

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**EXPLORING THE POTENTIAL OF ADDITIVE MANUFACTURING
IN LARGE SCALE STRUCTURES**

M.Sc. THESIS

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Department of Informatics
Architectural Design Computing Programme

JUNE, 2019

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**EKLEMELİ ÜRETİM SİSTEMLERİNİN POTANSİYELİNİN
BÜYÜK ÖLÇEKLİ UYGULAMALARDA İNCELENMESİ**

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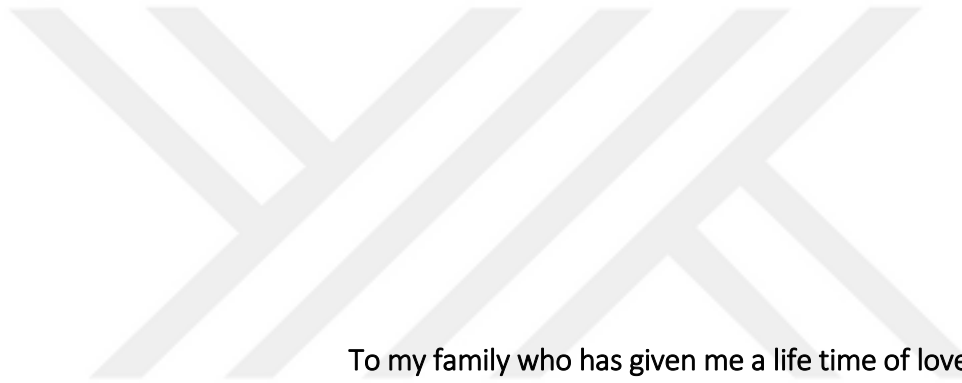
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To my family who has given me a life time of love and support,



FOREWORD

I was very enthusiastic about being accepted to ITU, Architectural Design Computing Program. Once the program has begun my enthusiasm was coupled with awe. Awe for the immense amount of knowledge and the new way of thinking design computing harbored. Prof. Dr. Gülen Çağdaş's class was one of my very first courses on the subject. Her tremendous knowledge on computational design was more than exciting for a novice like me. Still what really impressed me more was the participative, open and supportive environment she created in her classes. During my thesis studies, she extended her generous support, patience and intellectual guidance to me which never ceased to inspire me. It was a privilege to have been supervised by her.

My partner in crime, Aziz; during my studies he was the one who cheered me up when I was in full blown crisis and he was the one who always believed in me without a shadow of a doubt. It would not have been possible and more importantly, enjoyable without him.

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May, 2019

Yeşim ÜNAL
Architect

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ABBREVIATIONS

3DCP - 3D Concrete Printing
3DP - 3D Printing
ABS - Acrylonitrile Butadiene Styrene
ACES - Automated Construction of Expeditionary Structures
AI – Artificial Intelligence
AM - Additive Manufacturing
ASTM – American Society for Testing and Material
BJ – Binder Jetting
CAD - Computer Aided Designing
CAM - Computer-Aided Manufacturing
CC - Contour Crafting
CNC - Computer Numerical Control
DDM - Direct Digital Manufacturing
DED – Directed Energy Deposition
DLP - Digital Light Processing
DMD - Direct Metal Deposition
DMLS - Direct Metal Laser Sintering
EBM - Electronic Beam Melting
ESA - European Space Agency
FDM - Fused Deposition Modelling
FFF - Fused Filament Fabrication
IAAC - Institute for Advanced Architecture of Catalonia
LM - Layered Manufacturing
LOM - Laminated Object Manufacturing
ME – Material Extrusion
MIT - Massachusetts Institute of Technology
MJ – Material Jetting
MJM – Multi Jet Modelling
NASA - The National Aeronautics and Space Administration
PBF – Powder Bed Fusion
RM - Rapid Manufacturing
RP - Rapid Prototyping
SL- Stereolithography
SLA - Stereolithography Apparatus
SLM - Selective Laser Melting
SLS - Selective Laser Sintering
STL - Standard Tessellation Language
VP – Vat Photopolymerization



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EXPLORING THE POTENTIAL OF ADDITIVE MANUFACTURING IN LARGE SCALE STRUCTURES

SUMMARY

The latest developments in digital and computational design has caused a massive paradigm shift in contemporary architecture. While the power of the new computational tools allow 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. This integration 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 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 thesis 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. Therefore I find it crucial to examine the state of the art technologies in AM relating to Architecture, Construction, Engineering (AEC) industry to stay ahead or at least to be better informed.

My research on Additive Manufacturing (AM) and Large Scale Structures predominantly evolves through three stages; first a detailed insight into what AM is reviewed, moving on to current state of the art technologies and finally exploring whether it has a potential in large scale structures. Due to the novelty of the subject, the research on AM especially on Large Scale Structures proved to be rather challenging. Since AM is not a “theory only” subject and 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. During the case studies the lack of a widely accepted classification method led to merging a few of the methods and creating a new hybrid one. This classification system is used in Case Studies to better position each and every one of the chosen projects in a large group of project pool.

Before conclusion future potentials and possible further studies are discussed.

Finally, in the conclusion chapter, the advantages and challenges and the future prospects of AM in Architecture, Engineering and Construction industry is elaborated.



EKLEMELİ ÜRETİM SİSTEMLERİNİN POTANSİYELİNİN BÜYÜK ÖLÇEKLİ UYGULAMALARDA İNCELENMESİ

ÖZET

Dijital ve hesaplamalı tasarımdaki en son gelişmeler 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 (dikhotomi) sonlandırma gücüne sahip olmuştur. Tasarım ve yapma eylemlerinin arasındaki yeniden bütünleşme süreci mimar, mühendis ve uygulamacının da rollerini tekrar tanımlayarak sanayi devrimi öncesinde olduğu gibi bu rolleri birbirine yakınlaştırmıştır.

Dijital üretim teknikleri ve özellikle de Eklemeli Üretim teknikleri karmaşık geometrilerin üretimini kolaylaştırdığı için tasarımcıların tasarım esnasında düşünme biçimlerini de etkilemiştir. Modern dönemde “tasarım” malzeme ve üretim yöntemini dikte ederken, dijital araçların yaygın olarak kullanıldığı yeni dönemde artık döngüsel bir tasarım anlayışı egemen olmaya başlamıştır. Döngüsel tasarım anlayışında tasarımın malzeme ve üretim yöntemi üzerinde etkisi olduğu gibi malzemenin ve üretim tekniğinin de tasarımın üzerinde etkisi vardır. Bu sebeple de seçilen üretim tekniği çıkacak nihai ürünün tasarımında belirleyici bir unsur haline gelmiştir. Uzayda insan yaşamı ile ilgili araştırmaların hız kazanmasına paralel olarak son on yılda özellikle yapı ölçeğindeki Eklemeli Üretim sistemleri üzerindeki araştırmalar da hız kazanmıştır. Yapı ölçeğinde Eklemeli Üretim sistemlerinde kaydedilen gelişmeler ve bu gelişmelerden doğan fırsatlar bu tezin arkasındaki ana itici güç olmuştur. Yapı ölçeğindeki modül ve hatta monolitik üretimler güncel teknolojilerin mimarlık, inşaat ve mühendislik alanlarını hangi noktaya taşıdığı ve gelecekte vizyonun ne olduğunu anlamak için önemli bir ayrımdır.

Tez kapsamında Eklemeli Üretim sistemleri ve yapı ölçeğindeki uygulamalar üç aşamada ele alınmıştır. İlk aşamada eklemeli üretim sistemlerinin tarihçesi ve gelişim aşamaları incelenmiştir. Tarihçesine paralel olarak ilk kullanılmaya başlandıkları 1980’lerden bu yana sınıflandırma çabaları ele alınmıştır. Son olarak da ASTM’nin (American Society for Testing and Material) gerçekleştirdiği sınıflandırma referans alınarak güncel teknolojiler incelenmiştir. İlk bölümde Eklemeli Teknolojiler ile ilgili bir alt yapı oluşturulduktan sonra ikinci bölümde yapılarda Eklemeli Üretim sistemlerinin incelenmesi için bir yöntem geliştirilmeye çalışılmıştır.

Yapı ölçeğinde Eklemeli Üretim sistemleri henüz gelişmekte olan ve çok yeni bir konu olması sebebi ile ve aynı zamanda da yoğun olarak uygulamaya dayanan bir konu

olduğu için henüz üzerinde yapılan teorik çalışmalar kısıtlıdır. Her ne kadar teorik alt yapı kısıtlı olsa da sağlıklı bir örnek incelemesi yapabilmek için anlamlı ve tutarlı bir altyapı hazırlamak önem taşımaktadır. Bu sebeple yapı ölçeğinde Eklemeli Üretim sistemlerinin incelenmesi için bir sınıflandırma sistemi önerilmiştir. Önerilen sınıflandırma sistemine paralel olarak seçilen örneklerin incelemesi gerçekleştirilmiştir. Örnek seçiminde ise seçilen projenin ayırt edici özelliği olması ve konu alanında yapılan çalışmaları ileriye taşıyıcı özelliği olması kriter olarak kullanılmıştır. Önerilen sınıflandırma sistemi ile beraber gerçekleştirilen örnek incelemesi çok sayıda örneğin daha anlamlı ve tutarlı olarak incelenmesine olanak sağlamıştır. Yine aynı bölümde örnek incelemelerinin mevcut uygulamalara göre daha iyi konumlandırılabilmesi için ekonomik açıdan ve sürdürülebilirlik açısından konu üzerinde yapılan araştırmalara yer verilmiştir.

Örnek incelemesini takiben henüz uygulama alanı kısıtlı olan ancak gelecek potansiyeli taşıyan uygulamalar incelenmiş ve bu örneklere paralel olarak araştırma konusu önerisi getirilmiştir.

Üçüncü ve son aşamada da eklemeli üretim sistemlerinin avantajları, dezavantajları tartışılmış ve mimarlık, mühendislik ve inşaat alanındaki potansiyel etkileşimleri değerlendirilmiştir. Değerlendirme sonucunda Eklemeli sistemlerin tasarımcılara geometrik özgürlük getirdiği gibi sektörel olarak da malzeme, işçilik, zaman vb konularda verimliliği artırması beklenmektedir. Verimlilikteki artışa sebep olan süreçlere paralel olarak sürdürülebilirlik konusunda da iyileşmeleri getirmektedir. Ancak yapı ölçeğindeki uygulamalar her ne kadar çok hızlı gelişse de halen deneysel bir aşamadır. Sürecin daha da hızlanması teknolojik gelişmelere bağlı olduğu gibi aynı zamanda teknolojinin sektörde kullanırlılığının artması için gerekli yasal düzenlemelerin yapılarak yönetmeliklerin güncellenmesi gerekmektedir.

Son değerlendirmede ise Eklemeli Üretim sistemlerinin belirtilen avantajlarının ötesinde yarattığı gerçek farklılığın tasarımcıların düşünme ve tasarlama biçimlerinde olduğu tartışılmıştır.

1. INTRODUCTION

The latest developments in digital and computational design has 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 of planar shapes and cylindrical, spherical, or conical forms. Plan no longer “generates” the design; sections attain a purely analytical role. Grids, repetitions, and symmetries lose their past raison d’etre as infinite variability becomes as feasible as modularity and as mass-customization offers alternatives to mass production”

The integration of 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 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 thesis 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. Therefore I find it crucial to examine the state of the art technologies in AM relating to Architecture, Construction, Engineering (AEC) industry to stay ahead or at least to be better informed.

