**Perspectives on BIM-based 3D Printing for Sustainable Buildings**

Orly Tal-Yosef

**Abstract**

Three-dimensional (3D) printing, also called additive manufacture (AM), is a novel, automated method of printing a structure layer-by-layer directly from a 3D digital design model. Its potential ability to build complex shapes in a less costly and more sustainable manner may revolutionize the construction industry. There are three main 3D printing techniques: (a) contour crafting; (b) concrete printing and (c) D-shape. A disruptive technology, 3D printing creates a new market and value network, thus disturbing the established market. Building information modeling (BIM) is a comprehensive management approach encompassing the entire life cycle of the architecture and construction (A&C) process, including architectural planning, geometrical data, scheduling, material, equipment, resource and manufacturing data, and post-construction facility management. By maintaining safety and productivity in large-scale digital processes, BIM is critical to 3D printing’s success in construction. Integrating BIM and 3D printing techniques into A&C can potentially lead to an ecological architectural process that reduces waste and energy inefficiency, and prevents injuries and fatalities on construction sites, while increasing productivity and quality. This paper examines BIM-based 3D printing of sustainable buildings, which may revolutionize the construction industry and contribute to a sustainable environment.

**Keywords**: additive manufacturing (AM), building information modeling (BIM), 3D printing, architecture and construction (A&C)

**Dr.** **Orly Tal-Yosef** – School of Architecture, Ariel University; orlyt@ariel.ac.il

# Introduction

The construction industry has traditionally relied on specifications and two-dimensional (2D) drawings to convey a new structure’s material properties, performance details, and locational information. By creating small-scale models of the proposed structure, architects can evaluate their work throughout the design process. Today, specifications and 2D drawings are increasingly being replaced by 3D modeling, or, alternatively, 3D solid modeling techniques combined with digital fabrication methods in the virtual environment of building information modeling (BIM). In the digital fabrication process, the 3D objects are “sliced” and represented as a series of 2D layers, with the layers placed one on another sequentially to build up the desired object. Selectivity and control of the material theoretically offer the freedom to build any desired shape, a fundamental advantage of these processes over conventional techniques.

One of the most important contributors to 3D printing is Charles (Chuck) Hull, who invented the stereolithography 3D printer in 1983 and was the first to patent stereolithography in 1984. His invention was a milestone for the 3D printing world (Mitchell et al., 2018). Since the 1990s, technologies have been developed to manufacture solid objects by robotized depositing of stone-like materials without molds on a scale appropriate for buildings. A variety of deposition strategies, robots, printing heads, and materials have been used in 3D printing (Bos et al., 2016), and all 3D printing processes require coordinated interaction between the software, hardware, and materials.

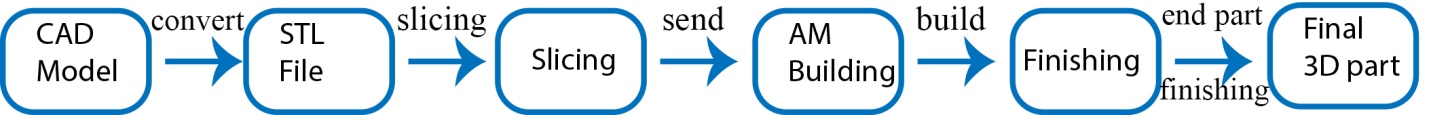
In 3D printing for construction, concrete is extruded through a nozzle in the printing head to construct building structural components layer-upon-layer without the need for any formwork (Wong & Hernandez, 2012). The BIM approach is based on continuous use of digital building models throughout a structure’ entire life cycle, from the early conceptual design and detailed design phases, to the construction and long operational phases (Borrmannet al., 2018). Applying the BIM method together with 3D printing results in a far more extensive use of computer technology in the design, engineering, construction, and operation of built facilities. (Borrmann et al., 2018).

