PERSPECTIVES ON A BIM-BASED 3D PRINTING FOR SUSTAINABLE BUILDINGS

Orly Tal-Yosef

**Abstract**

3D Printing which also called AM (additive manufacture), is a method of printing a structure layer-by-layer fabrication directly from a 3D digital design model. 3D printing technology is a new automated manufacturing process that can build complex shapes and may be able to revolutionize the construction industry. 3D printing concludes three main techniques: a. Contour Crafting- An extrusion process of polymer, ceramic, cement, and a variety of other materials and mixes to build onsite large scale objects with a smooth surface finish. b. Concrete Printing is also based on the extrusion of cement mortar, but has a smaller resolution of deposition and is printed offsite, c. D-Shape- Offsite process based on binder jetting (bj), where a binder is selectively deposited on each layer of powder material (mixed sand and magnesium-based cement). 3D printing is considered a disruptive technology process which is an innovation that creates a new market and value network and eventually disrupts an existing established market. Building Information Modeling (BIM) method is a pivotal piece in the success of 3D printing in construction to maintain safety and productivity in large scale digital process since BIM is a comprehensive management approach which covers the complete life cycle of the A&C process such as architectural planning, geometrical data, scheduling, material, equipment, resource and manufacturing data, and post-construction facility management. Integration of BIM with 3D printing technique for A&C industry is a combination of complementary technologies that have the potential to be an ecological architecture process of the environment by reducing waste and energy efficiency and decreasing of injuries and fatalities on construction sites, while increasing the quality and productivity of the final product. This paper presents the new technology of a BIM-based 3D printing of buildings for the sustainable buildings of the future. A BIM-based 3D printing of sustainable buildings is a promising method that has the potential to revolutionize the construction industry regarding sustainable environment but despite the benefits of 3D Printing technology regarding the traditional technology, it is still part of research effort and there many challenges technical and the material level.

**Keywords**: Additive manufacturing (AM), Building information modeling (BIM), 3D printing, Architecture and construction (A&C)

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### 1. Introduction

The construction industry has traditionally relied on specifications and two-dimensional (2D) drawings to convey material properties, performance details, and locational information – using small-scale models to create the object for evaluation as part of the design process. Increasingly, specifications and 2D drawings are being replaced by 3D modeling in the virtual environment of building information modeling (BIM). An alternative to 3D modeling is the use of advanced 3D solid modeling techniques in combination with digital fabrication methods. In the digital fabrication process, the 3D objects are ‘sliced' and represented as a series of 2D layers, with layer-based methods sequentially adding each layer to build up the desired object. It is the selectivity and control of the material that enables the freedom to build any desired geometry, which is the fundamental advantage of these processes over conventional techniques.

One of the most important points of development of 3D Printer relates to Charles(Chuck) Hull who invented the first 3D printed form by stereolithography 3D printer in 1983. Charles Hull was the first successful contender to patent Stereolithography (SLA) in 1984. His invention was a milestone for the 3D printing world

(Mitchell, Lafont, Ho, & Semprimoschnig, 2018).

Since the 1990s, technologies have been developed to manufacture solid objects through robotized deposition in stone-like materials without molds, on a scale that is relevant to buildings. A variety of deposition strategies, robots, printer heads, and materials have been used (Bos *et al*., 2016). All 3D printing processes require software, hardware, and materials to work together.

In 3D Printing concrete is extruded through a nozzle in the print head, to build structural components layer upon layer without need of formwork (Wong & Hernandez, 2012). By applying the BIM method with 3D Printing, much more profound use of computer technology in the design, engineering, construction, and operation of built facilities is realized (Andre Borrmann, Koch, & Beetz, 2018). Building Information Modeling is based on the idea of the continuous use of digital building models throughout the entire lifecycle of a built facility, starting from the early conceptual design and detailed design phases, to the construction phase, and the long phase of operation *(* Borrmann *et al*., 2018).

## 2. The computational process of a BIM-based 3D Printing

An additive manufacturing technique has five main steps as (Mahamood *et al*., 2014):

i) A 3D model design is created in different software (AutoCAD, Unigraphics, Revit, Rhino, 3D Studio, CATIA, and SolidWorks) or by scanning the object.

(ii) Conversion of the CAD data into a standard triangulation language (STL) format. STL format represents a 3D surface of an assembly of planar triangles containing the coordinates of their vertices. Conversion to STL file format has been adopted as a standard for consistency. Most CAD software has this file format in which the model can be saved.