1.1 Motivation

Additive manufacturing 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). Although 3D printing has been around since early 80’s, the term "3D printing" has recently become more common and much more accessible thanks to user friendly desktop 3D printers. On the other hand the term 3-D printing is actually an additive manufacturing (AM) technique for fabricating a wide range of structures and complex geometries from three-dimensional (3D) model data. (Ngo et al., 2018). 3D printing technologies are today implemented for very different products, such as jewelery, biological implants, automotive parts, bridges and houses. The more comprehensive term "additive manufacturing" has been defined by The American Society for Material and Testing in 2019 as: "the process of joining materials to make objects from 3D model data..." . In the following chapters while I will be analysing further in detail the four important concepts mentioned in the above definition: "process", "material", "model", and "data", the thing that I will be focusing on will be mostly be related to the large scale applications in Architecture Engineering and Construction (AEC) industry.

The main objective of this study is to further research whether the oppurtunities created by AM can be extended into larger scale structures efficiently and what are the challanges facing the AEC community. In the following chapters the state of the art AM technologies and materials will be presented in detail and through case studies environmental and economic challenges and oppurtunities will be discussed.

1.2 Approach and Methodology

This research on Additive Manufacturing (AM) predominantly evolves through five stages. (Fig: 1.1) In the first two chapters a detailed insight into AM is given, moving on to current state of the art technologies and finally exploring whether it has a potential in large scale structures.

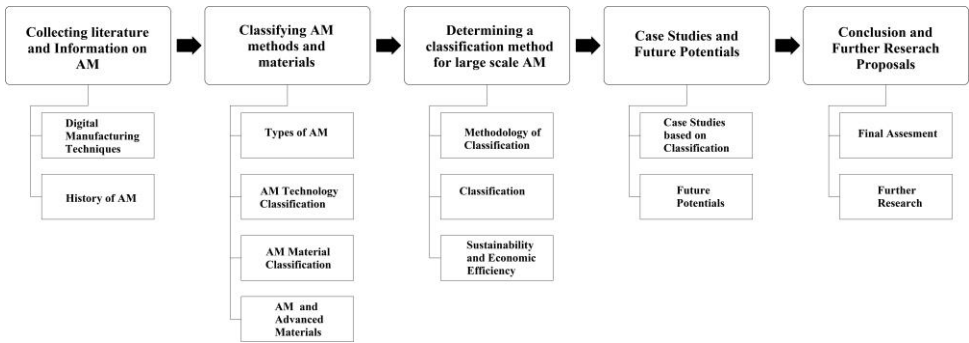


Fig 1.1: Schematic Overview of the Research (By the Author)

Due to the novelty of the subject, the research on AM especially on Large Scale Structures proved to be rather challenging. Since AM is not a “theory only” subject and 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. 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 analysing a specific phenomenon. In order to create a basis for case studies a large number of sources were generated consisting of;

- State of the art AM technologies;
- A brief research on materials;
- AM applications published in various medias;
- Regulatory institutions’ papers;

A particular importance is given to the classification in every phase of the research. Since The American Society for Testing and Materials (ASTM) (2009) provided a detailed classification of AM technologies it was a straight forward task to prepare a guideline on the subject. On the other hand though ASTM provides detailed material technical requirement it does not make a classification. The lack of an accepted classification forced the research choose one of the methods.

The same problem continues with the large scale structures. The lack of a widely accepted classification method led to merging a few of the methods and creating a new hybrid one. This classification system is used in Case Studies to better position each and every one of the chosen projects in a large group of project pool.

Before conclusion future potentials and possible further studies are discussed.

Finally, in the conclusion chapter, the advantages and challenges and the future prospects of AM in Architecture, Engineering and Construction industry is elaborated.



2. DIGITAL MANUFACTURING TECHNOLOGIES

This section takes a brief look at the evolution of Digital Manufacturing (DM) techniques and the four types DM techniques to better position Additive Manufacturing, the main subject matter of this thesis.

2.1 Digital Manufacturing Technologies

In the early 19th century, Industrial Revolution changed the face of production and “creating objects” evolved into a much extensive process called manufacturing. Today in contrast to the early days of Industrial Revolution it is much harder to find non-manufactured objects. We can classify the manufacturing processes into mainly four types; Subtractive, Forming, Casting and Additive manufacturing.

Depending on the manufactured objects’ requirements any of the above mentioned methods can be utilized. Complexity of the geometry of the object, material, or simply the budget of the project can help determine the manufacturing process . Nevertheless either subtracting material from a bigger mass, forming objects using stresses, casting specimens using moulds or additive manufacturing process will be a part of the manufacturing. The above mentioned techniques that are used in making objects are described briefly in the following sections. (Fig: 2.1)

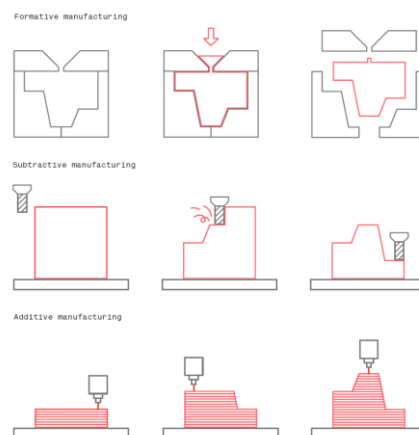


Fig 2.1: Formative, Subtractive and Additive Manufacturing processes (Varotsis, 2018)

2.1.1 Subtractive process

In order to create an object, material from a larger piece of material is removed by the help of machining processes such as milling, turning, lathing, chipping. The subtracted material is usually considered as waste and a second process is needed in order to recycle the material to create usable materials. Subtractive manufacturing is extensively used automobile spare part manufacturing. (Fig: 2.2)



Fig 2.2: Subtractive Process (URL – 1)

2.1.2 Forming

In order to create the desired geometric deformation the use of appropriate stresses like compression, tension and shear is required. In this process, no material is removed from the raw material, instead they are deformed and displaced. (Fig: 2.3)



Fig 2.3: Sheet Metal Forming (URL-2)

2.1.3 Casting

The process of pouring a liquid like material into a mould with the inverse shape of the desired geometry then leaving it to solidfy is called “Casting”. The finished product is removed from the mould either by directly ejecting if not possible by

breaking. In order to create a high quality finished product usually more than one method is applied.

Due to the nature of the process casting may not always create the desired shapes. So further reshaping and post production may be necessary to obtain the desired geometrics. (Fig: 2.4)



Fig 2.4: Casting (URL – 3)

2.1.4 Additive manufacturing

Additive Manufacturing (AM) is a process in which three-dimensional objects are made by adding layer-by-layer of material. The material used can be plastic, metal, concrete etc. The commonly used AM technologies includes the use of a computer, 3D modelling software (Computer Aided Design or CAD), machine equipment and layering material. We will go further in detail about the process in the following sections.



3. ADDITIVE MANUFACTURING - STATE OF THE ART

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”.

Additive Manufacturing does not require extra tools or moulds enabling the user to experiment freely with the geometry of the designed product.

Additive manufacturing is being used in fields like product design, consumer goods, industrial goods, medical and military applications for several years. From shoe soles to jewelry, from jet engine parts to car chassis parts, from designer lamps to medical implants layered construction has spread to many fields.

3.1 A Brief History of AM

Already in the early 1980's 3D printing were being discussed in the academic circles, only it wasn't called 3D printing but Rapid Prototyping. Dr Hideo Kodama in 1980 applied for the first patent RP technology. On the other hand the origins of 3D printing goes back to 1986, stereolithography apparatus (SLA) being the first technology to be patented as 3D printers. Charles Hull first invented SLA machine in 1983. Because Hideo did not complete the accreditation forms he was only credited with the first demonstration of a “printed” three dimensional (3D) plastic model photopolymerization. Chuck both took the credit for stereolithography, and also patented the technology in 1984. (Paull, 2017) .

Stereolithography uses ultraviolet laser light to solidify every layer. Following SLA, the other most commonly used techniques are introduced in 1988 namely; Selective Laser Sintering (SLS), a powder based material sintered by laser and Fused Deposition Modelling (FDM) methods. (Goldberg, 2018)

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 the cells of human patients. (Moon, 2014)

In 2005, the rip rep movement, an open-source initiative enabled the users to print parts of a 3D printer by another 3D printer. (Goldberg, 2018) This was 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 began experimenting 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)

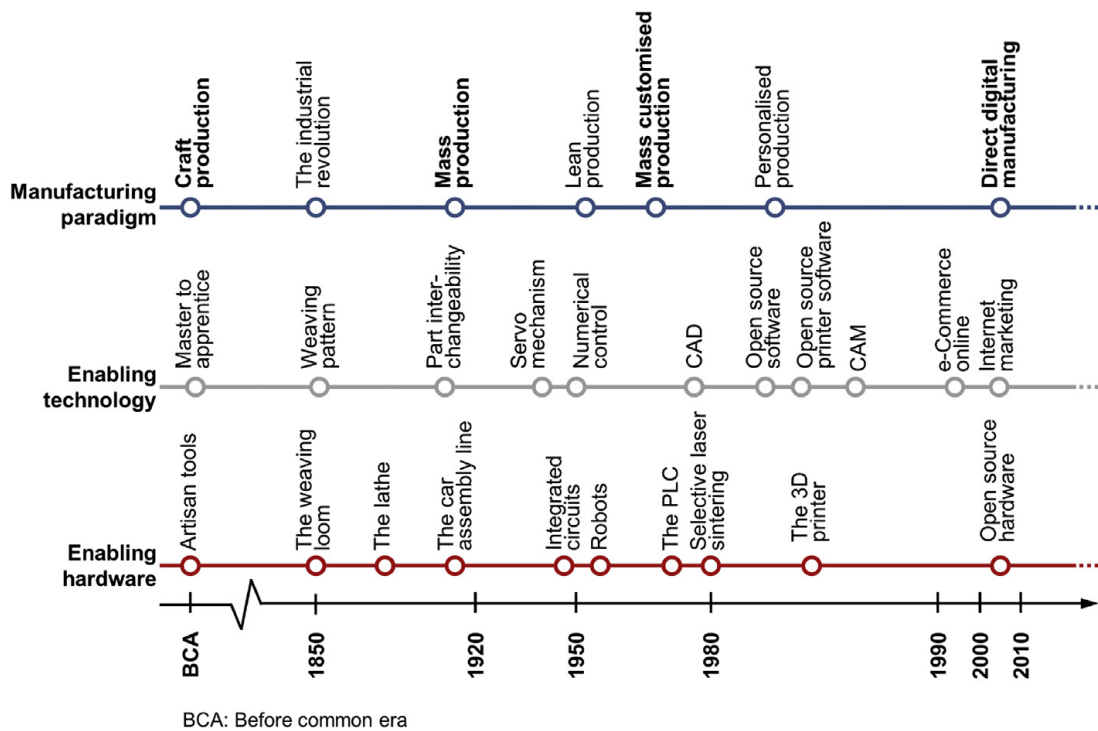


Fig 3.1: A time line of different manufacturing paradigms (Chen,2015)

The above graphic in Figure 3.1 very well summarises the historic relationship between manufacturing paradigms and societal changes. As Menges(2015) argues

“.....the convergence of the computational and the physical, the rapid change of industrial logics of production and the erosion of established disciplinary hierarchies are beginning to radically transform design. Reconciling the rift between the scientific world and the designer’s realm of modalities and intuition.”