# Computational Process of BIM-based 3D Printing

BIM-based 3D printing is accomplished using an additive manufacturing (AM) technique, which has five main steps (Mahamood et al., 2014):

1. A 3D model design is created in software (AutoCAD, Unigraphics, Revit, Rhino, 3D Studio, CATIA, SolidWorks) or by scanning the object.
2. The CAD data is converted into a standard triangulation language (STL) format, which represents a 3D surface of an assembly of planar triangles containing the coordinates of their vertices. Conversion to an STL file format has been adopted as a standard for consistency, with most CAD software using this file format for saving the model.
3. The STL file is prepared for the building process. The STL file is sliced into 2D cross-sections according to the geometry of the CAD model and the required build orientation. Each AM machine has its own proprietary slicing software. The program may also generate an auxiliary support structure for the object.
4. The 2D slice section of the model is built up layer by layer until the part is completed.
5. Removal and finishing are achieved by removing the object from the machine, cleaning it, removing any auxiliary support structure, and polishing and painting it.

The steps involved in AM technologies are illustrated in Figure 1.



**Figure 1.** Five main steps for the additive manufacturing technique (Yin et al., 2018).

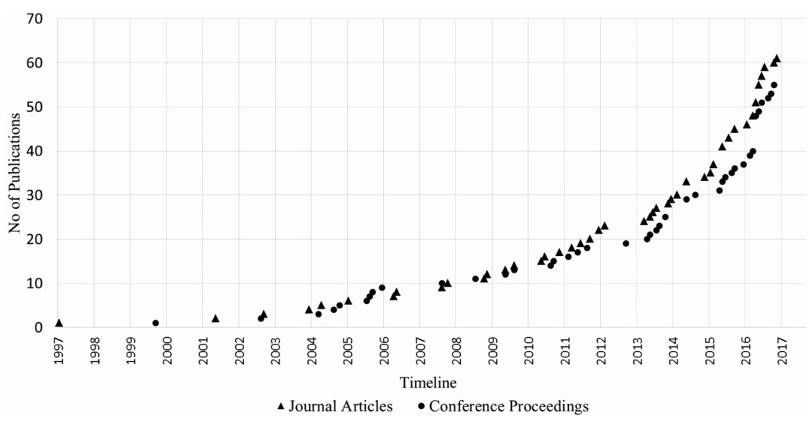
# The Growth of 3D Printing Research and Publications

Over the past 20 years, several companies and institutions around the globe have studied and developed large-scale AM to accommodate architecture’s needs, as described in Table 1.

**Table 1: Large scale 3D printers developed for construction (Keating et al., 2017)**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **3D printer name** | **Developer** | **Fabrication process** | **System fabrication** | **System mobility** | **Fabrication place** |
| Apis Cor | Apis Cor | Concrete extrusion | Arm | Static | Onsite |
| DCP | Mediated Matter—MIT | Spray foam | Arm | Mobile | Onsite |
| Contour Crafting | Southern California University | Concrete extrusion | Gantry | Static | Onsite |
| 3DCP | Eindhoven University of Technology | Concrete extrusion | Gantry | Static | Offsite |
| In-Situ Fabricator | ETH Zurich | Brick assembly | Arm | Mobile | Onsite |
| Minibuilders | Institute for Advanced Architecture of Catalonia (IAAC) | Polymer artificial marble | Swarm | Swarm of robots | Onsite |
| Concrete Printing | Loughborough University | Concrete extrusion | Gantry | Static | Offsite |

Today, the field is developing so rapidly that any research on existing techniques and examples is out-of-date almost upon publication. Research, including journal articles and conferences (see Figure 2) on the use of 3D printing in the architecture and construction (A&C) industry grew exponentially between 1997 and 2016. The United States and the United Kingdom contribute about 49% of the publications in the field, with most of these coming from the University of Southern California, Loughborough University, and the Massachusetts Institute of Technology. The increased research during these years is strongly linked to the gradual expiration of 3D printing key patent and trade secret protection between 2004 and 2015, mostly in the United States. These expired key patents have served as the basis for developing open-source 3D printing and collaborative innovation. RepRap, created in 2005 by Adrian Bowyer in the United Kingdom, was one of the first low-cost 3D printers. RepRap was designed to create an open-source 3D printer that could print its own components, thereby essentially reproducing itself. The ensuing 3D printer development was so dramatic that President Obama even mentioned it in his 2013 State of the Union Address. The next year, his administration pumped $500 million into 3D printing, given impetus to even more extensive research (Stein, 2017). Additionally, as computer, information and communication technologies and internet broadband increasingly penetrated our lives, it became easier to create worldwide developer communities. Furthermore, with time, hardware components for developing and producing open-source 3D printers have become cheaper and easier to use (Bechtold, 2015; Tay et al., 2017).