(iii) Preparation of the STL file for the building process. The STL file is sliced into a two-dimensional (2D) cross-section profile according to the geometry of the CAD model and the required build orientation. Each AM machine has its proprietary software; namely slicing software. The program may also generate an auxiliary support structure for the object.

(iv) 2D slice section of the model layer by layer until the part is completed.

(v) Removal and finishing are achieved by removing the object from the machine and cleaning it, removing any auxiliary support structure, and finalize with polishing and painting.

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

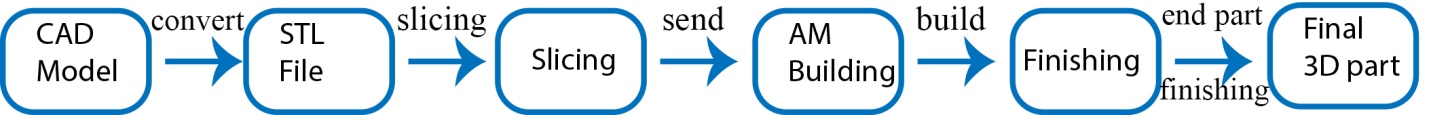


Figure 1.Five main steps for additive manufacturing technique (Yin *et al*., 2018)

### 3. The Growth of 3D Printing research and publication

Over the last 20 years, there were some entities from different places in the world that explore and develop large-scale additive manufacturing to accommodate the need for architecture as described in Table 1.

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

Table 1. Large scale 3D Printers developed for construction (Keating, Leland, Cai, & Oxman, 2017)

Nowadays, developments are going so fast that any research on existing techniques and examples is out-of-date almost as soon as it is published. The journey of 3D printing and the achieved milestones for example are the World's first 3D printed canal house in 2014 begins construction and a 3D printer called KamerMaker was invented for full-scale printing in the Netherlands. In 2015, Winsun builds the first 3D-printed tallest residence (five-story apartment block) in China and a 3D printed castle was built in Minnesota, USA and in 2016 a 3D printed office room emerged in Dubai, UAE (Micallef, 2015). Research interest in employing 3D Printing in the A&C industry has exponential growth between the years 1997-2016, including journal articles and conferences (as shown in Figure 2). USA and UK contribute about 49% of the total publications in the field mostly from the University of Southern California, Loughborough University, and Massachusetts Institute of Technology. The rise of the publication during these years is strongly linked to the expiration of 3D Printing key patents protection and trade secret protection, mostly in the USA, between the years 2004-2015 gradually. Once the relevant patents had expired, open source 3D Printing community and collaborative innovation were based on the expired key patents. RepRap was the first of the low-cost 3D printers made by Adrian Bowyer. RepRap was conceived to create an open-source 3D printer that would reproduce itself. Besides, In February 2013 president Obama mentions 3D Printing in his State of the Union address, and a year later the administration pumps $500 million into 3D Printing which leads to a flourishing of research groups (Stein & Stein, 2017). Furthermore, as computer and Information and communication technologies (ICT) and Internet broadband penetration increased around the globe, creating worldwide developer communities became easier and hardware components that are used in the development and production of open source 3D printers have become cheaper and easier to use over the years (Bechtold, 2015). (Tay et al., 2017).

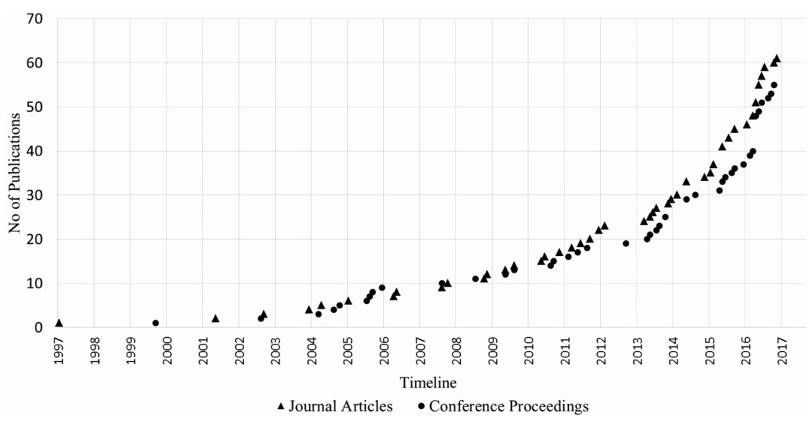


Figure 2. Increase in the publication of articles over the years (Tay et al., 2017)