3.2 The Principles of Additive Processes

The main principle of Additive Manufacturing is universal for all of the different methods: layering of a 3D CAD model by a special software. The horizontal cuts/layers of the 3D model are essentially repetitive sections. The layering process is also called slicing and the device used to manufacture the output is called the printer. The printers usually have a predetermined chamber size unless robotic arms are used then the size of the object may increase as the set up changes. Though the size varies greatly the process of consecutive layering whilst the previous layers are cured remains the same. Different methods require different curing processes; it can either be by exposition, heating, or bonding. The materials used in these processes will be further examined in the following chapters.

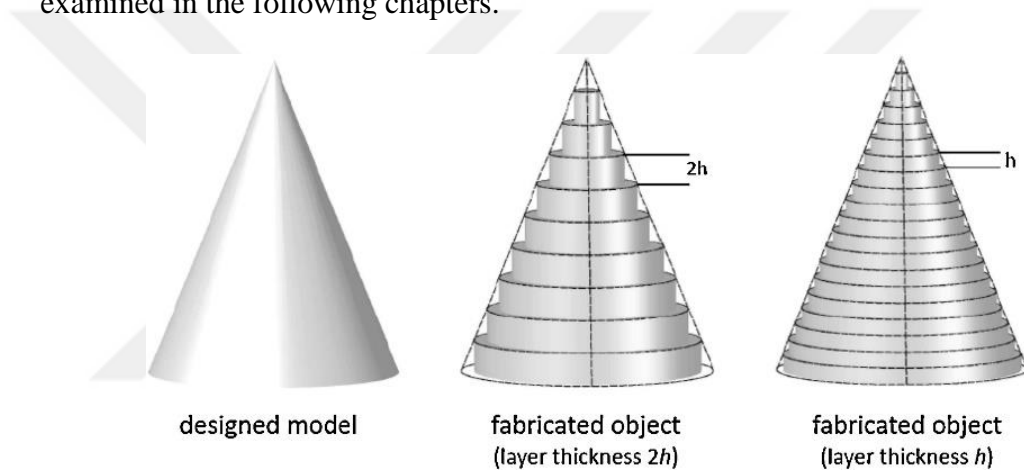


Fig 3.2: Stair-step effect resulting from layer-wise fabrication (Quan, 2015)

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 (Fig: 3.2). The smallest possible thickness of the layers are defined by the AM system used; it varies from millimetres to microns. The 3D printing of the model can take from a few hours to several days. Once the 3D printing process is completed it is followed by post processing such as removal of support fixings, surface cleaning, removal of uncured material, infiltration, and others.

3.3 From 3D Model to Material Product

Once the 3D CAD model is layered by a special software the printing process starts (Fig: 3.3). 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. Among this broad spectrum of materials plastics, resins, metals, ceramics, sand, biomaterials, textiles, glass, food and even lunar dust can be counted. Furthermore in order to achieve the exact design most of these materials also allow several finishing options. The material choice cannot be separated from the Additive Manufacturing technology to be used. Some materials work with specific AM technologies therefore when choosing the material the technology is also chosen simultaneously.

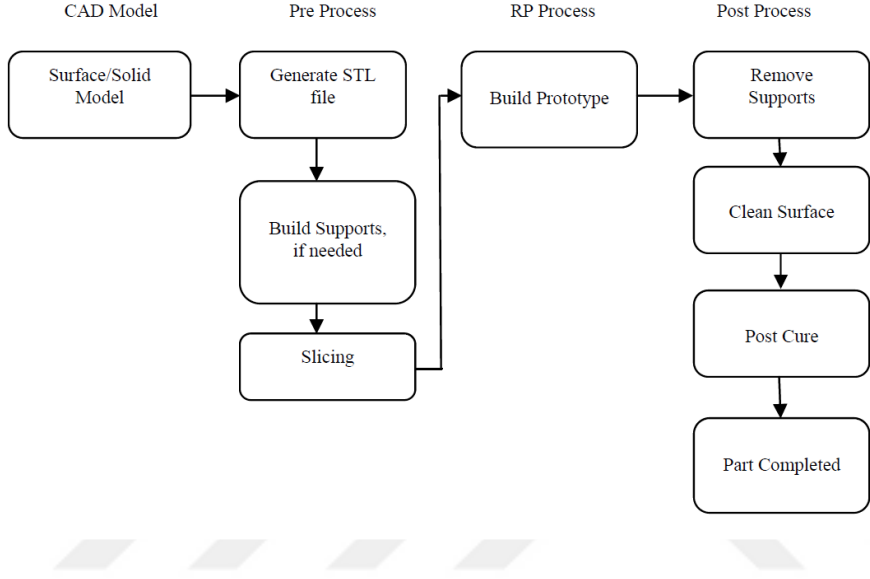


Fig 3.3: The AM Process from design to production (Prakash, 2018)

In AM to generate a 3D model, the vertical Z axis is needed in addition to the two horizontal axes X and Y. Depending on the individual print method used either the movable printheads /light beams or the work platform will be moving on the Z-axis.

Some of the AM methods require supports for the cantilevered or protruding geometries. Unless a specific support is required usually the intermediary software used for 3D printing determines the necessary supports. The surface quality of the object may be effected depending on the types of supports used.

On the other hand the main determining factors in surface quality are the chosen manufacturing method and the materials used. By choosing the right type of manufacturing method that is in line with the necessity of the project the user can influence the final quality of the manufactured parts. Though all methods are based on a layered manufacturing system, the stepped surface effect can be managed with arranging levels of resolution as well as changing the scanning speed. On the other

hand most methods generate varying levels of stepped surface because of the manufacturing technique.

3.4 Types of Additive Manufacturing

The terms additive manufacturing, three dimensional printing, rapid prototyping and direct digital manufacturing are being used interchangeably. Though these terms in general are very similar to each other still each carry a different meaning.

3.4.1 Rapid prototyping (RP)

In the late 80's Rapid Prototyping was able to capitalize the developments in Additive Manufacturing technologies. It has allowed the designers and engineers to make scale prototypes using 3D computer aided design (CAD) data without going through the rigorous and costly process of mould making. From the early days of AM technology it was mostly used to make prototypes that's why sometimes the terms are used interchangeably. (Miller, 2012) Though Rapid Prototyping mostly use layered additive manufacturing it can also utilize moulding and casting.

In relation with the AM methods the term rapid is a relative term because the manufacturing process can take up several days depending on the part trying to be manufactured. Nevertheless the term rapid is used in comparative perspective to traditional manufacturing methods like producing a conventional injection moulding.

3.4.2 Direct digital manufacturing (DDM)

Direct digital manufacturing (DDM) is an AM based technology and is used to produce end use / final products directly from a 3D CAD file. It is often confused with Rapid Prototyping (RP) yet in practice DDM requires a much more extensive research and planning period. Considering the fact that DDM produces the end use product it is only natural to have further considerations and requirements that are not taken into account for prototyping. (Gibson et. al., 2015)

DDM still cannot be used for mass production purposes due to comparatively unfavorable economic position. Therefore it is mostly used for customized low-volume production applications. On the other because it reduces the time between design and production and lowers the investment for tooling it will become a more viable option in the long run once technology cost lowers. (Chen et al., 2015)

3.4.3 3D Printing

The term 3D printing first used for the technology invented at MIT in 1995 when they used an inkjet printer head to extrude a binder on to a powder bed to manufacture three dimensional objects from a CAD file. Since the process carries similarities with the traditional printing process it was named 3D printing and the term has caught on with the public because of its familiarity. (Miller, 2012)

3.5 Classification and Overview of the most common AM processes

In order to better understand the several different technologies and materials involved in AM processes we need a classification method. Yet the classification of the additive manufacturing processes have been a long disputed subject. One of the most common classifications methods is based on the state of the material used; solid, liquid, powder etc. Yet it has been an inconsequential effort due to disputes on which material belonged to which state. (Jimenez et. al., 2019) One of the most cited classification of process based on materials belongs to Kruth et. al. (1998).

According to Jimenez et. al. (2019) who has comprehensively dealt with the standartization proceses in AM, the classification method based only on materials did not satisfy every group involved in the process such as industry, trade, academic and consumer groups. Since the early stages of AM there has been several further attempts for the development of specific standards for AM. American Society for Testing and Materials' (ASTM) studies began in 2010 and in 2015 the widely accepted standards set by ASTM were also accepted by International Organization for Standardization (ISO).

They have agreed on the standard terminology to be used, the processes and the materials utilized, test methods and the data formats. For this study's purpose only the classification methods based on materials and processes will be analysed in detail.

ASTM identifies the following groups of AM based on technology used: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization. (Monzon et. al., 2015)

From the point of view of the material, ASTM and ISO have agreed on setting the standards on general, mechanical, thermal and electrical properties of the raw materials and the final products yet did not make a more comprehensive classification. (Monzon

et. al., 2015) Therefore in literature the classification of AM materials varies greatly. It is either based on the state of the material or the material itself; i.e. plastic, metal, glass etc. As the AM technology develops rapidly, the number of materials used increases making the classification of the materials based on their states more of an encompassing choice. In this thesis material classification will be based on the materials' state due to the more universal nature of the approach.

Classification of materials based on their states seems to be a straight forward task. On the other hand there isn't only one classification system based on states due to lack of agreement both on the "states" and which material belongs to which state. For example Labonnote et al. (2016) classifies the materials into four groups; i. solid-like materials, ii. viscous-like materials, iii. powder-like materials, iv. liquid-like materials. Tofail et. al. (2018) classifies the materials into two groups; i. liquid based and ii. Solid based. Labonnote creates two distinct groups for powder and solid materials where as Tofail places powders, sheets and filaments under solid based materials. On the other hand one of the earliest and most widely accepted classification made by Kruth et al (1998) uses three states i. powder based, ii. liquid based and iii. solid based.

3.5.1 Classification of additive manufacturing based on the technology used

In the following section the AM technologies defined by ASTM will be summarised. The seven technologies determined by ASTM are; Vat photopolymerization (VP), Powder bed fusion (PBF), Material extrusion (ME), Material jetting (MJ), Binder jetting (BJ), Directed energy deposition (DED), Sheet lamination (SL). While defining each technology, its advantages, disadvantages and the materials used will be discussed. Though all technologies are not relevant for additive manufacturing of large scale structures it is assumed to be necessary in order to better position the technologies and maybe help propose a hybrid system for further research.

All the AM technologies mentioned below are explained with graphic representation and in Table 3.1 adapted from Tofail et al (2018) ASTM categories of AM coupled with basic principles, advantages, disadvantages and materials are summarised. Further detailed comparison of Additive Manufacturing technologies in large scale structures will be made in the following chapters.

Table 3.1: ASTM categories of AM Summarised (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 Widespread use	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)	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 Relatively inexpensive	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)	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

3.5.1.1 Vat photopolymerization (VP)

Liquid photopolymer in a vat is selectively cured into solid by exposure to light through the process of light-activated polymerization. Widely used materials are: Photopolymer resins. Some of the example technologies are: Stereolithography (SLA), Digital Light Processing (DLP), Select, Scan and Selectively Cure (3SP) and Continous Liquid Interface Production (CLIP) (Fig: 3.4).