**Figure 2.** Increase in the publication of relevant articles over the years (Tay et al., 2017).

Currently, there are three primary large-scale processes in the public domain aimed at the A&C field: Contour Crafting, an onsite extrusion process mixing polymer, ceramic, cement, and other materials to build large-scale objects with smooth surfaces, developed by Dr. Behrokh Khoshnevis; Concrete Printing, an offsite process that extrudes cement mortar with a lower deposition resolution, developed by Loughborough University; and D-shape, based on binder jetting, where a binder is selectively deposited on each layer of powder material (mixed sand and magnesium-based cement), invented by Enrico Dini. All three methods have been used successfully to manufacture components of significant size, and all are suitable for A&C applications. The crane-mounted deposition head of all of these printers consists of the frame and robot (Evans & Campbell, 2003; Lim et al., 2012).

# Application of 3D Printing for Architecture

Several 3D-printed building projects have already been undertaken. In 2014, construction began in the Netherlands on the world's first 3D-printed canal house. For this project, the Ultimaker company created a 3D printer, KamerMaker, meaning “room maker,” for full-scale printing. Somewhat later in 2014, a man from Minnesota successfully erected a 12-foot-high 3D-printed castle. This was followed by the then tallest 3D-printed building – a five-story apartment block in China – constructed by WinSun China in 2015. The next milestone came in 2016, with a 3D-printed office in Dubai, UAE (Micallef, 2015). Figure 3 shows some noteworthy examples of 3D printed projects in the A&C field.

|  |  |  |
| --- | --- | --- |
| a | b | c |
|  |  |  |
| d | e | f |
|  |  |  |

**Figure 3.** Noteworthy examples of 3D printed application for A&C: (a) five-story apartment building in China; (b) two-story villa in China; (c) Gensler “office of the future” in Dubai (Yin et al., 2018); (d) Lewis Grand Hotel in the Philippines; (e) Apis Cor in Russia;; and (f) the Canal house, Netherlands. See descriptions of each project in the text.

Notes for each building in Figure 3:

(a) Five-story apartment (1100 m2) building in Jiangsu Province, China, 2015. Construction: WinSun China, constructed using Contour Crafting with component assemblies. This structure was built with a new material consisting of a combination of construction waste and additives, such as fiberglass and asphalt (Ma et al., 2017).

(b) Two-story villa in China, 2016. Construction: HuaShang Tengda. This building was printed entirely onsite using a unique process whereby the construction team first erected the structure’s frame, complete with rebar support and plumbing, and then printed over it with their massive 3D printer, which works with any cementing material.

(c) “Office of the Future” (240 m2), office building in Dubai, United Arab Emirates, 2016. Architect: Gensler. This project was built offsite using Contour Crafting with component assemblies. The parts were printed in China and then shipped and assembled in Dubai, using a new hybrid material containing concrete and fiberglass (El Sayegh et al., 2020).

(d) The world’s first 3D-printed hotel suite north of Manila, Philippines, 2015. Architect: Lewis Yakich, owner of the hotel and a materials science engineer. This addition to an already existing hotel is the world’s first 3D-printed operational commercial structure to receive official approval. The materials used in the 3D printing process created a structure stronger than one built with conventional construction methods employing hollow block. The printing process had to be stopped several times to allow the construction team to install plumbing, wiring, and rebars.