3D printing for the A&C fields is a new manufacturing technique that started with the invention of the 3D printer. Currently, in the A&C field, there are three primary large-scale processes targeted at construction and architecture in the public domain, namely: Contour CraftingTM was developed by Dr. Behrokh Khoshnevis, D-shape was invented by Enrico Dini and Concrete PrintingTM developed by Loughborough University. All three methods have proven the successful manufacturing of components with significant size and all are suitable for construction or architectural applications. The deposition head mounting is the frame, robot, or crane mounted (Evans & Ian Campbell, 2003) (Lim *et al*., 2012).

### 4. Application of 3D printing for Architecture

There are several 3D printing building projects. Here are some Noteworthy examples of 3D printed projects in A&C fields (Figure 3):

|  |  |  |
| --- | --- | --- |
| 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 55 (f) The Canal hose, Netherlands.

a) Five-story apartment (1100 m2) building in Province Jiangsu, China, 2015. Structure Architect: Winsun. This project was built for dwelling purposes by Contour Crafting with component assemblies. It was built with a new material that includes a combination of construction waste and additives such as and fiberglass and asphalt (Ma, Wang, & Ju, 2017).

b) Two-story Villa in China, 2016. Structure Architect: Hua Shang Tengda. It was printed entirely on-site in a unique process. The team first erects the frame of the house, complete with rebar support and plumbing pipes, and then prints over it with their gigantic 3D printer. The 3D printer works with any cementing material.

c) “Office of the Future” (240 m2), Gensler building in Dubai, United Arab Emirates, 2016. Structure Architect: Gensler. This project was built off-site for workplace purposes by Contour Crafting with component assemblies. The parts were printed in China and then shipped and assembled in Dubai. The material used is a new hybrid material that includes concrete and fiberglass (Sayegh & Manjikian, 2020).

d) World’s first 3D printed hotel suite in North of Manila, Philippines, 2015. Structure Architect: Lewis Yakich, owner of the hotel and material science engineer. This is the first fully permitted 3D printed operational commercial building in the world. This is an expansion of an existing hotel. It is stronger than the current construction methods of the hollow block. During the process they have to stop several times to install plumbing, wiring, and rebars.

e) Apis Cor in Stupino town (38 m2), Moscow, Russia, 2016. Structure Architect: ApisCor & PIK. Their 3D Printer is unique for his mobility and automatic mix and supply unit and his built-in automatic horizon alignment and stabilization system. The printer can execute the printing process of construction both inside and outside. The project was built concrete ink at the coldest time of the year in Russia (-35°C) so the machine can cope with adverse weather conditions. To provide structure to the house, Apis Cor placed horizontal fiberglass reinforcements in the walls. Coupled with the specific flat roof design means the house can handle heavy snowfall.

f) The 3D Print Canal House, Netherlands, 2014. This project, for tourism and sightseeing, investigates the use of printing techniques in the field of architecture. In this project, a large 3D Printer was installed in a container using new kind plastic made from recycling microfiber and vegetable oil. After being printed, the elements were assembled directly. Alternatively, hollow forms filled with concrete can be used for load-bearing purposes (Teizer et al., 2018)

## 5. The BIM-based 3D printing for the lifecycle of sustainable buildings

Building Information Modeling (BIM) uses three-dimensional (3D) and real-time dynamic building modeling software aiming to enhance inter-organizational working collaboration in the construction industry, that will increase productivity whilst improving design and construction and protects the natural environment specifically in the design, planning and construction processes as illustrated in Figure 4 (Wong & Hernandez, 2012),(Yin et al., 2018).