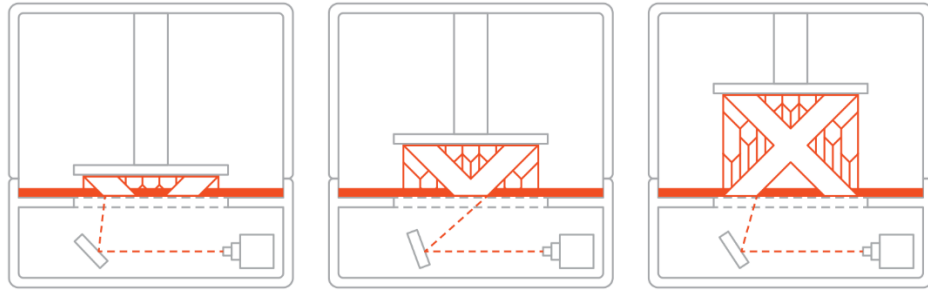


Fig 3.4: The SLA 3D printing process (Varotsis, 2018)

SLA is the first patented AM technology in 1986. The advantage of SLA is; it creates a very high accuracy or smooth surface finish with relatively low costs.

3.5.1.2 Powder bed fusion (PBF)

Powder based material is selectively solidified by a heat source like a laser. It has a high accuracy rate. Additionally the parts produced have good mechanical properties. Also since the printed products are sintered in a powderbed they require no supports. (Fig: 3.5)

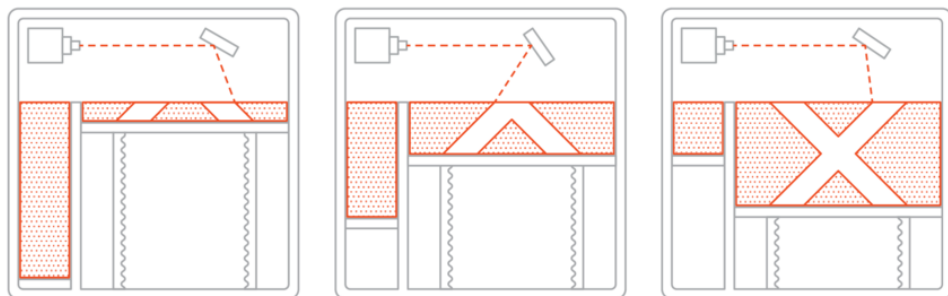


Fig 3.5: The SLS printing process (Varotsis, 2018)

One of the characteristics of the process is the surface finish has a as high as 30% porosity. Some of the example technologies are: Selective Laser Sintering(SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Multi Jet Fusion (MJF)

3.5.1.3 Material extrusion (ME)

The chosen material is extruded through a nozzle either by heating or dispensing it like a syringe. Some of the example technologies are: Fused Deposition Modelling (FDM), Fused Filament Fabrication (FFF). Typical materials are thermoplastic filaments, liquids and slurries.

The desktop market for 3D printers is dominated by FDM technology. It is the most widely used AM technology: due to relatively low cost of the printers. In desktop printers usually thermoplastics are used. They are melted by a heated nozzle and cured by themselves (Fig: 3.6).

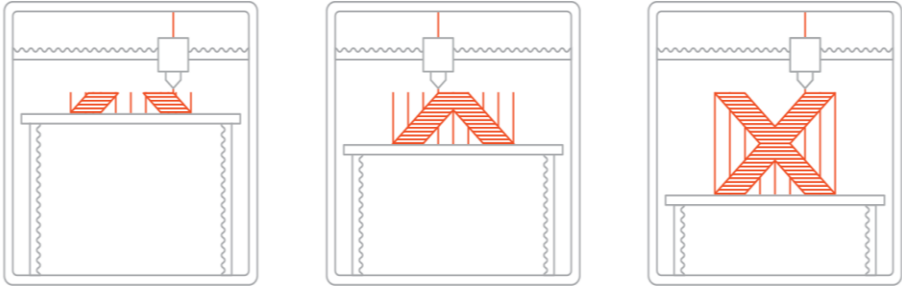


Fig 3.6: The FDM printing process (Varotsis, 2018)

FDM is the most cost effective with the lowest lead time AM technology. On the other hand it is also the least accurate with low printing resolution does not have high mechanical properties. In Figure: 3.7 surface properties of two leading AM technologies can be observed.

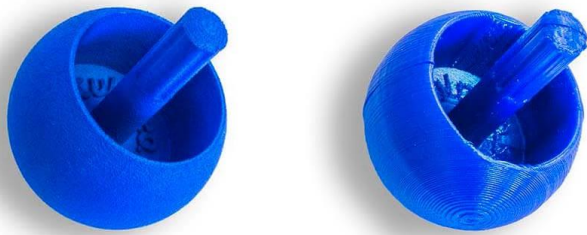


Fig 3.7: The SLS (left) vs FDM (right) technology (Sculpteo, 2019)

3.5.1.4 Material jetting (MJ)

Material jetting is very similar to Selective Laser Sintering (SLS) that are both in powder bed fusion family. In both technologies, same thermoplastic polymers are used and particles are fused through sintering. They differ in their heat sources; SLS uses a laser to scan and sinter each cross-section, while in Material Jetting an ink (fusing agent) is dispensed on the powder that promotes the absorption of infrared light. And in the last step an infrared light source is passed over the inkjet bed letting the fusing

agent cure. Some of the example technologies are: Polyjet, Multi Jet Modelling (MJM), Smooth Curvature Printing (Fig: 3.8).

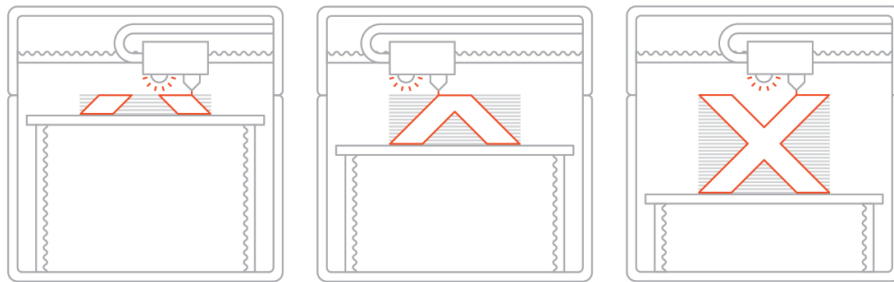


Fig 3.8: The MJM printing process (Varotsis, 2018)

It is a combination of the SLS and Binder Jetting technologies. Below you may see the surface structure with high porosity is very similar to SLS technology (Fig: 3.9).



Fig 3.9: The MJM surface (Varotsis, 2018)

3.5.1.5 Binder jetting (BJ)

In order to join the powder form material a liquid bonding agent is selectively applied. Typical materials used powdered plastic, metal, ceramic, glass and sand. Some of the example technologies are: 3D Printing, Voxeljet, ExOne. (Fig: 3.10)

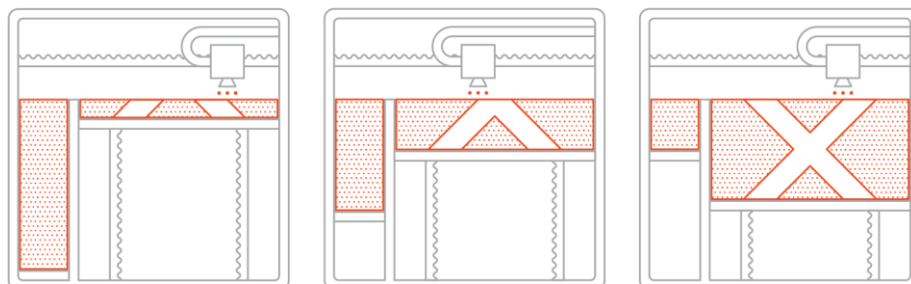


Fig 3.10: The Binder Jetting printing process (Varotsis, 2018)

3.5.1.6 Directed energy deposition (DED)

In this process a focused thermal energy like laser or plasma is directed at the material creating a melt pool and fuse the consecutive layers. This is very similar to welding but automated version. Typical materials used are metal wire or powder with ceramics. Some of the example technologies are: Laser Metal Deposition (LMD), Laser Engineered Net Shaping (LENS) (Fig: 3.11).

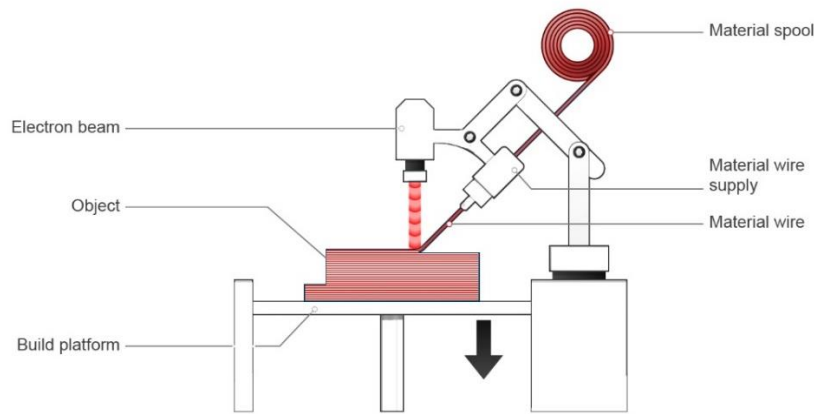


Fig 3.11: The Directed Energy Deposition process (Varotsis, 2018)

3.5.1.7 Sheet lamination (SL)

In order form the final object sheets are laminated together through either adhesives (paper/plastics) or ultrasonic welding (metals). Advantages are high volume manufacturing rates and is relatively low cost. Some of the example technologies are: Laminated object Manufacture (LOM), Selective Deposition Lamination (SDL), Ultrasonic Additive Manufacturing (UAM).

3.6 AM 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 bit of atom 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 optimisation both in form and material distribution. In macro scale, with topology optimisation the layout of the material is being organised based on the load the design receives and in microscale it allows the designer to control material heterogeneity. In order better understand the process

around materials it is our best interests to understand the scope of the materials used in AM processes.

As mentioned previously 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 thesis the widely accepted classification of Kruth et al (1998) will be used (Fig: 3.12). Kruth et al (1998) classifies the materials based on their deposition states; liquid based, solid based, and powder based.

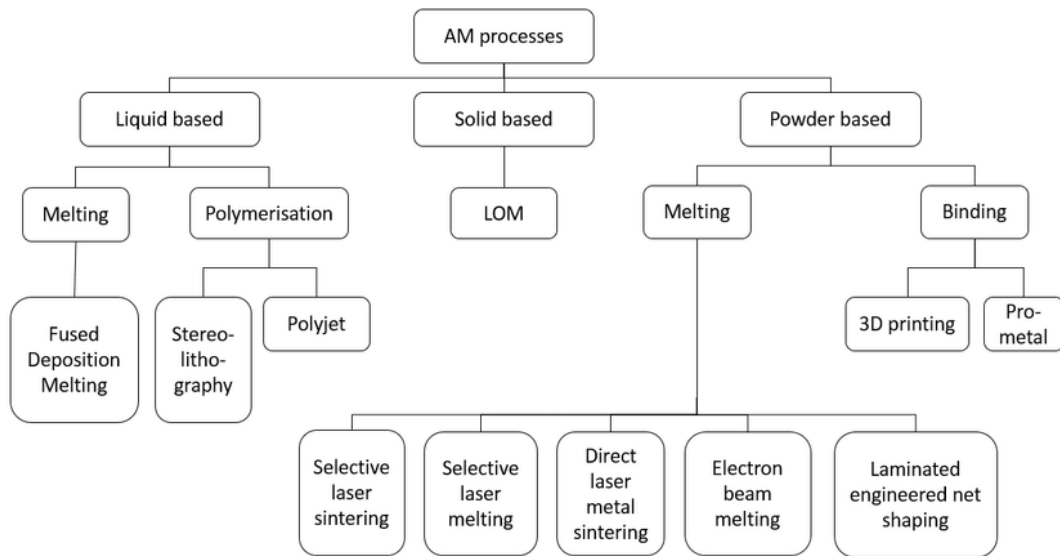


Fig 3.12: The different states of a material before deposition (Deradjat, Minshall, 2016)

3.6.1 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 glueing / 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.

