A Proposal for Classification of Additive Manufacturing in Architecture

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The increasing pace of developments in computational design has caused a massive paradigm shift in contemporary architecture. While the power of the new computational tools allows the designers to design fluid and dynamic transformational forms replacing the rigid norms of current processes, it also accelerates the integration of design and making. Digital manufacturing and in particular Additive Manufacturing (AM) has shown to have a big impact on how designers think of complex mechanisms and geometries while designing. This article is motivated by the latest developments in Additive Manufacturing (AM) in large scale structures and the opportunities arising from manufacturing components, modules and even monolith buildings. This paper is part of a larger research on Additive Manufacturing (AM) and has evolved organically out of necessity while trying to map out the latest developments about large scale AM processes. The aim of this paper is to better understand and position the developments happening in the last decade therefore challenges on a number of diverse subjects through a proposed classification method.

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Mimaride Eklemeli Üretim Sistemlerinin Sınıflandırması için bir Öneri

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Dijital ve hesaplamalı tasarımdaki hızla sayısı artan çalışmalar çağdaş mimarlıkta paradigma kaymasına sebep olmuştur. Yeni hesaplamalı tasarım araçları mimarın tasarım esnasında kullandığı form yelpazesini genişletmiş ve rijit formlar yerine daha akışkan ve dinamik formlar kullanmasına imkan sağlamıştır. Ancak yeni hesaplamalı tasarım araçları çağdaş mimarinin sadece form yelpazesini genişletmekle kalmamış aynı zamanda tasarlama ve yapma eylemlerinin arasındaki kopuşu sonlandırma gücüne sahip olmuştur. Dijital üretim teknikleri ve özellikle de Eklemeli Üretim teknikleri karmaşık geometrilerin üretimini kolaylaştırdığı için tasarımcıların tasarım esnasında düşünme biçimlerini de etkilemiştir. Yapı ölçeğinde Eklemeli Üretim sistemlerinde kaydedilen gelişmeler ve bu gelişmelerden doğan fırsatlar bu makalenin arkasındaki ana itici güç olmuştur. Makale Eklemeli Üretim sistemleri üzerine yürütülmüş daha geniş kapsamlı bir araştırmanın parçası olup, en son gelişmelerin anlaşılması ve daha büyük resimde sağlıklı bir şekilde konumlandırılabilme ihtıyacı sonucu ortaya çıkmıştır. Önerilen sınıflandırma ile son on sene içinde kaydedilen gelişmelerin ve uygulamadaki örneklerin incelenmesi hedeflenmiştir.

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Anahtar Kelimeler: Eklemeli Üretim, 3B Yazıcılar, Hesaplamalı Tasarım, Yapı Üretimi

1. INTRODUCTION

The latest developments in computational design have caused a massive paradigm shift in contemporary architecture. The power of the new computational tools allows the designers to design fluid and dynamic transformational forms replacing the rigid norms of current processes. Kolarevic (2003) in his book of “Architecture in the Digital Age: Design and Manufacturing” argues that “The topological, curvilinear geometries are produced with the same ease as Euclidean geometries.” Therefore, declaring the end of widely accepted use of grids, repetitions, and symmetries in architecture which opens up new doors to infinite variability and mass-customization.

Integrating design and manufacturing around digital technologies restructures the roles of the architect, the engineer and the builder and creates a more seamless organic way of doing things eliminating the dichotomy between designing and making.

Digital Manufacturing (DM) and in particular Additive Manufacturing (AM) significantly impact how designers think of complex mechanisms and geometries while designing. This article is motivated by the fast-paced changes in Additive Manufacturing (AM) in large-scale structures and the opportunities arising from manufacturing components, modules and even monolith buildings.

AM commonly known as 3D printing has been identified as a truly disruptive innovation, and as one of the five emerging technologies (among AI, Robotics, Augmented Humans, Internet of Things) that are believed to significantly impact the future (Prentice, 2014). The widely accepted definition of Additive Manufacturing is the automated building of physical models, layer by layer from three-dimensional (3D) computer aided design data. Whilst additive manufacturing can refer to any process where a product is created by a layering principle, it predominantly indicates technologies and processes involving 3-D printing with scale and precision in mind. (Ngo et al., 2018). When we look at the developments in second decade of 21st century 3D printing technologies are implemented for very different products, such as jewelry, biological implants, automotive parts, bridges and houses.

This article is part of a research on Additive Manufacturing (AM) and has evolved organically out of necessity while trying to map out the latest developments about large scale AM processes. Due to the ever-increasing interest on the subject both in academia and private sector there is an immense number of applied researches. Since the subject matter involves several disciplines i.e. material science, robotics, architecture, engineering, business etc., the research area is also very diverse. This aims to better understand and position the latest developments therefore challenges on a number of diverse subjects through a proposed classification method.

This article predominantly evolves through three stages. After the introduction chapter the authors give a brief overview of the subject and then introduce the methodology on classification of large-scale Additive Manufacturing, moving on to the proposed classification through case studies and finally in the last chapter we discuss the current challenges and future potentials.

2. A BRIEF OVERVIEW AND METHODOLOGICAL APPROACH

2.1 A Brief Overview

Additive Manufacturing is a term that encompasses several varying technologies of layered production of artifacts. The American Society for Testing and Materials (2009) defines Additive Manufacturing as "the manufacturing of objects through the deposition of a material using a print head, nozzle, or another printer technology".

In the early 1980's 3D printing was being discussed in the academic circles, it was not called 3D printing but Rapid Prototyping (RP). Though Dr. Hideo Kodama applied for the first patent RP technology in 1980, Charles Hull was the one who both took the credit for stereolithography, and also patented the technology in 1984 (Paull, 2017). 1999 was a milestone year in terms of printing biological materials. Scientists at Wake Forest Institute printed synthetic scaffolds of a human bladder and then coated them with human patients' cells (Moon, 2014). In 2005, the Rep Rap movement, an open-source initiative enabled the users to print parts of a 3D printer by another 3D printer (Goldberg, 2018). This was the breaking point for desktop 3D printers. This development marked the beginning of the maker movement. In the early 2010's, large scale robotic 3D printers emerged and experimented on pavilions and other small-scale structures. In 2017, already several projects were competing with time to become the first 3D printed house (Varotsis, 2018).

The main principle of Additive Manufacturing is universal for all of the different methods and scales: layering of a 3D CAD model by a software. The layering process is also called slicing and the device used to manufacture the output is called the printer. Different methods require different curing processes; it can either be by exposition, heating, or bonding.

The size and the preferred resolution of the model determines the number of layers on the model. The resolution of the 3D printed object is ruled by the thickness of layers.

