3-D Printing in Building Construction: A Literature Review of Opportunities and Challenges of Reducing Life Cycle Energy and Carbon of Buildings

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Abstract. Buildings consume approximately 48% of global energy each year as embodied and operating energy. Embodied energy is consumed in all products and processes used in building construction, maintenance, replacement, renovation and demolition. Operating energy is consumed in heating, cooling, lighting, and operating building equipment. To effectively reduce life cycle energy usage, both embodied and operating energy must be optimized. However, in spite of advancements in building envelope technologies, building systems/controls, building energy modelling, and material production, the energy and carbon footprint of buildings is still enormous. Perhaps, a new paradigm is needed to transform the way our buildings are designed and constructed. One emerging technology that could possibly help bring this paradigm shift is 3-D printing or additive manufacturing. Although, its application to mainstream construction is yet to be tested, it surely demonstrates energy and carbon benefits through innovative materials and construction processes. In this paper, we conduct a systematic review of literature to study the state of the art of 3-D printing or additive manufacturing in building construction. The goal will be to identify challenges and opportunities of saving operating and embodied energy and show future research directions to use 3-D printing technologies for energy optimization.

1. Introduction
Buildings consume over 48% of annual global energy supply over their life cycle as embodied and operating energy, respectively releasing significant amounts of carbon to the atmosphere (~40% of global carbon emission) [1]. The construction of buildings and other infrastructure alone depletes 16% of water, 25% of virgin wood, and 40% of sand and gravel each year globally adding significant pollution and waste to the biosphere [2]. Although the industry has seen advancements in building envelope materials, building systems, energy modelling techniques, building automation systems as well as in the technologies of energy production, manufacturing, and transportation, an effective approach to comprehensively reduce the energy and environmental impacts of built environments is yet to be found [2]. Emerging technologies of digital fabrication such as additive manufacturing or 3D-printing have been already applied to manufacturing sector. Such technologies are getting popular in the building design and construction industry [3–4]. Although these technologies are still at a research and development stage, particularly with respect to their application to the construction industry, their potential to influence the energy and environmental footprint of buildings is promising [5–8]. Studies [5–6] have argued that these technologies may represent a paradigm shift in the ways we design, construct, and manage our buildings, and may need to be informed by methods such as life cycle
assessment (LCA) or material flow analysis (MFA) to maximize their sustainability benefits. To do that, a review of their potential opportunities and challenges to reduce energy and environmental footprint is essential [7]. In this study, we systematically review relevant literature to identify opportunities that may help reduce buildings’ life cycle energy and material consumption.

1.1. 3D Printing or Additive Construction Techniques

Two types of digital fabrication methods are discussed in literature: (1) reductive, which includes milling, cutting, or eroding material, and (2) additive, which covers lamination, extrusion, and other 3D-printing methods [5–6, 9]. Both small and large scale additive methods are being considered for construction applications [3]. However, for maximizing the environmental benefits of onsite application of 3D-printing, large-scale printing of buildings and their components is highly recommended [4–5]. To print at large-scale, the concept of Freedom Construction was introduced, which included three key methods [10–11]: (1) Contour Crafting (CC), which was introduced by Khosnevis [12], who proposed a gantry-based system of nozzles to pour concrete in layers within a mold [7, 13]; (2) D-Shape, which involves depositing a structural ink (magnesium oxide or magnesium chloride) over sand [7, 13]; and (3) Concrete printing, which, like CC, uses extrusion of cement mortar [13]. However, the deposition resolution of concrete printing is finer than CC allowing more control of internal and external geometries and not requiring any formwork [13–14]. The three methods also differ in the head mounting or the way of delivering a material, which is done using either a frame, robot, or a crane in CC, D-Shape, and concrete printing, respectively [13]. With 4-6 mm of material layer delivery, the D-Shape and concrete printing offer finer resolution than CC that prints with 13 mm layers [13]. However, CC is faster than the other two [13–14], which may offer additional benefits through reduced time and cost. The existing methods of 3D-printing may help reduce cost, material, and construction efforts, which can be translated into savings in embodied energy and environmental impacts [5–6]. For instance, just by removing the use of formwork, a 3D-printing method can save up to 35–60% of the total construction costs [15–16]. The fact that these methods are digital also allows the integration of computational models to optimize material use for a given structural or thermal performance [5]. Other indirect sustainability benefits may include increased reliability, construction quality, worker safety, and personal control over building design [6–7]. The issue of lacking skilled workforce may also be addressed by such methods [3, 7].