3.6.2 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 clean up 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.

3.6.3 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.

3.7 AM and Advanced Materials

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) In this thesis because the subject matter coincides with the subject matter of the thesis 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 physical 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.

3.7.1 Functionally graded materials

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 (Fig: 3.13). The materials can be designed for specific function and applications.

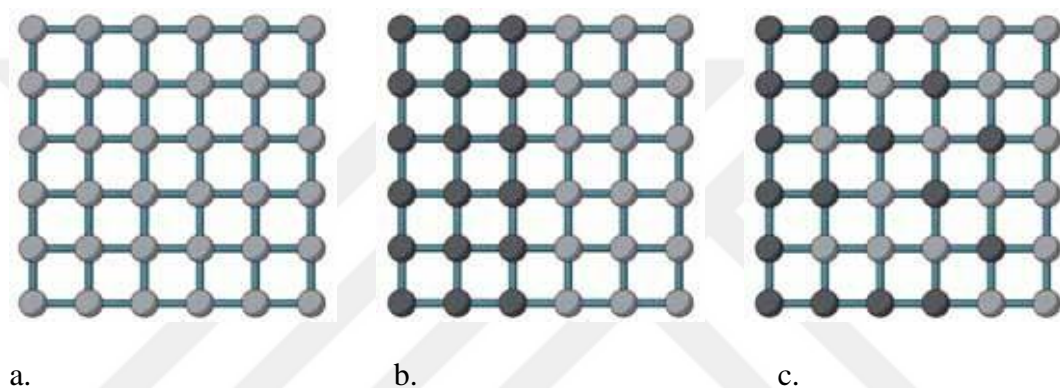


Fig 3.13: a.) Homogenous material; b.) joined material; c.) Functionally Graded Material (FGM) (Strauss, 2013)

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 Inkjetting, 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 (Fig: 3.14).

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 aluminium frame connect in a unitised 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.”



Fig 3.14: Close up interior view of the fabricated multi-material skull interface (Grigoriadis, 2019)

FGM's is one of the fastest developing subjects. For instance, Aerosint, an Additive Manufacturing company, has announced that they have started to utilize multi-material powder bed for manufacturing FGMs. On the other hand, like most other companies in the sector, they emphasize the need for voxel-level spatial control over the material to have further three-dimensional freedom. (Scott, 2018)

3.7.2 Smart materials

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 other than mentioning that the studies on nanocomposites

will mostly have an impact on biengineering, physics and chemistry. 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.

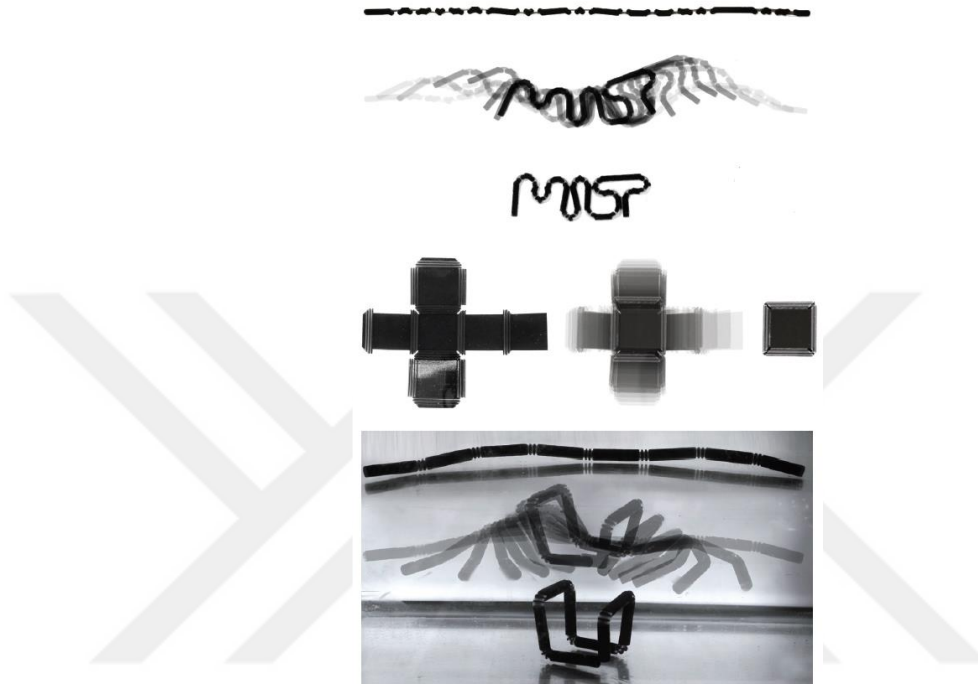


Fig 3.15: 4DP examples : self folding (MIT, Stratasys Ltd, Autodesk Inc.)

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4D printing is another popular subject on which several leading researchers in universities and companies are making big strides. 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 (Fig: 3.15). (Young, 2017)

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.

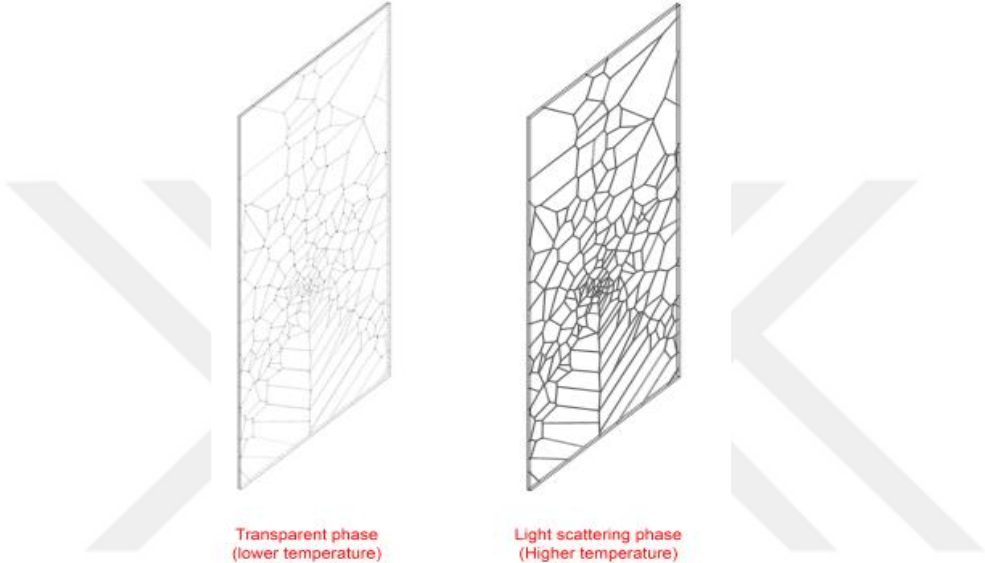


Fig 3.16: Phases of the hydrogel glazing with changing temp. (Khoo et al , 2018)

Biomaterials and 4D printing is also a fast developing research area. Though there are several materials that are in the development phase hydrogels are worth mentioning because of their potential in AEC industries. Smart hydrogels are materials with high water content with an ability of self healing and shape memory (Fig: 3.16). With 4D bioprinting, smart hydrogels will have the ability to respond to external stimulus such as electric, temperature, light etc. Especially there are several projects to make use of hydrogels in self actuating responsive facade systems.

4. TOWARDS LARGE SCALE ADDITIVE MANUFACTURING

4.1 Overview of the most common Large Scale Additive Manufacturing processes

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 on a whole different level in conceptual transformation of design thinking.

Though 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. The advances in computational design and manufacturing have brought on many disruptive technologies and a new way designing and making linking computational tools, material systems and robotic fabrication like it has never been before. Gramazio and Kohler (2008) correlates the design and making of current architectural typologies with repetitive elements to the industrialization of building therefore first to be challenged with the rise of the computational technologies.

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.

The above technologies uses three different deposition head mounting gear; it is either frame, robot or crane (Fig: 4.1). Labonnete et al (2016) adds a fourth approach, swarm robotics.

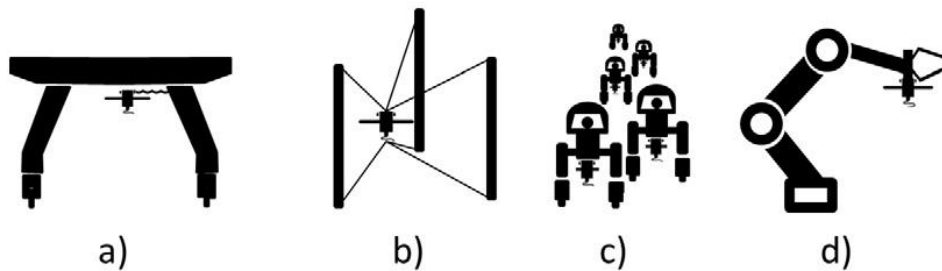


Fig 4.1: Different technological solutions. a) Crane, b) cable-suspended, c) swarm, d) robotics (Labonette et al, 2016)

Contour Crafting uses a crane-mounted device for in-situ applications. Both D-Shape and Concrete Printing are again crane based but they are developed to be ex situ applications. The three processes uses AM technology but the materials and the processes differ.

Contour Crafting has been developed in University of South California by Koshnevis, as early as 1996, is an extrusion based AM process using a cement-we43fgcrbased paste. The process involves the extrusion of the object surfaces, and a filling process to the built core (Fig: 4.2).

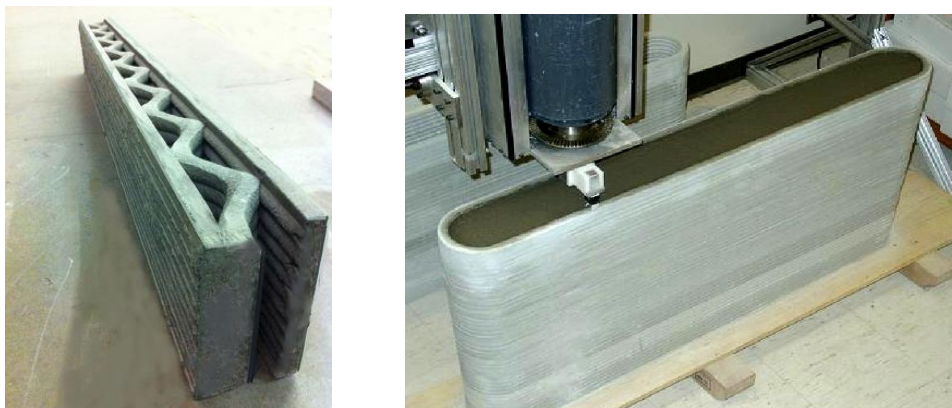


Fig 4.2: Different Contour Crafting applications (URL – 35)

On the other hand the D shape process uses binder jetting method with a powder deposition process, which selectively hardens using a binder. After process is complete the final product is cleaned up from the loose powder bed. This method is used in the making of one of the earliest 3D printed pavilions called Radiolaria (Fig: 4.3).