Before the actual printing process starts which material will best suit the needs required for the object should be decided. Materials used in 3D printing has a broad spectrum which will be discussed later. Some materials work with specific AM technologies therefore when choosing the material, the technology is also chosen simultaneously. On the other hand, the main determining factors in surface quality are the chosen manufacturing method and the materials used.

Menges, in his 2015 article, Material Synthesis: Fusing the Physical and the Computational, states that the material technologies and construction methods have always shaped architecture, making it impossible to separate architectural design from advancements in production, fabrication, assembly and construction. Nonetheless the developments in cyber-physical production systems in the manufacturing industry created a paradigm shift in conceptual transformation of design thinking.

Although AM, as a Digital Manufacturing technology has been around since the 80’s its potential in large-scale architectural typologies is being explored only for the last decade. The AEC industry has always been slow to adapt technological advancements due to difficulties in changing the traditional way of designing and making things.

2.2 Methodological Approach

Due to the novelty of the subject, the research on AM especially on Large Scale Structures proved to be rather challenging. Since AM is deeply connected with real life experiments and applications both in the industry and the academia, it was difficult to bring together all the research in a meaningful and a coherent manner. Therefore, specific case studies are chosen based on their significance in order to map the necessary approach for classification of architectural scale AM applications. As Yin (2003) argues case study is a deliberately chosen method when the observation of a recent phenomenon within its real-life context, has blurry limits between that phenomenon and its context. This method allows researchers to keep the coherent characteristics of real-life events while analyzing a specific phenomenon.

The lack of a widely accepted classification method led to merging a few of the methods and creating a new hybrid one. In the proposed method, the categories are determined based on the general literature review of the subject but also equally inspired by the necessity of not having an all-encompassing classification system to better position each and every one of the case studies chosen from a large group of project pool. While each category in the proposed system, on its own is a thorough research area and has several in depth studies on them, it is very rare to find a comparative study based on classification of different and broad applications.

During the research for the subject matter several academic databases and other online resources are screened including Elsevier, Science direct, Ebsco, Proquest, YÖK Ulusal Tez Merkezi etc. The keywords used in literature review is defined in **Table 1**. Duplicate entries and articles outside the scope of the article are removed, ensuing 45 articles and 15 other resources being used in the final version **(Figure 1)**.

Both in database and other online resource researches nine additive manufacturing terms, ten construction terms and twenty eight other related viable terms have been used.

Table 1: Keywords.

Category	Included terminology
Additive manufacturing	3D printing, [3-D printing], additive construction, direct digital manufacturing, automation in construction, concrete printing, clay printing, contour crafting, binder jetting, material extrusion
Architecture & Construction	Building, pavilion, architecture, cement, clay, civil engineering, concrete, construction, large-scale, computational
Viability	Classification, types, typology, structure, load-bearing, reinforcement, sustainability, material, technology, mould, formwork, module, component, joint, monolith, form, materiality, building code, cost, design, economics, efficiency, energy, in-situ, optimization, productivity, strength, time

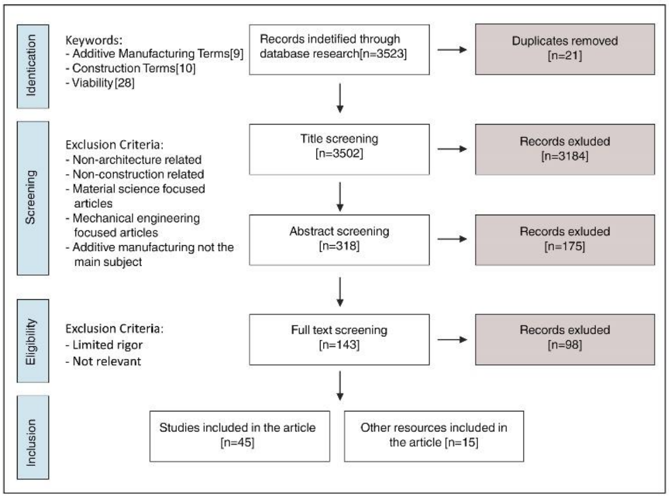


Figure 1: The Flow Diagram for the research conducted is summarized

The finding from the resources eased determining some of the main categories of the proposed classification in this article due to them being accepted by large institutions like The American Society for Testing and Materials (ASTM). On the other hand some subcategories were more open to discussion. When we move on to our proposed classification approach, under each category these discussions will be mentioned if there is any.

The main categories of the proposed classification are; Technology used, Materials Used, Type of Process, Site of Manufacturing, Deposition gear, Structure type, and Reinforcement type. Each category defines a different aspect of an application without going into too much detail for the purposes of creating a broad basis that enables a comparative study.

3. THE PROPOSED CLASSIFICATION

The evaluation of case studies in a comparative perspective through the lens of existing methods led to a merging of a few different approaches and rewording some of the categories to create a consistency of the language used. The main seven categories and their subcategories which constitute the classification criteria are described below:

3.1 Categories

- Classification of Additive Manufacturing based on the Technology used: Although several new technologies are introduced every year there has not been a new technology that would shift the widely accepted existing classification done by The American Society for Testing and Materials (ASTM) (2009). All the new technologies introduced can classified under one of the seven technologies that are widely accepted. The seven technologies determined by ASTM are; Vat photo polymerization (VP), Powder bed fusion (PBF), Material extrusion (ME), Material jetting (MJ), Binder jetting (BJ), Directed energy deposition (DED), Sheet lamination (SL). In this article the AM technologies defined by ASTM and summarized in the Table2 will be utilized. The Table adapted from Tofail et. al. briefly summarizes the advantages, disadvantages and the materials used in different AM technologies.

- Classification of Additive Manufacturing based on Materials:

Additive Manufacturing is possibly the most direct method of bringing forms into material world. As the digital design is able house every bit information, the designer can control every detail manufactured by AM technologies. With such control over fabrication it is possible to generate every kind of form without any additional costs. This creates the possibility of optimization both in form and material distribution. In macro scale, with topology optimization the layout of the material is being organized based on the load the design receives and in micro scale it allows the designer to control material heterogeneity. In order to better understand the process around materials it is in our best interest to understand the scope of the materials used in AM processes. The classification of Additive Manufacturing materials has been a long disputed subject. The main discussion on the classification of materials is whether they should be classified based on their initial state or based on their deposition state. To go deeper into discussion would be inconclusive but most importantly would derail the general subject matter. Therefore, in this article the widely accepted classification of Kruth et al (1998) will be used. Kruth et al (1998) classifies the materials based on their deposition states; liquid based, solid based, and powder based. Whilst the main classification method for materials are based on three states, we also find it valuable to dedicate a separate discussion for advanced materials even though taxonomically they can be classified under any one of the three states.