(e) Apis Cor single-family house (38 m2), in Stupino, outside Moscow, Russia, 2016. Architect: Apis Cor & PIK. Their 3D printer is unique for its mobility and automatic mix and supply unit, as well as its built-in automatic horizon alignment and stabilization system. The printer’s 3D printing process, suitable for both indoor and outdoor construction, can clearly cope with adverse weather conditions, as the project was built using concrete ink during Russia’s coldest season (−35°C). To provide structure for the house, Apis Cor placed horizontal fiberglass reinforcements in the walls. These, coupled with the specific flat roof design, enables the house to withstand heavy snowfalls.

(f) The 3D-printed Canal House, Netherlands, 2014. This project, intended for tourism and sightseeing, was the result of a “Research & Design by Doing” project investigating the use of printing techniques in architecture. A large, 6-meter high 3D printer installed in a shipping container used a new kind of plastic made from recycling microfiber and vegetable oil to print components assembled directly onsite after printing. Alternatively, hollow forms filled with concrete can be used for load-bearing purposes (Teizer et al., 2018).

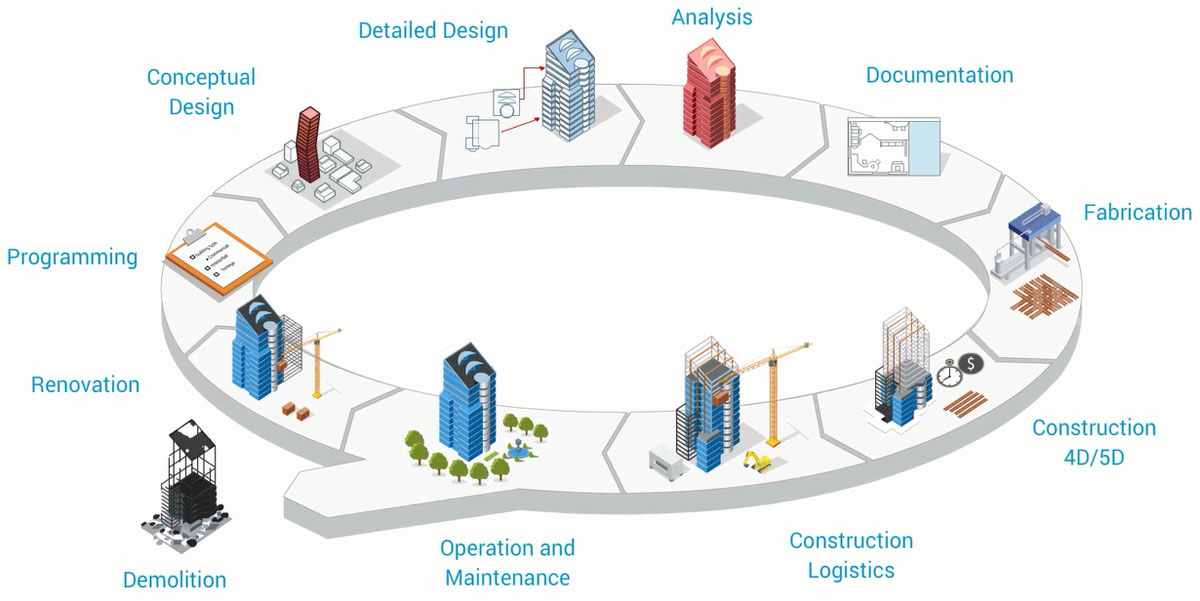
# BIM-based 3D Printing for the Life Cycle of Sustainable Buildings

The U.S. National Building Information Modeling Standard deﬁnes BIM as follows (Borrmann et al., 2018):

Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; deﬁned as existing from earliest conception to demolition. A basic premise of BIM is a collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reﬂect the roles of that stakeholder.

BIM involves consistent and continuous use of digital information across the entire life cycle of a built facility, including its conceptual, design, construction, and operational stages. BIM helps increase productivity by providing a large amount of precise information and reducing the overall process time, while lowering error rates, as mistakes can be detected and resolved before becoming serious problems (Mahamood et al., 2014).