Fig 4.3: D Shape binder jetting process (URL – 36)

Concrete Printing (Fig: 4.4) is developed by a team at Loughborough University in the United Kingdom. The process is very similar to Contour Crafting which is based on the extrusion of cement mortar. However because the Concrete Printing technology uses a smaller resolution deposition with high performance fiber reinforced fine aggregate concrete, it allows a higher 3D freedom. (Lim, 2012)



Fig 4.4: Bench manufactured with Concrete Printing (URL – 37)

A study of the major additive manufacturing processes created a basis of technological framework for the thesis. 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.

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 analyse several digitally fabricated structures whether they are moulds or not. They classify the mould making process as the Indirect Intervention and manufacturing of the final product as the Direct Intervention. In this thesis the same classification method will be used only using the word “manufacturing” instead of “intervention” to ensure consistency in wording.

4.1.1 Indirect Additive Manufacturing : Formwork / Moulds

Additive manufacturing technology in construction industry is still in its infancy stage. Though 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.

4.1.2 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.

4.1.2.1 Modules, components and joints

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)

4.1.2.2 Monoliths – in-situ fabrication

Monolithic structures based on their scale are mostly on site in situ fabrications. ‘Contour crafting’ and ‘concrete printing’ by means of a crane or cable suspension are developed to manufacture monolithic structures. Though both techniques have many advantages 3D freedom is not one of them therefore lacking one of the main advantages AM brings. However swarm robotic method proves to be more efficient due to its greater efficiency in every scale and mobility.

Both module based and monolithic AM processes are from fully automated optimum solutions. 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: though 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.

4.2 AM and Sustainability in Large Scale Structures

In order to better evaluate the problems in construction sustainability, it would be meaningful to mention the statistics for energy consumption within the construction industry. According to a study made by United Nations Environmental Programme (2012) the construction sector is responsible 40% energy consumption, 40% solid waste generation, 38% GHG emissions and 12% water depletion. Only the construction process itself takes up the 6% of the total energy consumption let alone manufacturing and transportation of materials. Furthermore the construction is one of the least efficient industries in terms material use and production processes.

Today world’s most populated areas are environmentally least regulated countries. In these countries in parallel to the rise in population the number of buildings increase exponentially. For example according to a research made in 2015 by United Nations Development Program (UNDP) more than half of the urban built environments in China are constructed after the year 2010. The above statistics carries global significance considering the fact that China’s population is almost 1.5 billion.

According to the widely accepted definition of sustainability in United Nations' The Brundlandt report (1987) 'Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' . Yet this definition gives a broad understanding of the term sustainability. If we go further in detail and try to define construction sustainability we have to introduce the term 'triple bottom line assessment'. In triple bottom line assessment social, economic and environmental considerations are all taken into account. This definition encompasses the buildings' whole life cycle; fabrication, operation, refurbishment and decommissioning.

Gardiner (2011) evaluates the construction sustainability in six steps all considered in terms of from construction to decommissioning: material use, energy use, air pollution, water use/recycling, biodiversity support and occupant comfort.

Though all six of the reference points will not be evaluated in this thesis it can be used as a guideline for further study.

In terms bringing a resolution to the above mentioned criteria large scale Additive Manufacturing addresses most of the issues.

Ford and Despeisse (2016) defines three areas AM will most likely be the most efficient.

“Improved resource efficiency: improvements can be realised in both production and use phases as manufacturing processes and products can be redesigned for AM;

Extended product life: achieved through technical approaches such as repair, remanufacture and refurbishment, and more sustainable socio-economic patterns such as stronger person product affinities and closer relationships between producers and consumers;

Reconfigured value chains: shorter and simpler supply chains, more localised production, innovative distribution models, and new collaborations.”

In terms of material use AM is inherently much more efficient due the fact that it only deposits the amount of material that is needed. In comparative perspective to traditional construction industry much of waste as formwork can readily be eliminated. Also in situ production techniques lowers the environmental impact of transportation.

For example, several large scale 3D print companies like Winsun and WASP choose low cost materials like construction waste or locally sourced clay, saving between 30-60% on raw materials used, both benefiting from economic and sustainable advantages of recycled materials. On one hand lower manufacturing costs create an advantageous

position for developing countries on the other hand also benefiting more developed nations due to low labour costs while simultaneously satisfying the environmental requirements. (Kidwell, 2017)

Another added benefit AM is that since it is a digital technology connected to optimized design processes the parts produced can also topologically be optimised meaning less material use.

Furthermore AM goes hand in hand with developments in material science. Since the technology of AM allows the use of any material that is in line with its requirements the environment friendly bio inspired developments in material science can effectively be used. This will be further discussed in future potentials of the technology.

4.3 Economic efficiency of AM in Large Scale Structures and Mass

Customization

Schuttera (2018) emphasize the main significance of AM in construction industry as a logical evolution of Computer Aided Design (CAD) tools to automated construction, making the process fully digitalized. As a direct result of fully digitized process it is only natural to see a reduction in construction times and a rise in quality creating an overall productivity increase.

Kidwell (2017) as a proponent of AM references a study made by Associated General Contractors of America. In this study the statistics show that 70% of construction firms are having a hard time filling hourly craft position and 51% of those firms also claim that they are having a hard time filling concrete worker positions. This statistic carries a significance such that most developed countries are facing similar problems of finding workers for blue collar works. In the developing countries the problem is reverse though the labour supply is high finding higher qualified worker proves to be difficult. Statistical graphics in Fig 4.5 show that in developed countries the use of additive manufacturing technologies in large scale structure prove to be more profitable due to high cost of raw material and labour. In less developed countries the cost of raw material and labour is lower therefore the use of AM technologies in large scale structures may not justify initial investment cost.

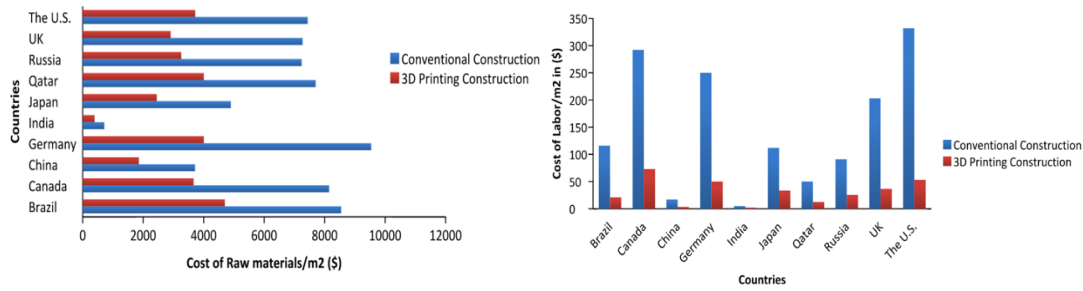


Fig 4.5: Cost and Material Savings (Kidwell, 2017)

According to an industry report as shown in Fig 4.6 the number of large scale applications has seen a significant rise in the last decade. Since 2016 it has seen a 800% growth and is expected to become a 40 billion dollar industry by 2027. (URL – 30)

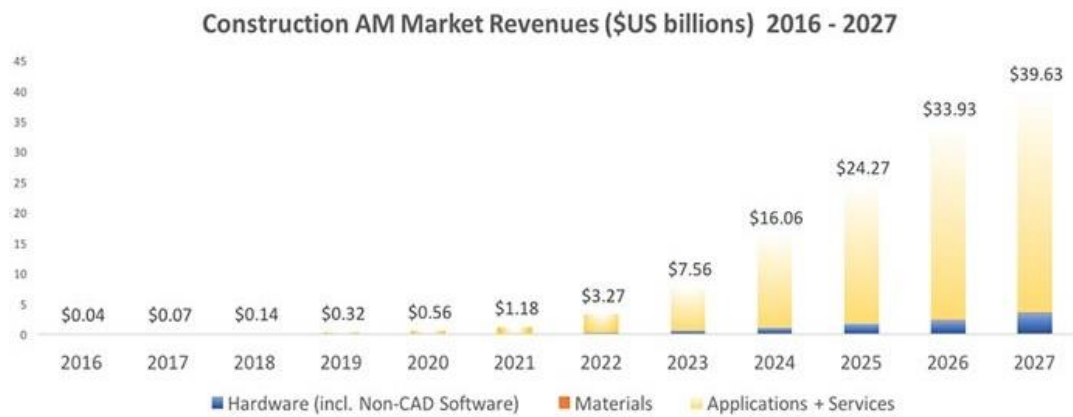


Fig 4.6: The expected market revenues of AM in AEC sector (URL – 30)

The 3D printed Dubai Office Project (Fig 4.7) is reportedly printed in 17 days, constructed in 48 hours, with only 18 workers. (URL-5) The building is said to have cost 140.000 USD which is argued to be 50% less than what could be with traditional methods. Dubai known for its rapid development has announced that by 2030, 25% of country’s new builds will be based on 3D printing technology.



Fig 4.7: Dubai “Office of the Future” -2017 (URL-5)

5. CASE STUDIES IN ADDITIVE MANUFACTURING

The indepth study of additive manufacturing processes prepared the foundation work of the thesis. In this section several relevant applications of large scale additive manufacturing will be investigated. As mentioned previously the number of additive manufacturing applications has seen a tremendous increase in the last decade yet 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 realised 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(Fig: 5.1). (URL - 29)



Fig 5.1 Buildings 3D printed by Chinese company WinSun since 2013(URL - 29)

Like WinSun there are several other construction companies utilising 3D printing. As of 2019 the following companies are the leading companies in 3D printing construction sector; Apis Cor (Russia), BatiPrint (France), WASP (Italy), KamerMaker (Netherlands), WinSun (China), Cazza (USA), Contour Crafting (USA), XtreeE (France), D-Shape (Italy).

The above mentioned companies are mostly working on commercial projects. 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.

5.1 Indirect Additive Manufacturing - Moulds

5.1.1 Zurich Deep Facade – ETH Zurich

ETH – Zurich Deep Facade, a six-metre-high aluminium structure is significant because the molten aluminium is cast in a mould made of sand. The mould is 3D printed using binder jetting technology (Fig: 5.2).



Fig 5.2: 3D printed sand mould and cast metal facade (URL - 6)

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 realise complex forms relatively cost effective and in a short period of time.

Designed with a differential growth algorithm and topologically optimised panel is cast in 26 articulated modules and combined on site.

5.1.2 Organic Column – XtreeE

This 4m-high columns in the playground of a school in France have load bearing properties. They are designed with topological optimization tools in two parts; the formwork, and the concrete that is cast inside the formwork (Fig: 5.3).