Solid based materials: All solid-state materials either in the form of a sheet or a roll fall under the category of solid based materials. Solid-based AM systems work with selective gluing / joining methods. These processes are different from one another, though some of them use the laser in the process of fabricating prototypes. They all utilize solid in one form or the other, as a material to create the final product. Laminated object Manufacture (LOM), Selective Deposition Lamination (SDL), Ultrasonic Additive Manufacturing (UAM) are the most common technologies using solid based materials.

Powder based materials: Powder based AM systems work on the principle of transforming a material from a powder to a solid state by melting or binding. The method of melting or binding differs for all the systems, some employ a laser and others use a binder/glue to achieve the joining effect. Binder based powder systems work on the basis of depositing a binder material on to the selective regions of powder particles to produce a layer of bonded particles. Since the process uses a powder bed usually the protruding parts do not need a support. To remove the unbonded powder particles a cleanup process is required. Some of the most used powder-based AM processes are Laser Sintering, Power Binding Printing, Selective Laser Melting and Selective Laser Sintering.

Liquid based materials: Liquid based AM systems involves transforming a material from a liquid to a solid state. The solidification process can happen either by photo curing or curing by itself. If the chosen method is deposition of a liquid state material via a printing nozzle solidification of the material is achieved by curing by itself. The material can be in solid state before extrusion like a polymer and can be melted via a heated nozzle only to solidify again in the desired form. Some of the extrusion-based processes are Fused Deposition Modelling, Inkjet and PolyJet.

Table 2: ASTM categories of AM Summarised. Abbreviations: Vat photo polymerization (VP), Powder bed fusion (PBF), Material extrusion (ME), Material jetting (MJ), Binder jetting (BJ), Directed energy deposition (DED), Sheet lamination (SL). (Adapted from: Tofail et. al., 2018)

ASTM category	Basic principle	Example technology	Advantages	Disadvantages	Materials
BJ	Liquid binder/s jet printed onto thin layers of powder. The part is built up layer by layer By glueing the particles together	3D inkjet technology	Free of support/substrate Design freedom Large build volume High print speed Relatively low cost	Fragile parts with limited mechanical properties May require post processing	Polymers Ceramics Composites Metals Hybrid
DED	Focused thermal energy melts materials during deposition	Laser deposition (LD) Laser Engineered NetShaping (LENS) Electron beam Plasma arc melting	High degree control of grain structure High quality parts Excellent for repair applications	Surface quality and speed requires a balance Limited to metals/metal based hybrids	Metals Hybrid
ME	Material is selectively pushed out through a nozzle or orifice	Fused Deposition Modelling (FDM)	Widespread use Inexpensive Scalable Can build fully functional parts	Vertical anisotropy Step-structured surface Not amenable to fine details	Polymers Composites
MJ	Droplets of build materials are deposited	3D inkjet technology	High accuracy of droplet deposition Low waste Multiple material parts Multicolour	Support material is often required Mainly photopolymers and thermoset resins can be used	Polymers Ceramics Composites Hybrid Biologicals
PBF	Thermal energy fuses a small region of the powder bed of the build material	Direct Metal Laser Sintering (DMLS) Selective Laser Sintering/Melting (SLS/SLM)	Relatively inexpensive Small footprint Powder bed acts as an integrated support structure Large range of material options	Relatively slow Lack of structural integrity Size limitations High power required Finish depends on precursor powder size	Metals Ceramics Polymers Composites Hybrid
SL	Sheets/foils of materials are bonded	Laminated Object Manufacturing (LOM) Ultrasound consolidation/Ultrasound Additive Manufacturing (UC/UAM)	High speed Low cost Ease of material handling	Strength and integrity of parts depend on adhesive used Finishes may require post processing Limited material use	Polymers Metals Ceramics Hybrids
VP	Liquid polymer in a vat is light-cured	Stereo Lithography (SLA) Digital Light Processing (DLP)	Large parts Excellent accuracy Excellent surface finish and details	Limited to photopolymers only Low shelf life, poor mechanical properties of photopolymers Expensive precursors/Slow build process	Polymers Ceramics

Advanced Materials: As mentioned previously different advanced materials can classified under different states of deposition (solid, liquid or power based) yet it is worth mentioning some of the latest developments in material science. Though these advanced materials have not found their place in large scale applications yet with the fast pace of ever-changing developments we can expect to see their application in near future. Since early 80's the number of materials produced by AM has increased immensely and comparatively advanced materials have seen a rise in interest for the last decade. (Khooa, et al, 2015) We will be focusing on two types of advanced materials; (i) Functionally Graded Materials and (ii) Smart Materials.

Sometimes FGM and Smart Materials can be confused with each other. FGMs can be simply defined as gradient materials whereas the definition of smart materials is more disputed and vary between different researchers. Leo (2007) argues that in order for a material to be accepted as smart it has to demonstrate a conversion of energy between two psychical states such as conversion of thermal energy into mechanical. Varadan et al (2006) further defines smart materials as materials that can sense an external stimulus, respond to it changing their material properties or geometries and return to its original state as soon as the stimulus is removed. On the other hand, Khooa et al (2015) defines a category of passive materials, which lack the inherent capability to transduce energy.

Functionally Graded Materials (FGMs) are defined by the variation in composition and structure in a controlled gradient resulting in different material properties in a single part **(Figure 2)**. The materials can be designed for specific function and applications.

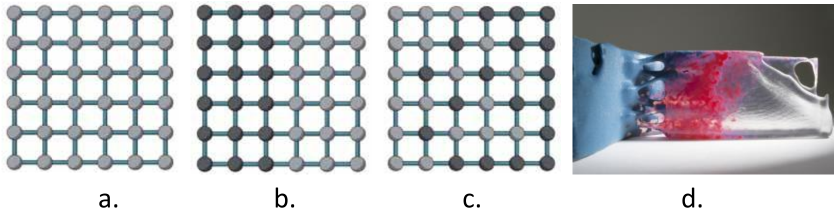


Figure 2: a. Homogenous material, **b.** Joined material, **c.** Functionally Graded Material (FGM) (Strauss, 2013), **d.** Close up interior view of the fabricated multi-material mullion interface (Grigoriadis, 2019)

The material properties allocated in the CAD file help different resolutions of the material particles to be manufactured. The AM process used is based on Ink jetting, which sprays viscous plastic droplets onto a building platform at high-speed enabling different materials to be melted together to form a true gradient. (Strauss, 2013) The variation can be from flexible to rigid or soft to hard enabling the user to design an object in one manufacturing process **(Figure 2.d).**

As Grigoriadis (2019) puts it "Discrete boundaries will be replaced by gradients. For example, this method is targeted to the area in the facade where glass and aluminum frame connect in a unitized curtain wall panel. The component-based make-up of the facade system is associated with problems such as environmentally hazardous production processes, and post-installation failures. A component-less, continuous FGM connection would eliminate these issues."

