologies, such as vernacular earthen traditions or the socially-motivated experimentation of the 20th century, C3DP, in addition to its clear technological value, may also have the power to serve vulnerable populations and environments.

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Figure 4. ***EL COSMICO 3D-printed hotel.*** Bjarke Ingels Group.

Figure 5. ***Tecla 3D printed house.*** WASP.

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