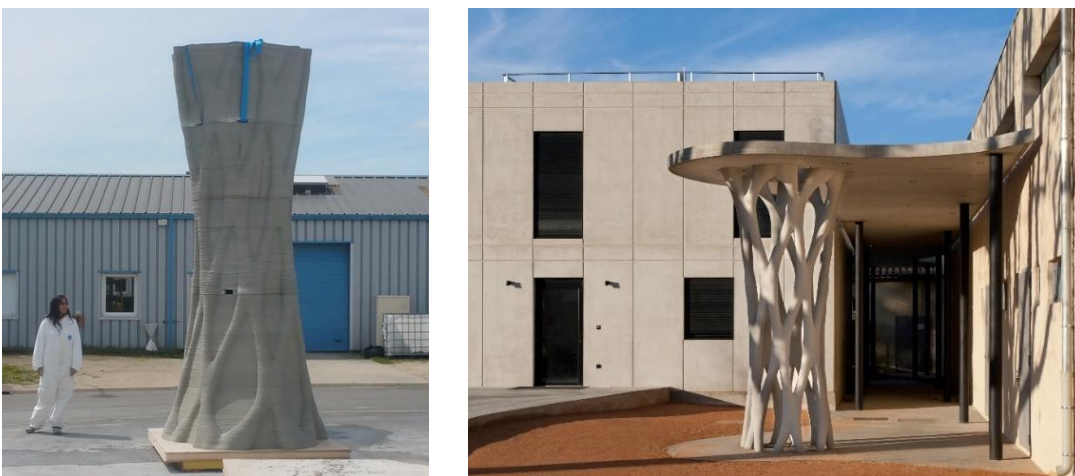


Fig 5.3: 3D printed formwork and load bearing AM column

The printer is an extrusion based printer using two types of cement mixture; one for the formwork and the other for the structure. The structure is printed in four parts and the total printing time is 15 hours and 30 minutes. The modules are assembled on site.

5.1.3 Concrete Formwork – AI Build

The custom mould uses and extrusion based printing technology. 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 (Fig: 5.4).

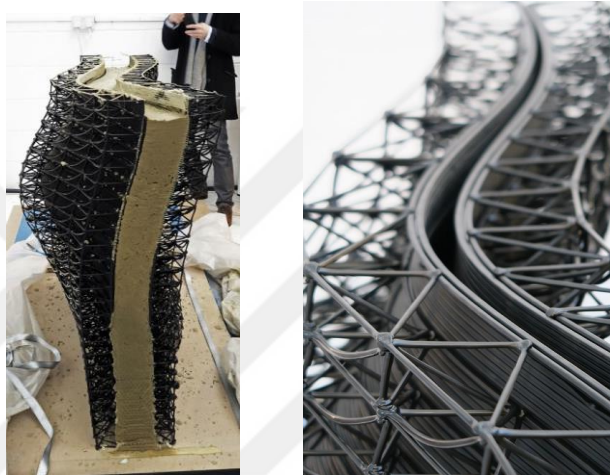


Fig 5.4: 3D Printed Custom Formwork (URL – 7)

5.1.4 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 . The lightweight concrete slab is cast into a 3D printed sand mould using binder jetting technology (Fig: 5.5).

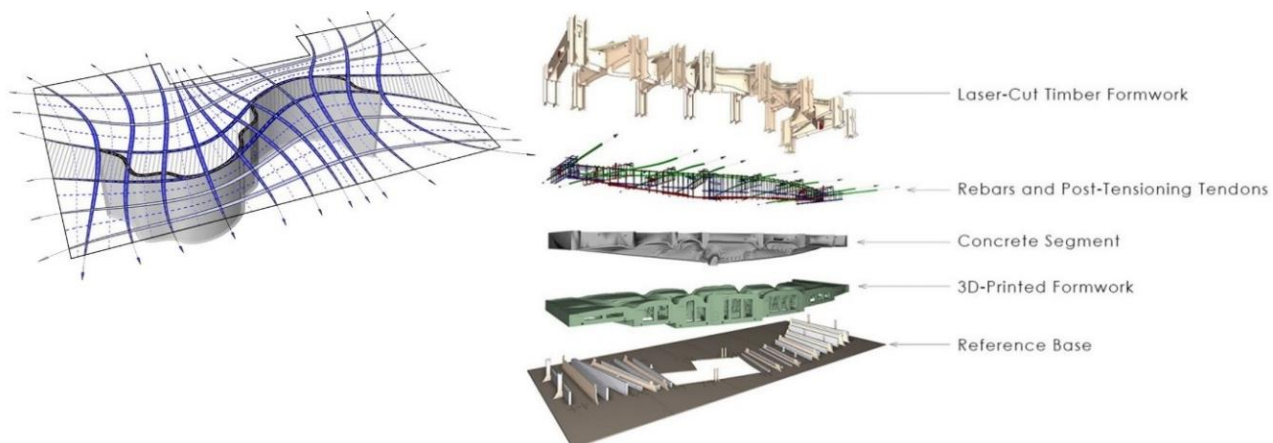


Fig 5.5: Smart Slab Drawings (URL – 8)

The design of the concrete slab is topologically and structurally optimised meaning less material is used with increased structural strength. The formwork of the concrete slab would be the most labour intensive process if done with traditional methods.

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 (Fig: 5.6).

The largest cantileverin point is 4.5 metres with varying depth between 30 and 60 centimetres. As a result the weight of the slab is 70% less than a traditional slab.

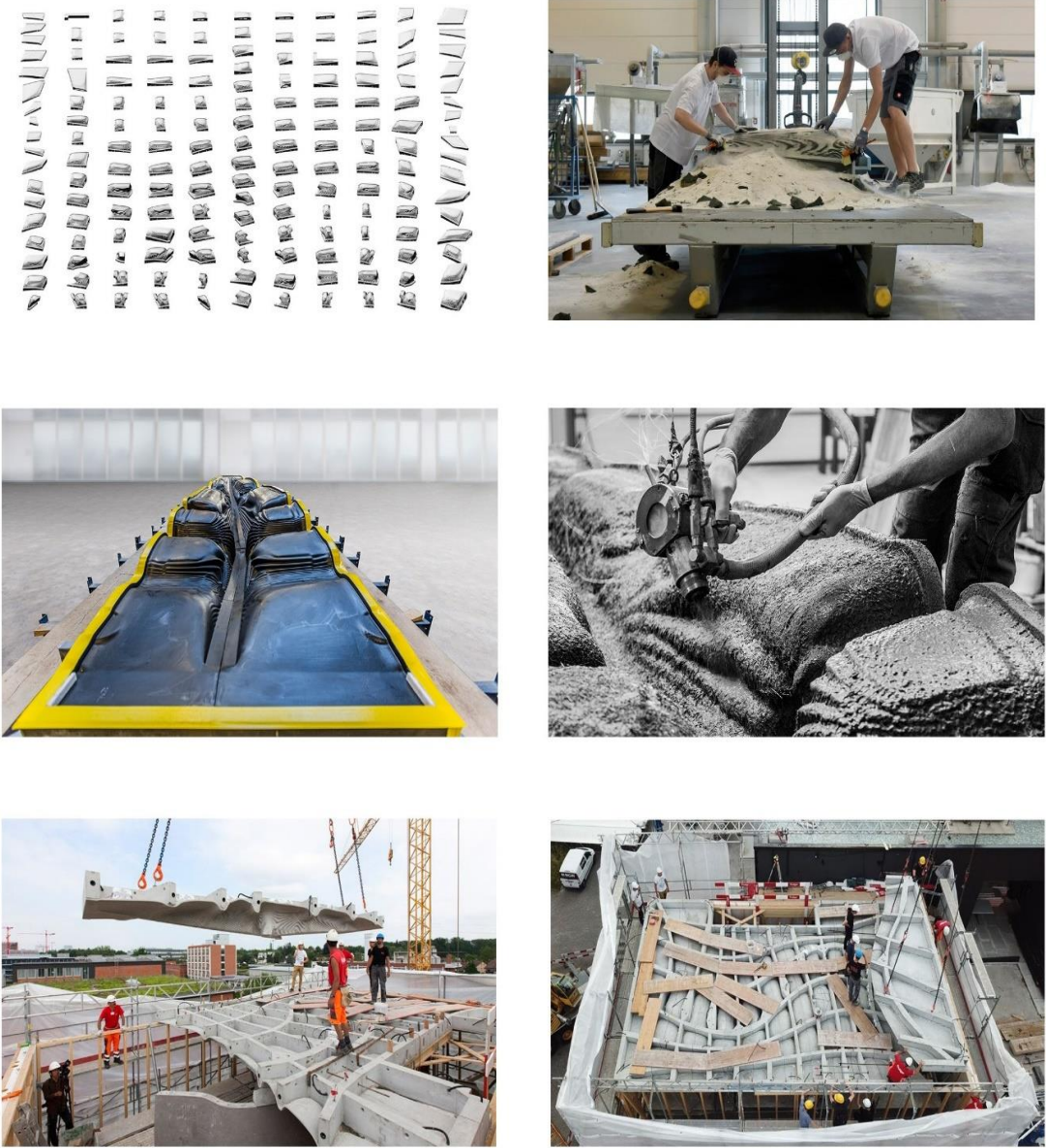


Fig 5.6: Smart Slab Processes (URL – 8)

5.1.5 Foam Formwork – MIT

The system is based on a mobile robotic arm with extrusion based 3D printer nozzle head. The structure is designed as to 3D print the formwork using insulation foam. The whole process took about less than 14 hours of printing time (Fig: 5.7).

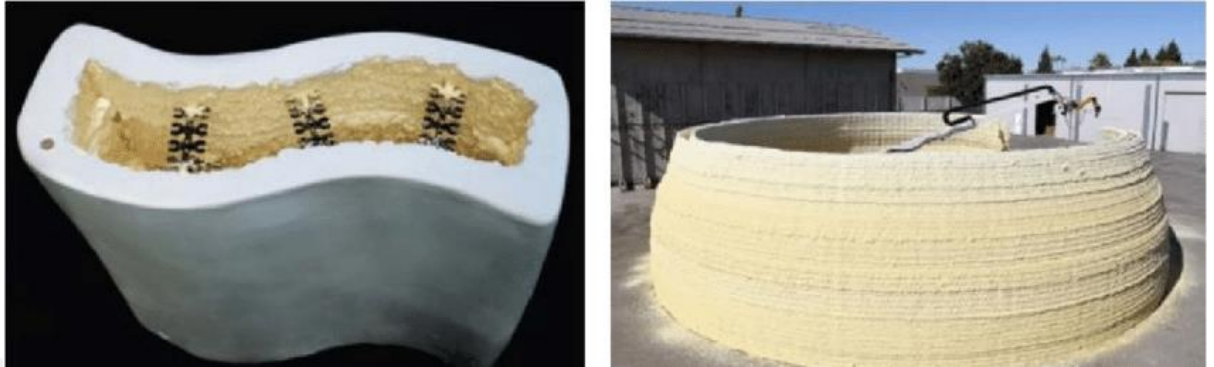


Fig 5.7: Foam Formwork / MIT (URL -9)

The idea came from commercial insulated-concrete formwork techniques but modified to be geometrically more freeform . Because the idea is based on a existing material system it is in compliance with existing building codes therefore can be used readily.

5.1.6 Yhnova - Nantes



Fig 5.8: 3D Printed Foam House (URL – 10)

The 3D print house project led by University of Nantes have 5 rooms with an area of 95 m². The patented BatiPrint3D technology uses a laser-guided, four-meter-long robotic arm to deposit layers of different construction materials (Fig: 5.8).

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.

5.1.7 3D Optimised Joints – Arup

Arup Group has developed the optimised 3D printed joints out of a need to find a solution for one of their projects. The projects design involved a trio of large tensegrity structures used as street lighting, in a shopping street in The Hague (Figure:5.9).