Khoo et al (2015) classifies Smart Materials based on the number of materials used in the printing process: with a combination of multiple materials or with a single material.

Both in single material or combination material components the most important thing is the inherent properties of the raw material being used. It is this material that defines the self-adaptability, self-sensing, shape memory and decision making (Varadan et al. 2006).

Another term that is used predominantly within the smart materials context is 4D printing. Pei (2014) defines 4D printing as the process of making of an object using AM technologies with inherently responsive materials. The final object reacts to stimuli from its surroundings resulting in a physical or chemical change of state through time.
In 4D printing with single material smart nanocomposites and shape memory alloys are most commonly known materials. Nanocomposites is a very specialized subject and we will not go into detail. On the other hand, shape memory alloys (SMA) is used in a wide variety of sectors; from dental wires to helicopter blades. SMA is a type of smart material that can convert thermal energy into mechanical work, remembering their original shape and returning to it after deformation from a stimulus.

Among the leading 4D printing companies and research labs are MIT's Self-Assembly Lab, Stratasys, and Autodesk. In 2014, one of the leading researchers of MIT, Skylar Tibbits, started working with Autodesk on creating a computer system that allows geometry inputs to measure how 3D printed objects will be able to change post-print

Another important institution working on Smart Materials is Defense Advanced Research Projects Agency (DARPA). DARPA's Engineered Living Materials (ELM) program are working on 4D technology to create a micro scale self-building army and "living biomaterials" that has the structural properties of traditional building materials with the ability to rapidly grow, self-repair, and adapt to the environment.

- **Classification of Additive Manufacturing based on the Type of AM Process:** The selected case studies are classified first based on whether they are manufactured as a mould or not. After the first division the categories are subdivided once again based on their scale; whether the printed structures are modules or monolith structures. The first division is based on a study of Martins and Jose (2014) in which they analyze several digitally fabricated structures whether they are moulds are not. They classify the mould making process as the Indirect Intervention and manufacturing of the final product as the Direct Intervention. In this article the same classification method will be used only using the word “manufacturing” instead of “intervention” to ensure consistency in wording.

- Indirect Additive Manufacturing: Formwork / Moulds

Additive manufacturing technology in construction industry is still in its infancy stage. Although there several breakthroughs, currently available AM techniques may not answer some of the needs of the construction process. It may seem like the logical procession to assume that directly printing the structure or parts of it is the most economically efficient way to go, in some cases using a mould might be the best available option. On the other hand, using a mould does not necessarily mean limiting the three-dimensional freedom. This is where AM technology creates an opportunity not only the giving the designer 3D freedom but also increases the structural efficiency with more economic and sustainable solutions.

- Direct Additive Manufacturing: Modules/components, joints and monoliths

In AEC industry scale is an important issue. Depending on the project’s needs the structure may be planned either based on modules/components or in a monolithic manner.

Usually the manufacturing of modules/components or joints takes place in a controlled environment. Both crane and cable-based solutions can be used. The only limitation is the transportation of the manufactured part. The same robot manufacturing the part can also be used to assemble the pieces together, in this case the whole process will be fully automated from CAD data to final product (Labonnote, 2016).

Monolithic structures based on their scale are mostly on site in situ fabrications.

- **Classification of Additive Manufacturing based on the Site of Manufacturing:** Due to environmental and economic concerns the site of manufacturing carries a great importance. In order to lower the carbon foot print of the construction it is always ideal to be able realize the manufacturing process on site with the least amount of material and minimum necessity for transportation of components. Therefore, identifying whether the application is an in-situ (on site) or ex-situ (off site) helps determine the efficiency of the project. Currently the 3d-printing gear, especially in experimental projects, do not allow them to be used in an environment that is exposed to elements.

- **Classification of Additive Manufacturing based on the Deposition Gear:** The first attempt to adopt AM in large scale applications has been by using cement-based materials by Pegna in 1997. Consecutively three large scale AM processes have been introduced to construction and architecture industry: Contour Crafting (Khosnevis, 2006), D-Shape and Concrete Printing (Lim, 2009). All three technologies have been widely adopted and are further developed by several researchers both from the academia and the industry.

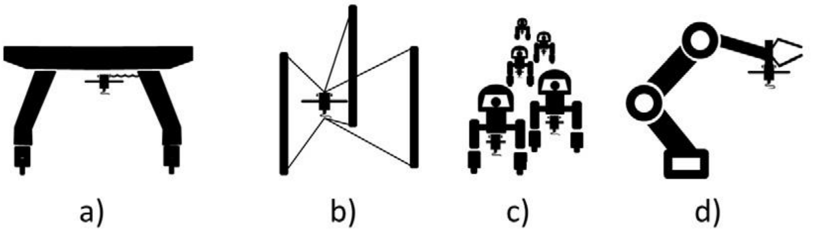


Figure 3: Different technological solutions. **a.** Frame, **b.** cable-suspended crane, **c.** swarm, **d.** robot arm (Labonette et al, 2016)

The above technologies uses three different deposition head mounting gear; it is either frame, robot or crane **(Figure 3).** Labonnete et al (2016) adds a fourth approach, swarm robotics.

'Contour crafting' and 'concrete printing' by means of a crane or cable suspension are developed to manufacture monolithic structures.

Although both techniques have many advantages, 3D freedom is not one of them therefore lacking one of the main advantages AM brings. However, swarm and robotic arm methods prove to be more efficient due to its greater efficiency in every scale and mobility. Some of the methods involved in traditional construction like damp proof membranes or sound insulation etc. are still addressed through traditional methods. Also, Paoletti (2018) states the fact that the trade-off between printing resolution and speed is another potential problematic area: although the hierarchy among elements as to their functional relevance allows the user to choose more high accuracy and isotropy prone areas, the techniques should be further developed to allow further detailed control in the 3D printing process. Multiple material nozzles or Functionally Graded Materials for construction might answer some of the above problems.