2. Research Goal and Methods

The goal of this paper is to discuss the potential environmental benefits of 3D-printing by reviewing the current literature, and to identify opportunities and challenges of reducing energy and carbon footprints of buildings. Note that we mainly rely on discussions, analyses, and experiments presented in the literature to offer a qualitative summary of the state of research. Also, due to the limitation of article length, we will present only the key findings of the literature review, including only a limited number of studies. The main research questions are:

- What energy and environmental benefits the existing 3D-printing methods may offer?
- What challenges must be addressed to achieve and maximize these benefits?
- What may be the recommendations and future directions to maximize the energy and environmental benefits of a 3D-printed built environment?

We mainly used Google Scholar search engine, as it covers a wide variety of scientific journals, industry reports, and conference papers, and searched literature using keywords such as “3D printing and additive manufacturing,” which resulted in a number of publications mostly in the manufacturing industry sector. We then narrowed our search down to the construction sector using a combination of keywords such as, “3D printing + construction,” “3D printing + construction + life cycle assessment,” “3D printing + embodied energy,” “additive construction + embodied energy,” “additive manufacturing + embodied energy + construction,” and “additive manufacturing + embodied energy.” We also searched the studies cited by the referred papers to find additional literature. This search resulted in roughly 85 publications, which relate directly to 3D-printing in construction. However, due to the limitation of article length, we
included only 37 most relevant studies in this review, which: (1) discussed specifically the impact of 3D-printing on either sustainability, energy efficiency, or environmental quality of buildings; (2) analyzed the savings of material and construction processes due to 3D-printing; and (3) focused solely on 3D printed concrete structures, their benefits and challenges.

3. Results

3.1. Energy and Environmental Benefits of 3D-Printing in Construction

The referred studies either discussed, analyzed, or substantiated a wide range of benefits of 3D-printing in construction such as reduced time, material use and cost as well as maximized quality, design performance, efficiency, and productivity. Because each of these benefits relates to building design, material use, and construction processes, it can be mapped to one or more of the four major life cycle energy components of a building: (1) initial embodied energy (IEE); (2) operating energy (OE); (3) recurrent embodied energy (REE); and (4) demolition energy (DE) [1-2]. IEE is consumed directly in onsite and offsite construction, installation, fabrication, transportation, management, and other related processes and indirectly through the use of materials, assemblies, equipment, and vehicles, each of which consumes energy during its manufacturing process [1–3]. As over 90% of IEE is attributed to material use, any material and waste savings generated by 3D-printing technology could help reduce IEE significantly. When occupied, a building consumes OE in the processes of heating, cooling, lighting, and powering building appliances [1–2]. Because 3D-printing technologies allow printing with materials and complex geometries to gain multi-dimensional and dynamic thermal properties, OE use could also be potentially lowered by reducing heating, cooling, and lighting loads. During the use phase, REE is consumed through construction products and processes involved in maintenance, repair, replacement, and renovation processes, which could also be reduced by 3D-printing with advanced materials with longer service life and lower maintenance requirements [1–2]. At the end-of-life, DE is used in building demolition, materials reuse and recycling, and disposal processes, which can also be enhanced by 3D-printing with highly recyclable and reusable materials [1–2]. Any savings of embodied and operating energy could generate proportional savings in associated carbon emissions.