BIM uses 3D and real-time dynamic building modeling software designed to enhance interorganizational collaboration in the construction industry, increase productivity, improve design and construction, and protect the natural environment, specifically in the design, planning, and construction processes, as illustrated in Figure 4 (Wong & Hernandez, 2012; Yin et al., 2018).



**Figure 4**.The concept of building information modeling relies on digital information across the entire life cycle of a built facility (Josseaux, 2018).

Among the numerous tools available for design, analysis, checking, display, and reporting that can contribute to BIM in construction are Revit, Bentley Systems, ArchiCAD, Rhinoceros Grasshopper, Solidworks, Ecotect, and Tekla Structures.

[Fig 5 near here]

BIM incorporates building information for sustainable building that ranges from geometry, spatial relationships, energy performance analysis, carbon emission analysis, solar radiation, lighting analysis, natural ventilation system optimization, water usage analysis, and acoustic analysis, to thermal and comfort analyses. These features enable designers and engineers to monitor relationships between building components and their respective construction and maintenance details. While the benefits of BIM are implicitly understood by designers, they could become explicit to other project stakeholders, such as owners, contractors, subcontractors, fit-out companies, municipalities and more (Ghaffarianhoseini et al., 2017; Lu et al., 2017).

The BIM approach dramatically improves the coordination of the design activities, the integration of simulations, the setup and control of the construction process, and the handover of building information to the operator. By reducing the manual re-entering of data to a minimum and enabling the subsequent reuse of digital information, laborious and error-prone work is minimized, resulting in increased productivity and quality in construction projects (Borrmann et al., 2018)**.**

**Table 2: BIM-supported life cycles of sustainable projects**

|  |  |  |  |
| --- | --- | --- | --- |
| Concept | Design | Construction | Operation |
| Calculating cost estimation under budget | Clash detection between partial model | Determine costs for the contractors | Well-organized handover to the owner |
| Helping to minimize construction waste | Identify conflicts between the design disciplines at an early stage | Increasing the productivity in aspects of carbon emission, resource consumption, and life cycle cost | Monitoring sustainability performance |
|  | Sustainability analysis | Waste reduction |  |
|  | Comparison of different design options | Increasing the quality |  |
|  | Ensure building delivered is functional, sustainable, operational, safe, and secure |  |  |
|  | Faster cost estimation |  |  |

## BIM at the Conceptual Stage of Sustainable Buildings

At this earliest conceptual stage, a conceptual building model can be created incorporating cost information to help developers determine whether a building of a given size, quality, and desired requirements can be built within a specified cost and time budget (Yin et al., 2018). Applying BIM methods at the concept and design stages can potentially contribute to reducing construction waste. In fact, various BIM-based estimation systems for construction waste, which extract and process the component information of each building element in a BIM model, have already signiﬁcantly improved waste estimation and planning in a number of projects (Ghaffarianhoseini et al., 2017).

## BIM at the Design Stage of Sustainable Buildings

The majority of sustainable BIM applications are designed for building performance analyses and simulations (Fadeyi, 2017; Lu et al., 2017). Since projects using BIM tools are visualized at an early stage, owners are given a clear idea of design intent, enabling them to easily make alterations to effectively meet client requirements (Ghaffarianhoseini et al*.*, 2017).

One of the most significant advantages of using BIM is that most of the technical drawings, such as horizontal and vertical sections, are generated directly from the model. In this way, inconsistencies between different partial models can be identified, and conflicts between the design demands of the different fields involved in building can be resolved at an early stage (Borrmann et al., 2018). BIM allows for multidisciplinary information to be superimposed on the 3D model, so that a sustainability analysis can be incorporated throughout the design process. This feature also facilitates accurate comparisons of different design options, which results in the development of more efficient, cost-effective, and sustainable solutions. The primary goal at the design stage is to ensure that the building will be functional, sustainable, operational, safe, and secured. Using these BIM applications, architects and engineers can more eﬀectively share a wide range of simulations related to sustainability, including structural analysis, building performance simulation, evacuation simulation, or lightning analysis, daylighting and energy consumption. Thus, the sustainability analysis can be seamlessly integrated into the design process.