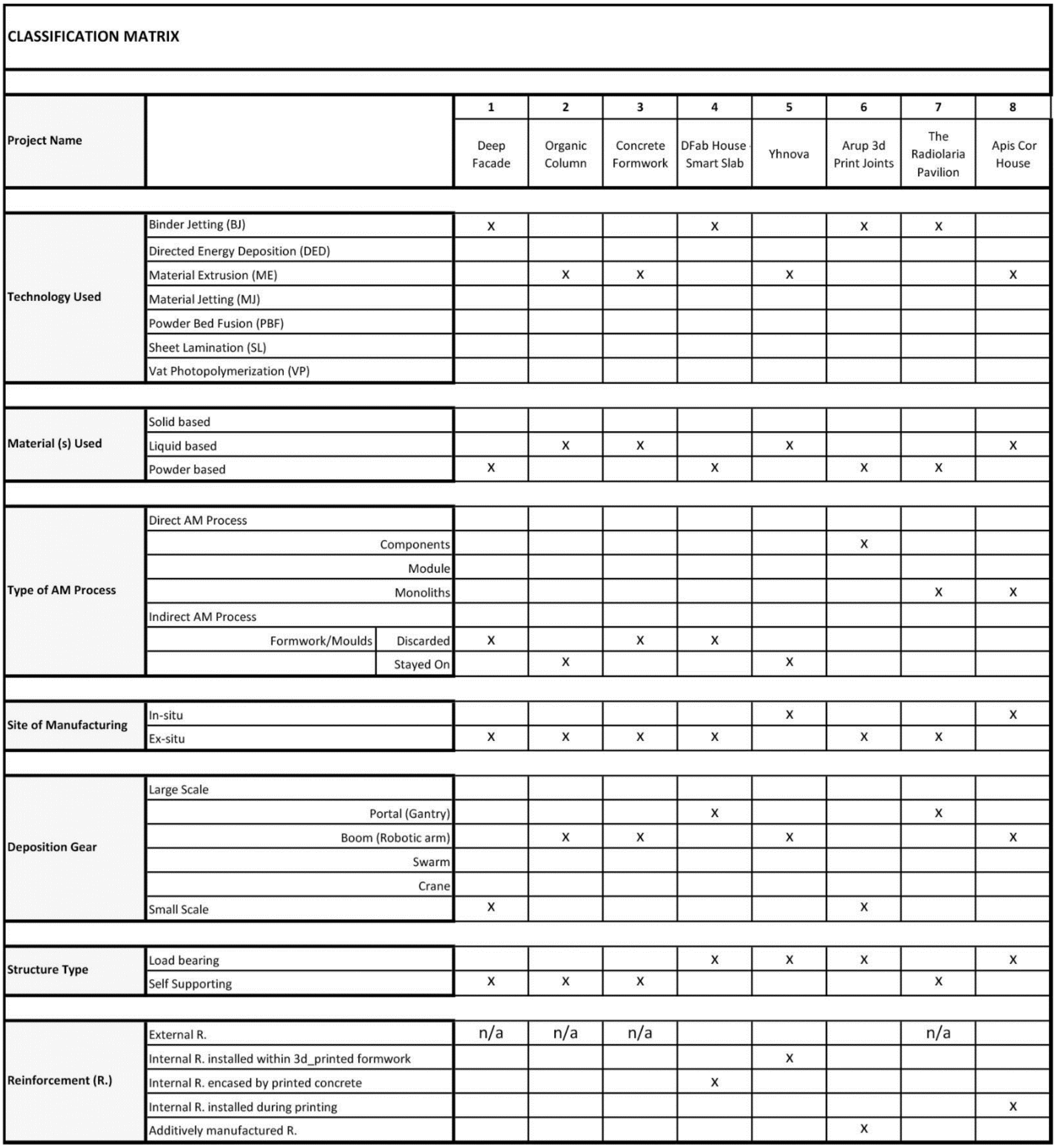
- Classification of Additive Manufacturing based on the Structure

Type: The structures can be divided into load-bearing and self-supporting. Load-bearing structures are those that carries and transfer the loads to the next load bearing element and finally to foundation. By providing a spatial rigidity it guarantees the strength and stability of the structure. Load-bearing walls, columns, beams, slabs are among the elements of a load bearing structure. Due to the fact that AM is presented as a manufacturing technique that will enable a fully automatized construction process, the manual placement of steel reinforcement bars in concrete is a problem waiting to be resolved. Although in some research-based applications, mixture of steel fibers and concrete is experimented to increase the rigidity of concrete against tensile forces, the result cannot rival the conventional method of reinforced concrete. Self-supporting structures can transfer the loads received from its own weight to foundation. In most applications either the designed structure can only transfer the load of its own weight or the structure is rigid enough under compression but not tension which again constitutes a problem for a fully automatized process.

- Classification of Additive Manufacturing based on

Reinforcement technique: As previously mentioned due to the low tensile strength of concrete without reinforcement is a problematic area. To resolve the issue about tensile performance of 3d printed concrete, several reinforcement techniques had been tested in research-based AM processes (Sartipi, 2020). These are; External reinforcement, internal reinforcement installed within 3D-printed formwork, internal reinforcement encased by printed concrete, internal reinforcement installed during printing, additively manufactured reinforcement. In the below table **(Table 3)** the proposed classification system has been tested with a wide range of AM Applications.

Table 3: Proposed Classification Matrix for Large Scale AM



CLASSIFICATION MATRIX

			1	2	3	4	5	6	7	8
Project Name			Deep Facade	Organic Column	Concrete Formwork	DFab House Smart Slab	Yhnova	Arup 3d Print Joints	The Radiolaria Pavilion	Apis Cor House
Technology Used	Binder Jetting (BJ)		X			X		X	X	
	Directed Energy Deposition (DED)									
	Material Extrusion (ME)			X	X		X			X
	Material Jetting (MJ)									
	Powder Bed Fusion (PBF)									
	Sheet Lamination (SL)									
	Vat Photopolymerization (VP)									
Material (s) Used	Solid based									
	Liquid based			X	X		X			X
	Powder based		X			X		X	X	
Type of AM Process	Direct AM Process									
		Components						X		
		Module								
		Monoliths							X	X
	Indirect AM Process									
	Formwork/Moulds	Discarded	X		X	X				
		Stayed On		X			X			
Site of Manufacturing	In-situ						X			X
	Ex-situ		X	X	X	X		X	X	
Deposition Gear	Large Scale									
		Portal (Gantry)				X			X	
		Boom (Robotic arm)		X	X		X			X
		Swarm								
		Crane								
	Small Scale		X					X		
Structure Type	Load bearing					X	X	X		X
	Self Supporting		X	X	X				X	
Reinforcement (R.)	External R.		n/a	n/a	n/a				n/a	
	Internal R. installed within 3d_printed formwork						X			
	Internal R. encased by printed concrete					X				
	Internal R. installed during printing									X
	Additively manufactured R.							X		