3.1.1. Initial Construction Phase: Initial Embodied Energy (IEE). Table 1 lists possible reduction, due to 3D-printing technologies, in the number, type, and amount of construction materials, water, and energy sources used onsite. It also lists a potential decrease in the number and usage of construction vehicles and equipment along with labor and staff. Overall, reducing material use, construction, and transportation efforts would decrease IEE. Building services (e.g. plumbing and wiring) may be integrated into 3D-printed building components generating embodied impact benefits during a building’s initial construction and maintenance. Table 1 also illustrates the level of impact 3D-printing technologies may have on IEE, OE, REE, and DE, with symbols such as “√” and “*” depicting, profound and moderate impact, respectively of the resource categories shown at the top of columns 2–7. A saving in the following resources may generate life cycle energy benefits:

**Construction Materials**: The reduced use of construction materials generates the largest embodied energy savings, while minor savings result from decreased transportation and construction processes [6–13]. As shown in Table 1, advanced 3D-printing materials may decrease the number (e.g. multi-layered vs. singular material in a building envelope), type (e.g. natural, recyclable, and local), and the amount of traditional construction materials. 3D-printed building components tend to be smaller in size with better building performance, reducing material use, transportation, and construction [5–7, 17–19].

**Waste Factor**: Because materials are manufactured in standard sizes but are eventually cut and installed in custom shapes and sizes, a considerable amount of materials is wasted in traditional construction, which can be eliminated by 3D-printing because it mainly involves depositing layers of materials to fabricate building components [5–9, 18–21]. Connectors such screws, nails, and bolts may also be avoided if building components are 3D-printed [5, 19–20]. Any material savings due to less wastage would also add to the savings of construction materials as shown in Table 1.
Rework and Damage: 3D-printing approaches are also more precise and efficient due to robotic construction requiring standardized, accurate, and complete digital building information, which reduces the potential of rework due to human error and any information conflicts [3, 11]. Because onsite storage and movement of material and equipment is avoided, the possibility of any damage to stored materials, assemblies, or work-in-progress is reduced [3, 6, 10–11]. A complete automation may also mean lower human errors, which have traditionally caused over 80% of the housing construction defects [11]. Reduced rework and damage would further contribute to construction material savings (see Table 1).

Temporary Construction Structures: The traditional construction approaches utilize different types of temporary structures such as formworks and scaffolds, which are not needed in 3D-printing [15–16, 22] (see Column 2, Table 1). Studies focused on 3D-printed concrete construction found a significant reduction in formwork requirements resulting in 35–60% of construction cost savings [15–16]. Because material is printed using a crane or a robot, scaffolding requirements are also greatly reduced [23–24].

Computational Material Optimization: The fact that 3D-printing involves automated construction based on digitized information allows combining innovative computational models to generate and print complex forms to optimize the building performance, which is not possible in traditional construction [5, 25–26]. For instance, studies [5] found that computational modeling helped achieve enhanced thermal and structural performance consuming much less material than the conventional construction producing additional material savings [11, 13, 21].

Locally Available and Natural Materials: Although most 3D-printing research still utilizes cementitious materials, some studies are focusing on using natural and locally available materials, which could help save the transportation, construction as well as manufacturing energy, as most local materials are processed and installed using much less energy [5, 9–11, 27–28] (see Table 1). Natural materials could also reduce the toxicity of built environments if traditional materials constituting toxic chemicals are replaced [8, 29–31]. Local materials often suit to the local climatic conditions, and may also save some of the heating and cooling loads [1, 32].

Materials with Multi-dimensional and Dynamic Properties: The way current 3D-printing technologies extrude materials, limits the use of multiple conventional materials such as gypsum, steel, and insulation [10, 13, 32]. In fact, the limitation of extrusion nozzles necessitates developing and using materials that can provide multiple properties to replace multi-layered building assemblies [11]. For instance, a material with enhanced structural, thermal, and moisture control performance, can replace drywall, stud core, mineral wool, and a number of cladding materials used in a building envelope [9].