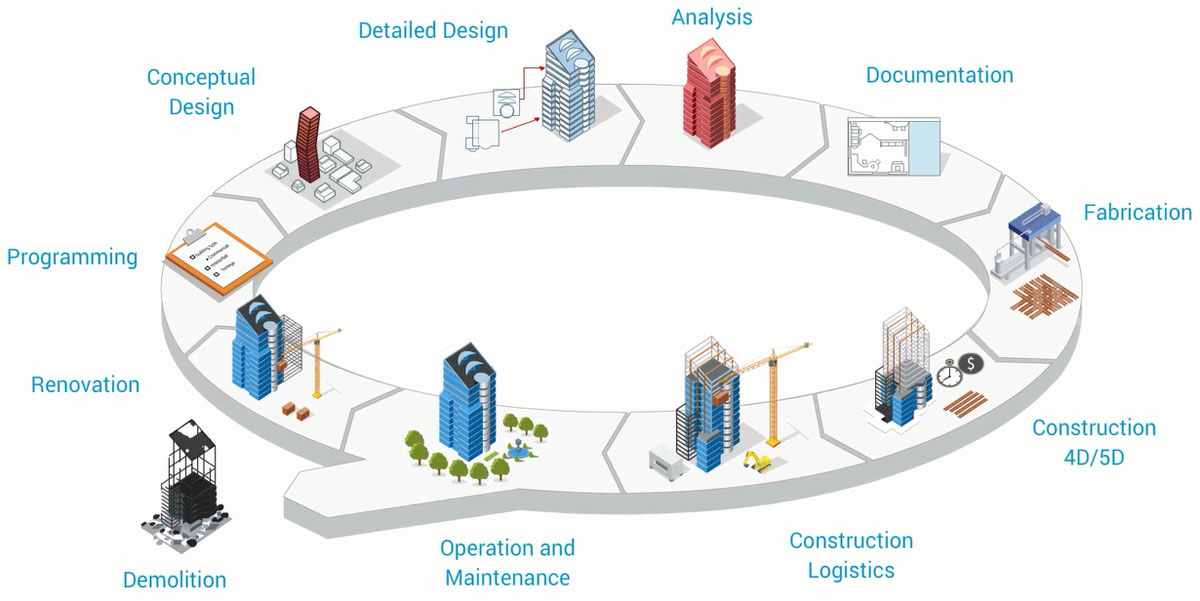


Figure 4.The concept of Building Information Modeling relies on digital information across the entire lifecycle of a built facility (Josseaux, n.d., 2018).

There are many tools for design, analysis, checking, display, and reporting that can contribute to BIM of a building such as Revit, Bentley Systems, ArchiCAD, Rhinoceros Grasshopper Solidworks, Ecotect, Tekla Structures, etc. Many information components and information types are needed to fully design, develop, and construct a building (Elmualim & Gilder, 2014).

BIM represents the consistent and continuous use of digital information across the entire life cycle of a built facility, including its conceptual, design, construction, and operation stages (as illustrated in Figure 5). BIM helps to raise productivity by providing a high amount of precise information and by reducing the overall process time while lowering error rates as mistakes can be detected and resolved before they become serious problems (Mahamood *et al*,2014).

BIM incorporates building information for sustainable buildings ranging from geometry, spatial relationships, energy performance analysis, carbon emission analysis, solar radiation, and lighting analysis, natural ventilation system optimization, water usage analysis, Acoustic analysis, and thermal and comfort analysis. These features, in turn, allow designers and engineers to keep track of relationships between building components and their respective construction-maintenance details. Whilst the benefits of BIM are implicitly understood by the designer, they could become explicit to other project stakeholders such as owners, contractors, subcontractors, fit-out companies, council, etc. (Ghaffarianhoseini et al., 2017) (Lu, Wu, Chang, & Li, 2017).

This approach dramatically improves the coordination of the design activities, the integration of simulations, the setup and control of the construction process, as well as the handover of building information to the operator. By reducing the manual re-entering of data to a minimum and enabling the consequent re-use of digital information, laborious and error-prone work is avoided, which in turn increases productivity and quality in construction projects (Andre Borrmann et al., 2018)**.**

|  |  |  |  |
| --- | --- | --- | --- |
| Conceptual | Design | construction | operation |
| - Calculating cost  estimation under  budget | **-clash detection**  **between partial**  **model** | **-Determine the 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 functional,**  **sustainable and**  **operational, safe and**  **secured** |  |  |
|  | **-Faster cost estimation** |  |  |

Table 2. BIM-supported life cycles of sustainable projects

The US National Building Information Modeling Standard deﬁnes BIM as follows (NIBS, 2012): "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." (Borrmann *et al*., 2018).