CLASSIFICATION MATRIX									
		9	10	11	12	13	14	15	16
Project Name		Mini Builders	Saltygloo	Load-Respon. Cellular Envelopes	Tecla	The Metal Bridge	Fiberbots	Striatus	Polymer Lattice Reinforcement
Technology Used	Binder Jetting (BJ)								
	Directed Energy Deposition (DED)					X			
	Material Extrusion (ME)	X	X	X	X		X	X	X
	Material Jetting (MJ)								
	Powder Bed Fusion (PBF)								
	Sheet Lamination (SL)								
	Vat Photopolymerization (VP)								
Material (s) Used	Solid based								
	Liquid based	X	X	X	X		X	X	X
	Powder based					X			
Type of AM Process	Direct AM Process								
	Components		X				X		
	Module			X				X	X
	Monoliths	X			X	X			
	Indirect AM Process								
	Formwork/Moulds – Discarded								
	Formwork/Moulds – Stayed On								
Site of Manufacturing	In-situ				X		X		
	Ex-situ	X	X	X		X		X	X
Deposition Gear	Large Scale								
	Portal (Gantry)								
	Boom (Robotic arm)			X	X	X		X	
	Swarm	X					X		
	Crane				X				
	Small Scale		X						X
Structure Type	Load bearing					X		X	X
	Self Supporting	X	X	X	X		X		
Reinforcement (R.)	External R.	n/a	X	n/a	n/a		n/a	n/a	
	Internal R. installed within 3d_printed formwork								
	Internal R. encased by printed concrete								
	Internal R. installed during printing								
	Additively manufactured R.					X			X

Table 3 (Continued):
Proposed Classification Matrix for Large Scale AM

3.2 Case Studies

A study of the major additive manufacturing processes constituted a basis of technological framework for this article. In the following chapter relevant case studies will be explored. Every project carries a significance either due to its production technique, materials or its scale. The fact that it is difficult to find two projects that carry same characteristics proves that the technology is in its very early stages.

Though a particular importance is given to explore a wide variety of case studies, as expected not all of them have innovative approaches. One of the largest additive manufacturing companies in AEC sector is a Chinese company called WinSun. In 2013 it has realized a first and like a factory belt line printed 10 single story houses consecutively in 24 hours with $4800 cost per house. Since then, the company was able to develop methods to build larger scale structures from 3 story villas to 5 story buildings.

There are several other companies working on AM technologies. Though some of them have significant contributions to the development of the method mostly their contributions are relatively limited. The following case studies are chosen based on their significance either because of the technology they use or because they are pioneers in the methods they utilize.

- Zurich Deep Facade – ETH Zurich

ETH – Zurich Deep Facade, a six-meter-high aluminum structure is significant because the molten aluminum is cast in a mould made of sand **(Figure 4.a)**. The mould is 3D printed using binder jetting technology. It is said to be the first metal based structure cast in a 3D-printed mould. The significance of the method is that it allows the designer to realize complex forms relatively cost effective and in a short period of time. Designed with a differential growth algorithm and topologically optimized panel is cast in 26 articulated modules and combined on site (URL – 1).

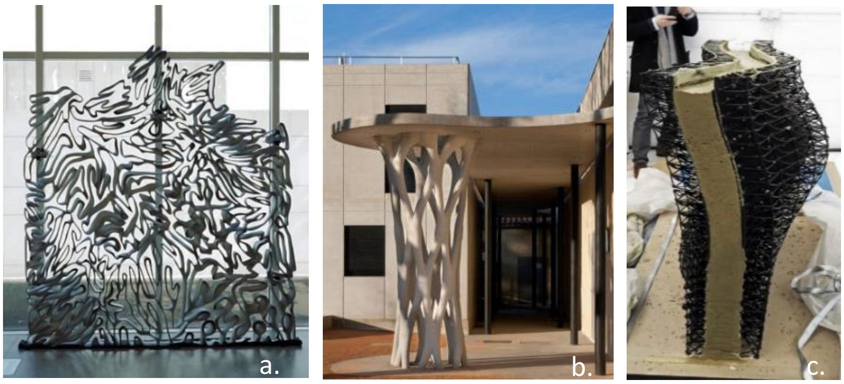


Figure 4: From left to right; **a.** Zurich Deep Facade – ETH Zurich (Dbt, 2019), **b.** Organic Column – XtreeE, (Material District, 2017) **c.** Concrete Formwork – AI Build (AI-Build, n.d.)

- Organic Column – XtreeE

This 4m-high column in the playground of a school in France have semi-load bearing properties **(Figure 4.b)**. They are designed with topological optimization tools in two parts; the formwork, and the concrete that is cast inside the formwork. The printer is an extrusion based printer using two types of cement mixture; one for the formwork and the other for the structure. The modules are assembled on site (Material District, 2017).

- Concrete Formwork – AI Build

The custom mould uses and extrusion based printing technology **(Figure 4.c).** The aim of the project is to explore different moulds for concrete work to give the designer increased flexibility. The significance of the project is that to create the 3D printed mould any recycled material can be used with zero waste manufacturing (AI-Build, n.d.).

- Smart Slab – ETH Zurich

The Smart Slab project as a part of the DFAB House Project is the first concrete slab fabricated with a 3D-printed formwork **(Figure 5.a)**. The lightweight concrete slab is cast into a 3D printed sand mould using binder jetting technology. The design of the concrete slab is topologically and structurally optimized meaning less material is used with increased structural strength. The cantilevering slab is placed on a s shaped load bearing wall and carries another two story unit above itself. It is manufactured in eleven modules and assembled on site using post tensioning cables. The largest cantilevering point is 4.5 meters with varying depth between 30 and 60 centimeters. As a result, the weight of the slab is 70% less than a traditional slab (DFAB HOUSE, n.d.).

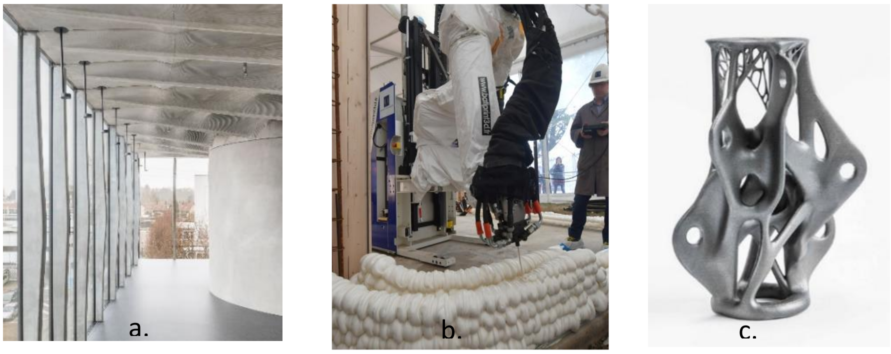


Figure 5: From left to right; **a.** Smart Slab – ETH Zurich (DFAB HOUSE, n.d), **b**. Yhona-NantesE, (Batiprint3D, n.d.), **c.** 3D Optimised Joints-Arup (ARUP, n.d.)

- Yhnova - Nantes

The 3D print house project led by University of Nantes have 5 rooms with an area of 95 m2 **(Figure 5.b)**. The patented BatiPrint3D technology uses a laser-guided, four-meter-long robotic arm to deposit layers of different construction materials. The extrusion based 3D printer has the capacity to print 3 different materials; foam like material for formwork, an insulation layer, and a concrete mixture (Batiprint3D, n.d.).