## BIM at the Construction Stage of Sustainable Buildings

The digital building model makes it possible to determine the services required and the contractor’s costs when preparing a bid, and facilitates precise billing at a later stage (Teizer et al., 2018, p. 421). Productivity is the amount of generated construction output from a set of inputs (e.g., materials, electricity, HVAC, labor, and equipment) used at a particular period. At the construction stage, productivity is essential and has a major impact on the environment in terms of carbon emissions, resource consumption, and life cycle costs. By improving productivity and helping to reduce waste, BIM-based printing contributes to sustainable construction (Fadeyi, 2017; Lu et al., 2017).

## BIM at the Operations Stage of Sustainable Buildings

The well-organized handover of all BIM information (e.g., room sizes, HVAC, electricity, telecommunication) to the owner is critical, including all relevant information from the design and construction phases (Teizer et al., 2018, p. 421). Monitoring buildings’ sustainability performance in the operation phase could verify the actual performance compared with the targets set in the design phase. Nevertheless, BIM use during the operation stage is still limited, primarily due to lack of awareness about the benefits of using sustainable BIM for operation management (Lu et al., 2017).

# Discussion

While 3D printing is an emerging ﬁeld in construction, the speciﬁc application of BIM for 3D printing is still in its infancy. With BIM’s usefulness of BIM being increasing recognized in the A&C industry, there is a pressing need to forge an up-to-date synthesis of the nexus between BIM and 3D printing for green buildings (Lu et al., 2017). BIM creates a comprehensive digital representation of a built facility containing a great depth of information about the 3D geometry of the building components and nonphysical objects, such as spaces and zones, at a deﬁned level of detail. It also includes a hierarchical project structure, and schedules. Objects are typically associated with a well-deﬁned set of semantic information, such as the component type, materials, technical properties, or costs, and the relationships between the components and other physical or logical entities. The term building information modeling (BIM) thus describes both the process of creating such digital building models and the process of maintaining, using, and exchanging them throughout the lifetime of the facility (Borrmann et al., 2018).

The construction industry has traditionally been criticized for lack of collaboration and innovation in its execution process. BIM, serving as the base for integrating automation applications such as 3D printing in the building printing process (Mahamood et al., 2014), appears to provide a viable solution to these issues. Most practitioners engaging in BIM-based sustainability analysis, typically at the planning and design stages, are architects and contractors, who usually use energy, daylighting and solar, building orientation, massing, and site analyses (Azhar & Brown, 2009). It is suggested that using BIM throughout the building life cycle, from the early conceptual design stages to demolition, is advantageous in terms of cost, sustainability and more. BIM is gradually becoming ubiquitous for generating and managing essential building design and project data in a digital format (Kazemian et al., 2017).

However, the use of BIM for 3D printing is still not widespread, and more research is needed to bridge the gaps between BIM and 3D printing. Interest in 3D printing for the A&C industry has increased dramatically in recent years, thereby enriching the literature in this discipline. However, research remains to be done, such as focusing on improving the design process. To date, most structures constructed by 3D printing have been rectilinear, solid, and designed on the basis of familiar shapes rather than being customizable. Innovative design methods using complex geometries could open up unexplored architectural possibilities, with topology optimization (TO) applied to BIM and 3D printing to generate optimal designs (Vantyghem et al., 2019). Other future research could focus on developing large-scale 3D printers that operate autonomously in various environmental conditions, are adaptable to a wide range of projects, and offer easy assembly (Yin et al., 2018).

Full-scale 3D printing for buildings presents challenges regarding materials. A printer has been have adapted at the research level to address this problem, but its use is still limited to experimentation and it is not yet ready for practical application. Large-scale 3D printing for building would represent a revolution in the construction industry, with a well-developed automated construction process offering numerous advantages, including design freedom, superior construction speed, and greater customization (Wong & Hernandez, 2012). Before AM can realize its full potential in construction, extensive research and experimental data are still needed, as are new materials (including multi-materials), new processes, faster printing, improved printing quality, optimized topologies, and data on mechanical properties (Sakin & Kiroglu, 2017, pp. 702–711).