| Table 1. 3DP or AC potential benefits for life cycle energy components |
|---------------------------------------------------------------|
| **Resources** | Construction materials & temporary structures | Water | Energy sources used in construction | Construction equipment | Construction vehicle | Labor & staff |
| **Life cycle embodied energy** | Number | Type | Amount | Number | Type | Amount | Number | Usage | Number | Usage | Number | Usage |
| Building material production (IEE) | √ | √ | √ | | | | | | | | | |
| Transportation (IEE) | | | | | | | | | | | | |
| Construction (IEE) | | | | | | | | | | | | |
| Operation (OE) | | | | | | | | | | | | |
| Maintenance & replacement (REE) | | | | | | | | | | | | |
| Demolition & disassembly (DE) | | | | | | | | | | | | |
Transportation: Any decrease in onsite and offsite use of material, equipment, and labor would generate proportional transportation savings [3, 6, 10–11, 20] (see Table 1). 3D-printing involves a robotically-controlled printing head or nozzle extruding a single or a limited number of materials, which saves a significant amount of transportation [5, 13]. Such methods also circumvent the need for equipment such as pumps, lifts, cranes, compressors and generators decreasing their onsite and offsite movement [6, 20, 33]. Because labor and staff needs are reduced, their work-related trips as well as any onsite transportation is also decreased [10–13]. Techniques such as D-Shape use local materials, which could save considerable transportation energy [13].

Construction: A portion of the IEE comes from the energy used in onsite and offsite construction, fabrication, and administration processes [1-2]. As shown in Table 1, the number (e.g. electricity, natural gas, and petroleum), type (e.g. renewable and locally-produced), and the amount of energy used onsite can be reduced through 3D-printing. With highly efficient robotic construction, 3D-printing not only avoids equipment and labor but also shortens construction time considerably reducing the use of construction energy [8, 19, 21, 33–35]. Some equipment and power tools may not be needed anymore, which conventionally consume a variety of fossil fuel-based energy sources such as electricity, natural gas, and diesel (see Table 1). A robotic systems mainly run on electricity, which can be supplied through local renewable sources [11]. The use of highly mechanized and automated robots means less dependence on human labor and lowered chances of delays due to labor strikes, economic downtime, and inclement weather [13]. Any reduction in rework or damage would further save construction energy [3, 33]. Studies [19, 33] also emphasized integrating services (e.g. plumbing, ductwork, and electrical work) within printed components to reduce the work and the involvement of different trades.

3.1.2. Use Phase: Operating Energy (OE) and Recurrent Embodied Energy (REE).

Building Operation: Although most of the 3D-printing research to date has been focused on initial construction, opportunities exist to decrease a building’s heating, cooling, and lighting energy through material and building design [10, 35]. Studies [21, 25, 32, 36] have suggested developing and testing materials with: (1) multi-dimensional and dynamic structural, thermal, and moisture control properties; and (2) embedded sensors to enable adaptability with changing environmental conditions. Such materials are recommended keeping in mind, for instance, the energy cost of unnecessary cooling required due to static insulation in an envelope that traps heat during heating days even if outside temperature is lower than inside [37].

Building Maintenance: Some studies emphasized designing materials with lower maintenance, longer service life, and enhanced durability to reduce overall life cycle recurrent embodied impacts [8, 18, 30, 32]. Since the REE of a building can be much higher than its IEE, reducing it could considerably save life cycle embodied energy [2]. Any benefits resulting from decreased material use, construction, and transportation discussed in Section 3.1.1 would also benefit replacement and maintenance activities, which use the same materials and methods [30]. Decreasing the number of materials may also reduce maintenance and replacement needs over the building’s life cycle (see Table 1).

3.1.3. Demolition Energy (DE): End-of-Life Phase. Some research is also focusing on exploiting material design to enhance the recycling and reuse of materials, assemblies, and equipment, particularly during the deconstruction stage [5–9, 17]. Unlike earlier efforts that were mostly focused on building design, material and assembly design can be informed by the strategies of recycling, reuse, and design for disassembly [5, 9]. If the variety of materials installed in a building is reduced, sorting of materials for recycling will be much easier. In fact, if a singular material is used, it can be ground down into a powder, remixed with a binder, and reprinted. Using natural and locally available material types can also be beneficial during demolition as such materials tend to be more recyclable [9–10]. The amount of DE savings, therefore, will depend on the number and type of materials (see Table 1).
3.2. Major Challenges to 3D-Printed Construction and Recommendations