- 3D Optimised Joints – Arup

Arup Group has developed the optimized 3D printed joints for a trio of large tensegrity structures used as street lighting, in a shopping street in The Hague **(Figure 5.c)**. The highly irregularly shaped design required 1,600 nodes to connect the cables to the struts. They have used selective laser sintering to print sand moulds and use molten steel to cast the parts. The 3D printing of sand moulds lowers the cost of manufacturing in comparative perspective to direct 3D printing of metal parts (ARUP, n.d.).

- The Radiolaria Pavilion – D Shape

The Radiolaria Pavilion is one of the very first attempts to 3D print in architectural scale and 'print' entire buildings as a unique piece printed at once **(Figure 6.a)**. In 2004 Enrico Dini an Italian engineer developed a manufacturing technique on an area of 6 by 6 m and limitless height. As technique uses selective binder jetting it does not need any supports and allows complex geometries. Though the pavilion represents a "first" in large scale 3D printing the binder jetting method is mostly not preferred due to difficulties in creating large scale powder bed manufacturing environment (Turner, 2009).

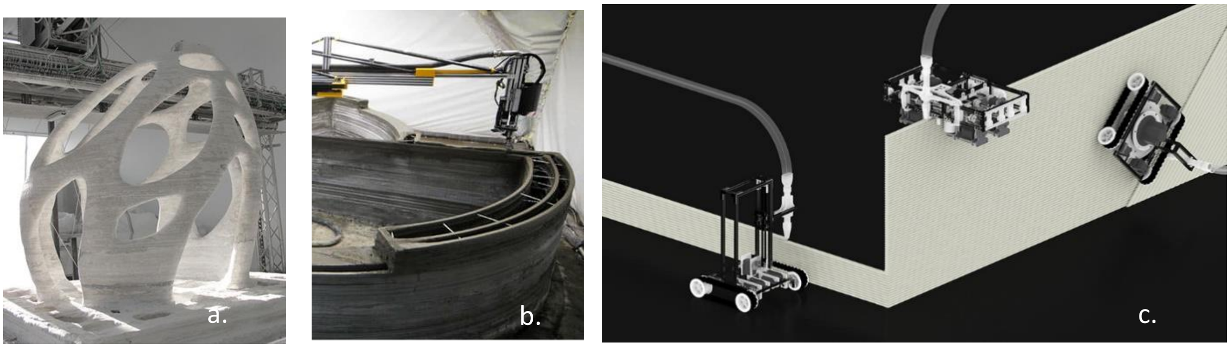


Figure 6: From left to right; **a.**The Radiolaria Pavilion – D Shape (Turner, 2009), **b**. Apis Cor House, Apis Cor, (Apis Cor, n.d.), **c.** Minibuilders – IAAC (Sttot, 2014).

- Apis Cor House – Apiscor

The house is said to be the first 3D printed house on site **(Figure 6.b)**. The technique used is extrusion based with a cement based material. The bot left a small gap between the interior and exterior walls in which the team then placed fiberglass reinforcements and sprayed a polyurethane-based mixture for insulation. Though the house carries significance due being the first fully functional in situ large scale AM we still cannot talk about a fully automated process. Since the reinforcements are placed by the team it can be accepted as a hybrid process (Apis Cor, n.d.).

- Minibuilders – IAAC

The researchers at The Institute for Advanced Architecture of Catalonia (IAAC) observed that the construction robotics all share one limitation that the size of the object printed is limited with the size of the system. **(Figure 6.c).** They develop a family of small-scale mobile construction robots who are assigned different tasks, working independently towards a single goal (URL – 10). There are three types of printing robots whose functions are differentiated. The first robot is able to print the foundation while the second one can attach itself to the already built structure and print more nonlinear forms. The third one has a vacuum apparatus and can directly attach itself to the wall of the structure printing vertically to increase the strength of the horizontally printed layers. All the multidirectional robots work on an extrusion based technique using fast setting artificial marble as material and use hot air to fasten the curing process (Sttot, 2014).

- Saltygloo – Emerging Objects

The Saltygloo is one of the earlier projects of Emerging objects. The project carries a significance due to the material experimented in 3-D printing. The group used locally harvested salt and designed component based pavilion with computational design tools **(Figure 7.a)**. The material used is a combination of salt and glue creating a strong, waterproof, lightweight and inexpensive material. The structure has 336 translucent panels supported with lightweight aluminum rods flexed in tension (Emerging Objects, n.d.).

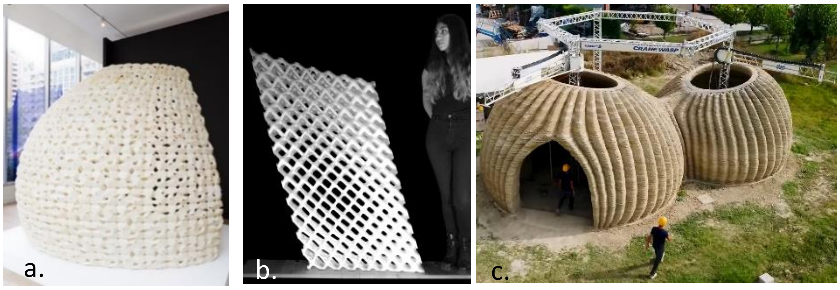


Figure 7: From left to right; **a.** Saltygloo – Emerging Objects (IAAC, 2018), **b.** Load-Responsive Cellular Envelopes (Naboni, 2017), **c.** Tecla - WASP (3D Wasp, 2021).

- Load-Responsive Cellular Envelopes – Politecnico di Milano

The researcher from Politecnico di Milano ties the motivation behind their latest work to increasing concerns over environment and a need to find a solution through nature inspired design. Using principles of morphogenesis and biological materials they have designed a load responsive cellular envelope **(Figure 7.b)**. With a design to fabrication workflow the approach encompasses the use of computational tools, Additive Manufacturing, and material experiments (Naboni, 2017).

- Tecla - WASP

The project combines a traditional material, unfired clay, with state of the art computational design tools and 3D printing technologies **(Figure 7.c).** In large scale additive manufacturing in order to increase structural capabilities several infill patterns are used. In this study by designing infill patterns the researchers were able to embed thermal properties in the wall section to control conductance. Extrusion based 3D printing technique allowed the researchers to create complex geometries (3D Wasp, 2021).

- The Metal Bridge – MX3D

The bridge is 6 meters wide and 3D printed with six-axis robots that control the welding machines using molten steel **(Figure 8.a).** The project adheres to local council's regulations allowing it to be used on a real life canal. The bridge is also equipped with sensors in collaboration with Arup Group to test its performance by collecting data such as strain, rotation, load, displacement and vibration. The collected data will be tested continuously on the virtual twin of the bridge (MX3D, n.d.).