### 5.1 BIM at the Conceptual Stage of sustainable buildings

At this stage, a conceptual building model can be created with cost information to help developers in determining whether a building of a given size, quality level and desired requirements can be built within a given cost and time budget (Yin et al., 2018). BIM also has great potential in helping to minimize construction waste especially at the concept and design stages. For example, various BIM-based estimation systems of construction waste, which extract and process the component information of each building element in a BIM model, have signiﬁcantly improved waste estimation and planning (Ghaffarianhoseini *et al*., 2017).

### 5.2 BIM at the Design Stage of sustainable buildings

One of the most significant advantages of using BIM is that most of the technical drawings, such as horizontal and vertical sections, are derived directly from the model so clash detection between the different partial models are identified and conflicts between the design disciplines at an early stage are resolved (Andre Borrmann et al., 2018). BIM allows for multi-disciplinary information to be superimposed on the 3D model, which creates an opportunity for sustainability analysis to be incorporated throughout the design process as well as it enables accurate comparison of different design options, which enables the development of more efficient, cost-effective and sustainable solutions. The primary goal at the design stage is to ensure building delivered functional, sustainable, and operational, safe, and secured. With the aid of 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, and thus the sustainability analysis can be seamlessly integrated into the design process. The majority of sustainable BIM applications are designed for building performance analyses and simulations (Lu *et al*., 2017) (Fadeyi, 2017). Since projects utilizing BIM tools are visualized at an early stage, owners are given a clear idea of design intent facilitating easy alterations to meet the client requirements effectively (Ghaffarianhoseini *et al.*, 2017).

### 5.3 BIM at the Construction Stage of sustainable buildings

Providing the digital building model makes it possible to determine the services required and costs for the contractors when preparing the bid and also 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 this stage, the productivity is very essential and has a major impact on the environment in aspects of carbon emission, resource consumption, and life cycle cost. BIM-based 3D printing provides improving productivity and contributes to waste reduction which is critical for sustainable construction (Lu *et al*., 2017) (Fadeyi, 2017).

### 5.4 BIM at the Operation Stage of sustainable buildings

A critical prerequisite is the well-organized handover of All BIM information (as (room sizes, HVAC, electricity, and telecommunication), from the design stage to the owner, including all relevant information from the construction phase (Teizer *et al.*, 2018, p.421). Monitoring the sustainability performance of buildings in the operation phase could verify the actual performance compared with the targets set in the design phase. However, the use of BIM during the operation stage is still limited mostly because lack of awareness about the benefits brought by using sustainable BIM for operation management (Lu *et al*., 2017).

# 6. Discussion

While 3D printing is an emerging ﬁeld in construction, the speciﬁc application of BIM for 3D printing is still in its infancy. As the usefulness of BIM has been widely recognized in the A&C industry, there is an urgent need to establish an up-to-date synthesis on the nexus between BIM and 3D Printing for green buildings (Lu et al., 2017). A Building Information Model is a comprehensive digital representation of a built facility with great information depth. It typically includes the three-dimensional geometry of the building components at a deﬁned level of detail. Besides, it also comprises non-physical objects, such as spaces and zones, a hierarchical project structure, or schedules. Objects are typically associated with a well-deﬁned set of semantic information, such as the component type, materials, technical properties, or costs, as well as the relationships between the components and other physical or logical entities. The term Building Information Modeling (BIM) consequently describes both the process of creating such digital building models as well as the process of maintaining, using, and exchanging them throughout the entire lifetime of the built facility (Andre Borrmann et al., 2018).