Material, Hardware, and Design Limitations: Although some studies have experimented with natural materials (e.g., D-Shape), existing 3D-printing materials are still limited to mainly cementitious materials such as concrete [3, 9–10, 13, 20, 32], which also suffer from the issues of reinforcement integration, workability, extrudability, buildability, and printing speed [6, 8, 27–28]. Hardware such as printing heads/nozzles are designed mainly for concrete, and simultaneous printing of multiple materials is yet to be accomplished [8, 28, 32]. 3D-printing machinery is also quite expensive and has limitations of printer size and printing speed [8, 10, 13, 19–20, 32]. Conventional design approaches also do not fit well with these technologies, as they must confirm to the machine constraints [20]. Recommendations: Studies [8–9, 28, 31] recommend developing multi-functional, dynamic, and recyclable materials from natural sources to ensure that the number and amount of different materials used is reduced [9]. Printing hardware including robots, printing heads, and frames must be standardized for printing buildings at different scales [3, 8, 13, 21]. The conventional design approaches and 3D-printing research must align so that design approaches are optimized for 3D-printed construction [20].

Construction Scale Limitations: Recently, a number of industry efforts have been made to print large scale buildings, especially in China [19]. However, most research is still focused on printing and testing small scale building components, which may hinder industry-wide application of 3D-printing [4, 10, 13, 19, 25, 38]. The size of printers, robots, and printing frames (e.g., gantry or crane) also constrains 3D-printing large scale buildings [32, 35, 38]. Recommendations: More research is needed to design and develop robotic configurations to print in-situ, small to large scale structures [28]. Material and workmanship standards must also be established to ensure quality and compliance [38].

Assessment Limitations: Only a limited number of studies have assessed 3D-printing for environmental and economic impacts, that too at a small scale. A decision-support system based on a quantitative environmental assessment at a building scale is lacking, which impedes any efforts to maximize energy and environmental benefits of 3D-printed construction [5, 30, 32]. Recommendations: current research on 3D-printing material, hardware, and building designs must be informed by environmental assessment techniques such as life cycle assessment (LCA) and Material Flow Analysis (MFA) using an iterative and integrated process involving design and construction professionals, material scientists, environmental scientists, computer engineers, mechanical and structural engineers [5, 39].

4. Discussion

The emerging technologies of 3D-printing represent a paradigm shift in the way our built environments are planned, designed, constructed, and managed. At this critical juncture in time, such technologies must be guided through a shared vision and a set of energy and environmental goals that guarantee radical changes in the business as usual, particularly to combat pressing global issues such as climate change. Such a common vision will help bring together existing isolated research efforts possibly resulting in research partnerships, which can deliver more effective and pragmatic 3D-printing options for buildings. Most efforts so far are grappling with material design, printing hardware and software issues, and are not informed by scientific data generated using LCA and MFA. What is required is to identify hotspots of energy and environmental impacts in the traditional construction approaches and target them systematically through 3D-printing technologies. This study proposes an iterative model of evaluation, refinement, and implementation as shown in Figure 1 to integrate LCA and MFA data to adapt to and mitigate the adverse effects of the already happening climate change. The mitigation aspect examines current 3D-printing materials, technology, building design, and codes and regulations through indicators such as greenhouse gas emissions, acidification and eutrophication potential, toxicity, and energy and non-energy resource depletion. Such assessment can be carried out using enhanced LCA or MFA methods to investigate current construction materials and methods, identify opportunities for improvement, and inform the emerging technologies of 3D-printing to maximize their energy and environmental benefits. Just focusing on mitigation may not be enough, as the globe is already facing radical weather, natural calamities, and outbreaks caused by climate change. The evaluation of current materials and methods for climate change adaptation must also inform the design of novel 3D-printing
materials and technologies including building codes. Adaptation indicators must evaluate potential risks of wind, water, wildfires, drought, earthquakes, and disease due to climate change, and inform 3D-printing research to generate design solutions and enhance climate change resiliency.

5. Conclusions
In this paper, a concise review of literature was conducted to start a discussion on opportunities that can be exploited and challenges that must be addressed to maximize energy and environmental benefits of 3D-printing buildings. Even though multiple opportunities exist to enhance the environmental quality of buildings through 3D-printing approaches, a number of challenges still plague their industry-wide application. Literature offers a set of recommendations that could potentially streamline and inform the evolution of such emerging technologies. Equally important is to develop and implement an iterative cycle of design evaluation, refinement, and implementation of 3D-printing technologies to enhance their benefits at a stage where these technologies are still evolving.

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