Figure 8: From left to right; **a.** Metal bridge – MX3D (MX3D, n.d.), **b.** Fiberbots - MIT (Hitti, 2018).

- Fiberbots – MIT

Neri Oxman in her 2013 work examined cocoons built by silk worms to better understand their weaving method. Robotically fabricated metal structure has been used as a scaffold to weave cotton threads to prepare a surface for the silkworms are attached. After the installation the metal scaffold has been removed and the silk worms are observed with the tiny sensors attached to their foreheads. In her seminal work she has observed that the silkworms are in a way working like a multiaxis 3D multi-material printer depositing silk fiber (Oxman, 2014). This observation has led to a second research which is based on a swarm of robots "designed to rapidly build high-strength tubular structures by winding fiberglass filament around themselves." (Kayser, 2018). The experiment's innovative approach comprised of 16 robots. The robots are identical, working simultaneously depositing fiberglass to fabricate self-supporting composite tubes **(Figure 8.b).**

The robots feed a mixture of fiberglass thread and resin and cured by the UV light attached to the robots' body. The tubular structures are made of fibers but also in macroscale the structures themselves can be considered as part of a fibrous structure, each of them carrying load bearing properties themselves. Though fiberglass is used in this study, for further studies smart fibers made of natural materials are being developed (Hitti, 2018).

- Striatus – ETH Zurich/Zaha Hadid Architects

This is a 16 metre long 3d-printed bridge realized by ETH Zurich in collaboration with the Computation and Design Group at Zaha Hadid Architects, Holchim (concrete manufacturer) and incremental3D **(Figure 9.a).** Due to the fact that the bridge is made of hollow blocks and is held in place by solely compression, it uses 70% less material and does not need any reinforcement or binders. It can be disassembled and recycled. The main difference from other printing gears is that, it uses a six axis robotic arm with a special printing head allowing to form non-uniform, non-parallel layers (Striatus, n.d.).

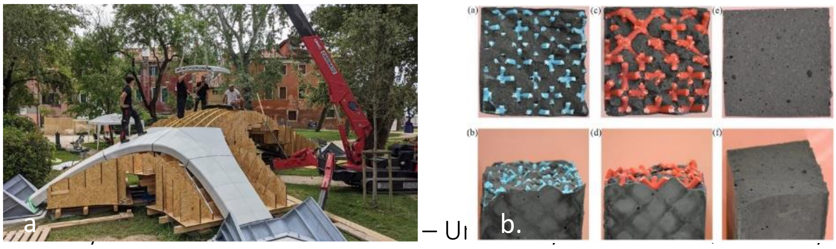


Figure 9: From left to right; **a.** Striatus – ETH Zurich/Zaha Hadid Architects (Striatus, n.d.), **b.** Polymer Lattice Reinforcement – University of California, Berkeley (Salazar et. Al, 2020)

Reinforcing concrete with polymer fiber particles is not a new development, yet the researchers were able to improve the efficiency of polymer reinforced concrete by a 3D printed lattice reinforcement which is designed to act as a series of trusses **(Figure 9.b)**. This design is able to support heavy loads from all directions. These polymer reinforcements are printed with material extrusion technology and in modules (Salazar et. Al, 2020).

5. CURRENT CHALLENGES AND FUTURE POTENTIALS

Although Additive Manufacturing technologies in AEC gained quite a bit of momentum in the last decade it has still several challenging limitations to overcome.

As of 2021 the tallest building built today is a five story building 3D printed in modules and assembled on sight by Winsun in China. This is a challenge due to the limitations of the printers in large scale manufacturing. Though there are promising studies on swarm printing (IAAC Minibuilders, 2014; Oxman, 2018) they are still in their infancy stage.

Material development is another challenge AM is facing. Concrete mixes that are compatible with 3D technologies should further be studied to resolve issues on durability and stress resistance. Reinforcement is another disputed subject to be resolved in order to fully automize the fabrication process. As of 2019 the automized rebar system developed in ETH Zurich by Gramazio Kohler seems to be best available option. Last but not least though there are multi material printers for small scale manufacturing they are not introduced in large scale applications. The multimaterial printers in large scale would resolve issues around the component based assembly system.

The understanding of matter has changed with the invention of electron microscope. The micro scale structure of matter in nature showed that the materials is rather fibrous than monolithic which in return led the architectural researchers to reconsider architectural systems (Snooks, 2012).

Menges (2015) also makes a case for fibrous systems and argues that in nature almost every load bearing biological structure carries very similar properties with fibrous composites. The fibrous nature of biological structures can be replicated through various manufacturing methods. Robotic manufacturing and AM technologies being one of these technologies allows further exploration of structural systems found in nature. Considering the current research focuses AM technologies have not been able to exploit morphological characteristics of biological structures. Though progress has been in increasing the efficiency in material use through topologically and structurally optimized designs still most of the researches are dictated by conventional way of construction.

We believe the real potential of Additive Manufacturing has not been explored in full depth. The forms and the methods that AM is experimented with mostly belong to the industrialized production system. Innovative architectural thinking coupled with technology has the power to transform the architectural landscape. At first glance the AM techniques promise a more sustainable, economically efficient and an easily built mass customizable future but in our opinion the greatest opportunities lie in the fact that it enables the architects/designers to explore new ways of thinking and designing.

6. DISCUSSION AND CONCLUSION

To an outsider Additive Manufacturing technologies may seem like an all-purpose, one size fits all technology. In reality it is very important to choose the right (or the most suitable) technologies for the right project. In this sense designers should be very well informed with capabilities and limitations of each technology and also the material associated with the said technology.

In this study we offer a classification through case studies to provide a unified and systematic characterization of large scale AM applications. This classification will help in identifying AM processes, provide guidance to better locate the gaps in future research topics. Some of the gaps can be listed as follows; there are seven identified AM technologies yet only three of them are being explored for their potential in large scale structures consequently the types of materials being used is again limited due to the fact that they are inherently connected to the chosen AM technology. On the contrary, the types of AM processes (direct/indirect) and site of manufacturing which are again inherently connected subcategories are fully explored. Another category that is explored maybe most vigorously is a cross section of robotics and mechanical engineering that is the deposition gear. Yet, one of most critical issues waiting to be explored further is how to automate the integration of structural reinforcement in AM processes.

On the other hand due the fast pace of technological developments on the subject, the categories of classification might need to altered. Another important issue is that though the main focus of this study has always been to create a broad classification system that would encompass all the latest developments it lacks focus of an in-depth study on every category or sub category would require. A further study through a computational mid mapping technique based on the current categories would better show the correlation between different technologies and case studies.

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