The future success of 3D printing in the A&C industry will depend on fine-tuning materials to the specific needs of each application (Wong & Hernandez, 2012). Moreover, the integration of the BIM method with 3D printing modeling will be effective for energy efficiency, better design, cost reduction, and base isolation. BIM-based 3D printing technology may be able to revolutionize the construction industry (Sakin & Kiroglu, 2017). The real challenge is creating the right models and optimally applying the right software tools that are already in use in the A&C field, such as Autodesk Revit and BIM 360, Graphisoft, Archicad, Tekla, and Grasshopper.

The implementation of BIM technology profoundly changes the way architects and engineers work and drives the digital evolution of the A&C industry (Borrmann et al., 2018). BIM in the A&C industry could become the standard method. Just as 3D printing is considered a game-changer for the industry, BIM-based 3D printing could also be a revolutionizing method offering obvious benefits and substantial savings in cost, and creating more sustainable building (Tay et al., 2017). In the context of sustainability, future work also needs to be dedicated to green infrastructure and the use of BIM in its delivery and performance requirements**.** To promote sustainability, it would be useful to investigate how BIM could reinforce the integration of economic and social sustainability metrics into construction phases and related domains, with the inclusion of lean principles that could result in a more seamless construction delivery process (Raouf & Al-ghamdi, 2019).

The construction industry plays a vital role in today’s world. Everything around us, such as infrastructure and buildings, is designed and created by construction companies, whose decisions have significant implications for society. However, construction companies are often referred to as late adopters of new technologies and have been shown to lag behind other industries when it comes to implementing innovative technologies (Sköld & Vidarsson, 2015). Further research could help them adopt less costly and more sustainable construction options.

# Conclusion

This paper examines sustainable A&C in terms of BIM-based 3D printing integration throughout the entire project life cycle of sustainable buildings. BIM is the synchronizing equipment for 3D printing technologies, yet this advancement is not used by all those involved in the A&C field industry. Using BIM-based 3D printing can improve the design details and accuracy of the designed buildings and generate specifications for accurate fabrication. BIM entails speeding up collaboration and improving feedback between the professionals involved in the building life cycle. Ideally, the design process should be linear, with each discipline involved receiving a complete design from the previous stage (as shown in Fig.4), but currently, this process is not effective. New virtual optimization tools, like TO and available simulation tools for a visualized building performance analysis (Grasshopper, Ecotect, Blender, etc.) in the planning phase, and BIM as an assessment tool for constructed building elements, will make BIM necessary and more effective with feedback loops between the different phases in different directions. To maximize the effectiveness of simulation tools in the design process, there must be a seamless way to shift from BIM to simulation tools and back to BIM. The integration of BIM with optimization tools will result in more standardization and automated fabrication in the A&C domains. The penetration of BIM in the A&C virtual world creates hybridization of technological tools and new multidisciplinary fields of study, such as software engineering, mathematics, and material science. The role of today's advanced technologies must be considered when designing an optimal digital architecture culture that takes environmental impacts into account. In the future, more research is needed to explore the environmental contribution of hybrid architecture in constructing sustainable buildings, and this requires more consideration of design optimization and architectural simulation from a methodological perspective. Realizing these future objectives of architecture will lead to a digital revolution and a change in architecture as we now know it in terms of optimized building appearance and sustainable structures that reduce materials while complying structurally, each of which represents a different but equally important aspect of the process.

Finally, BIM technology can be the missing component for making 3D printing a disruptive technology. BIM-based 3D printing has the potential to become the leading technology of the A&C industry. The more BIM-based 3D printing is used, the more benefits that can be obtained. While it is hard to imagine that 3D printing can replace traditional construction in the next few years, it is conceivable that BIM-based 3D printing technologies will have a growing presence in the industry (Sakin & Kiroglu, 2017).

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