The construction industry has always been criticized for lack of collaboration and innovation in its execution process and BIM has shown potential to be a viable solution for these issues. BIM is serving as the base for integration of automation applications such a 3D printing in the building printing process (Mahamood *et al*,2014). The majorities of practitioners who are employing BIM-based sustainability analysis are primarily architects and contractors typically at the planning and design stages. The analysis types with the most prevalent use are energy analysis, daylighting and solar analysis, building orientation analysis, massing analysis, and site analysis (D & Mbc, 2009). The use of BIM is suggested to be advantageous throughout the building project life cycle from the early conceptual design stages to demolition. Building Information Modelling (BIM) is gradually becoming ubiquitous, in which the essential building design and project data are generated and managed in digital format (Kazemian, Yuan, Cochran, & Khoshnevis, 2017). Usage of BIM for 3D printing is still not practiced widely and more research on this topic is needed to bridge the gaps between BIM and 3D printing. The interest in 3D printing for the A&C industry has increased drastically, in recent years and enriched the literature in this discipline. However, there are still research developments to be done such as focusing on improving the design process. As to date, most examples made by 3D Printing have been rectilinear, solid, and their design based on familiar shapes more than customizable. Innovative design methods could open up unexplored architectural possibilities with complex geometries. Topology optimization (TO) can be involved with BIM and 3D printing to generate optimal designs (Vantyghem, Boel, & Corte, 2019). Another future research is to develop large scale 3D printers that operate autonomously in various environmental conditions that are adaptable to a wide range of projects, and that offer ease of assembly (Yin et al., 2018). Full-scale 3D printing for buildings presents us with difficulties regarding the material and even adapts the appropriate machine and is not yet ready for use, but only as research experiments. However, large-scale 3D printing in the building construction would be a revolution in the construction industry. A well-developed automated construction process presents numerous advantages including design freedom, superior construction speed, and a higher degree of customization (Wong & Hernandez, 2012). Extensive research and experimental data are still needed and also providing new materials including multi-materials, new processes, faster printing, printing quality, optimized topologies, and data on mechanical properties before AM can realize its full potential in construction (Sakin & Kiroglu, 2017, p. 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 BIM method with 3D printing modeling will be effective for energy efficiency, better design, cost reduction, and isolation of structure. BIM-based 3D printing technology may be able to revolutionize the construction industry(Sakin & Kiroglu, 2017). The real challenge is in creating the right models and 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, Grasshopper, etc., most beneficially. The implementation of BIM technology profoundly changes the way architects and engineers work and drive the digital evolution of the A&C industry (Koch, Beetz, Foundations, & Practice, 2018). BIM in the A&C industry could become the standard method for the industry. As 3D printing is also considered a game-changer for the industry, BIM-based 3D printing can be a method that can bring obvious benefits and substantial savings in cost, and therefore the result we get is a more sustainable building (Tay *et al*., 2017). Under the context of sustainability Future work also needs to be dedicated to green infrastructure and the use of BIM in their delivery and performance requirements**.** With regards to sustainable building challenges, a promising area is to investigate how BIM can reinforce the integration of economic and social sustainability metrics into these construction phases related domains, with the inclusion of lean principles that may result to a more seamless construction delivery process (Raouf & Al-ghamdi, 2019). The construction industry plays a vital role in the world we live in today. Everything around us such as infrastructure and buildings is designed and created by construction companies, making them a necessity in today's society. Construction companies are often referred to as late adopters of new technologies and have shown to lag behind other industries when it comes to implementing innovative technologies (Vidarsson, 2015).

# 7. Conclusion

This paper examines sustainable A&C in terms of BIM-Based with 3D Printing integration through the entire construction project life cycle of sustainable buildings in the A&C industry. BIM is the synchronizing equipment for all entities involved in the A&C field related to 3D printing technologies yet this advancement is not used in the industry. Using BIM-Based 3D Printing can improve the design details and accuracy of the designed buildings and generate specifications for accurate fabrication. BIM is about speeding collaboration and effective feedback between the professional involved in the building life cycle. The design process should ideally be linear, where each discipline receives a complete design from the previous (as shown in fig.4) but currently it is not done effectively. New optimization virtual tools like topology optimization and available simulation tools for a visualized building performance analysis (as Grasshopper, Ecotect, Blender) in the planning phase and Scan to BIM 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 on the design process there must be a seamless way to go from BIM to simulation tools back to BIM. The integration of BIM with optimization tools will result in more standardization and automation fabrication in the A&C domains. The penetration of BIM to the A&C virtual world creates hybridization of A&C with technological tools and a combination of new fields of study as Software engineering, Mathematic and material science. The role of today's advanced technologies must be taken into account for designing optimal digital architecture culture considering their environmental impacts. In the future, more research groups that explore the aspect of hybrid architecture to build sustainable construction. That requires more consideration from a methodological perspective: design optimization and architectural simulation. Realizing the objective of architecture will lead to the digital revolution and a change of the architecture as we know it today both in terms of optimized building appearance and sustainable structure that reduces material while complying structurally. Both aspects are important but highlight a different side of the process. Finally, BIM technology can be the missing component for 3D Printing for being 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 can be leveraged. It is hard to imagine so far that 3D printing could replace traditional construction in the next few years. It is more possible, that BIM-based 3D Printing technologies will be present in the industry (Sakin & Kiroglu, 2017).

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