Fig 5.9: Tensegrity Lighting Structure (URL – 11)

The highly irregularly shaped design required 1,600 nodes to connect the cables to the struts. The unique joints were designed with optimisation tools and fabricated with additive manufacturing techniques in which both processes help lower material use while optimising strength.

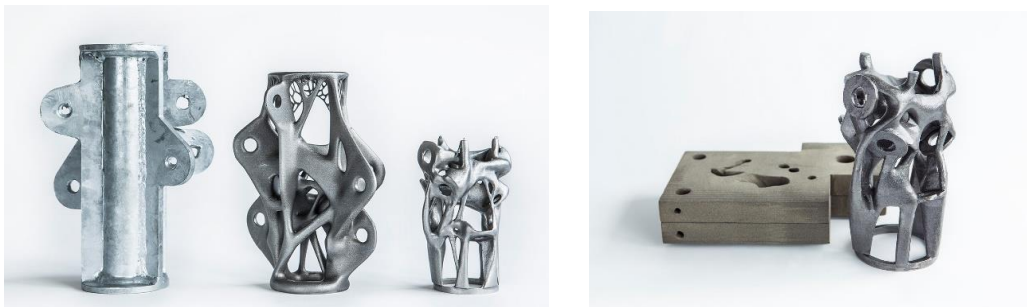


Fig 5.10: Optimised Joint (URL – 11)

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 (Fig: 5.10).

5.2 Direct Additive Manufacturing

5.2.1 Monoliths

5.2.1.1 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.

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. Limitation of the technique is that it uses sandstone as its material which has no structural strength (Fig: 5.11).



Fig 5.11: Radiolaria Pavilion

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. Especially anything larger than a pavilion would require several monolithic powder beds to 3D print the each module of the structure.

5.2.1.2 Apis Cor House – Apiscor

The house is said to be the first 3D printed house on site. 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 (Fig: 5.12).



Fig 5.12: Apis Cor House (URL – 13)

The house is 38-square-meter and it took 24 hours to print the house onsite with a cost of \$10,214. Though the house carries significance due to 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.

5.2.1.3 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 by the size of the system (Fig: 5.13).

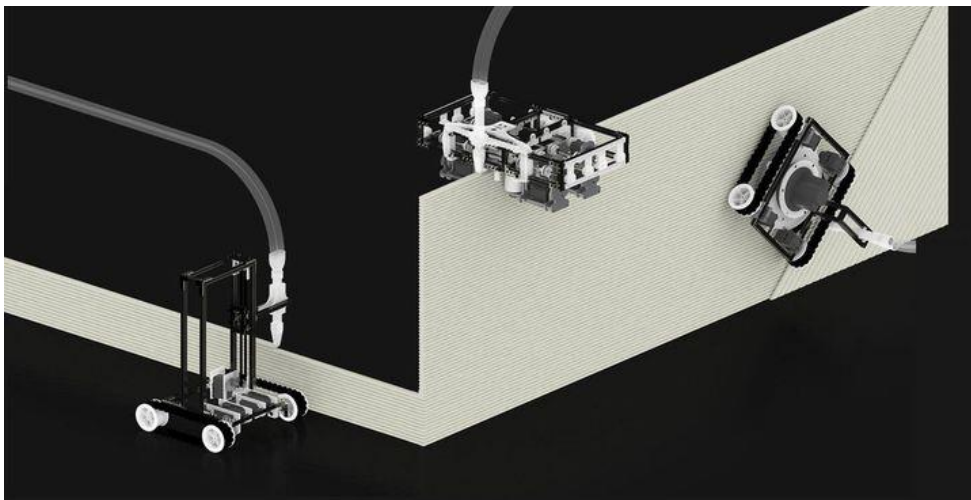


Fig 5.13: IAAC Minibuilders - Multidirectional Robots (URL – 15)

They propose a scalable system independent of the final structure's size. They develop a family of small-scale mobile construction robots who are assigned different tasks, working independently towards a single goal. 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(Fig: 5.14).

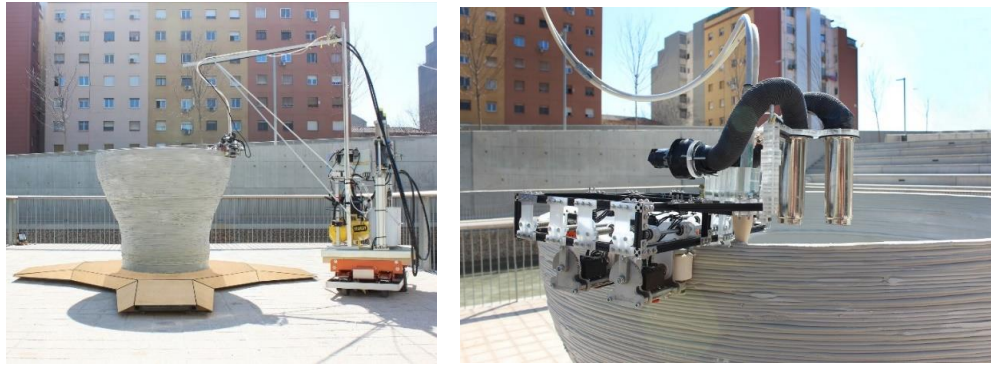


Fig 5.14: IAAC Minibuilders printing cement structure (URL – 15)

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.

5.2.2 Modules/componets and joints

5.2.2.1 Canal House – DUS Architects

The Canal House designed by DUS Architects may be one of the most well known large scale AM projects. The visit of Barack Obama himself in person catapulted the project into international symbol of 3D printed large scale structures (Fig: 5.15).



Fig 5.15: Canal House Rendering (URL – 16)

The significance of the project is that other than having 25 international partners, the material used is a bio-based printing material.

The printer is an extrusion based printer that can print up to 5m tall structures. The project was planned to be open to public in 2018 but there is no sign of opening in the near future.



a.

b.

Fig 5.16: a. Urban Cabin (2016) b. Mobile EU Building (2016) (URL – 16)

The other two projects of the group are The Urban Cabin and Mobile EU Building. The envelope of The Urban Cabin is bio-plastic and can be recycled and reprinted repeatedly. The same principle is also tested on the facade of the mobile EU building (Fig: 5.16).

5.2.2.2 Saltygloo – Emerging Objects



Fig 5.17: Saltygloo Pavilion (URL – 17)

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. The material used is a combination of salt and glue creating a strong, waterproof, lightweight, translucent and inexpensive material. The structure have 336 translucent panels supported with lightweight aluminum rods flexed in tension (Fig: 5.17).

5.2.2.3 Bloom - Emerging Objects - University of California Berkeley

Emerging Objects group has built the 4 meter tall pavilion with 840 customized 3D printed cement blocks (Fig: 5.18).



Fig 5.18: Bloom Pavilion and component details (URL -18)

Because the technology used is powderbased binderjetting technology the process requires no formwork and produces no waste. Each 3D printed block carries a number to indicate the blocks position in the overall structure. Blocks are assembled on site using stainless steel hardware (Fig: 5.19).

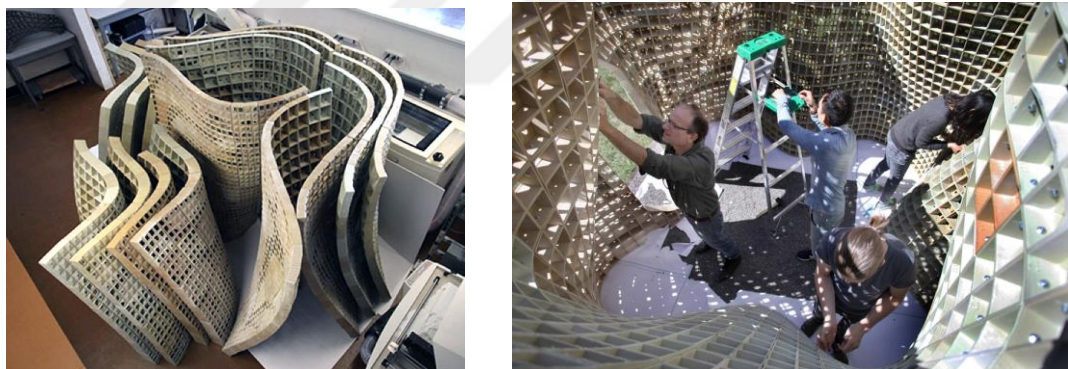


Fig 5.19: Bloom Pavilion Components (URL -18)

5.2.2.4 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 (Fig: 5.20).

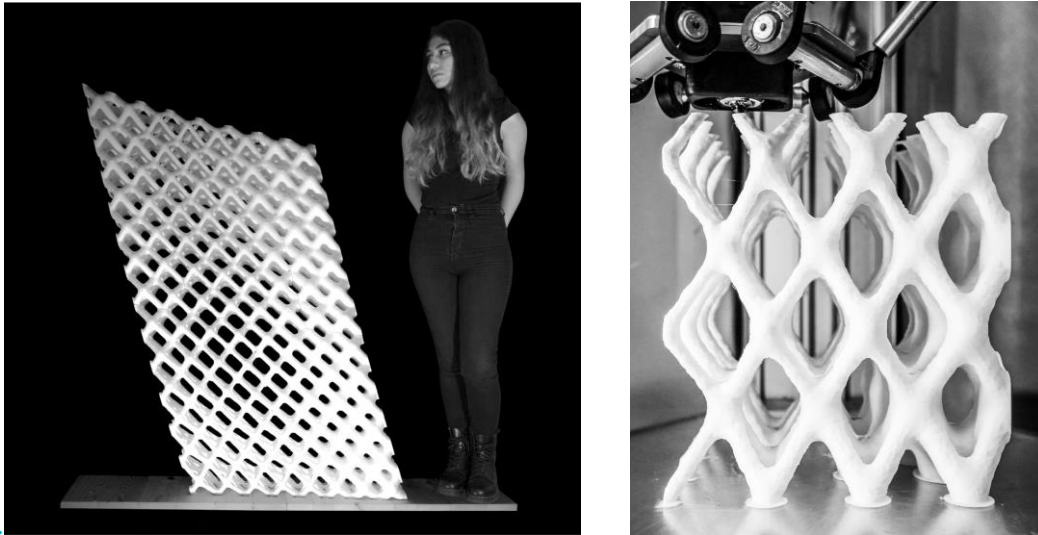


Fig 5.20: Load-Responsive Cellular Envelopes Modules (Naboni, 2017)

With a design to fabrication workflow the approach encompasses the use of computational tools, Additive Manufacturing, and material experiments. (Naboni, 2017)

5.2.2.5 Munich Deutsches Museum Facade – University of Munich

The facade is designed to integrate ventilation, insulation, and shading. They use polycarbonate as material and have designed such that elongated cells would provide stability, air-filled cavities would provide insulation, microstructured surface would ensure acoustics and the thin tubes would help circulate air for ventilation. The wave form used on the facade also have a function of generating shade (Fig: 5.21). (URL – 19)



Fig 5.21: Polycarbonate Facade testing (URL – 19)

5.2.2.6 Daedalus Pavilion – AI Build

Daedalus Pavilion is printed using an industrial robot arm equipped with A.I. algorithms to teach itself how to create a 3D printed structure. The algorithms are optimised to learn from their mistakes with the use of cameras to monitor its progress reducing the print time in half (Fig: 5.22).

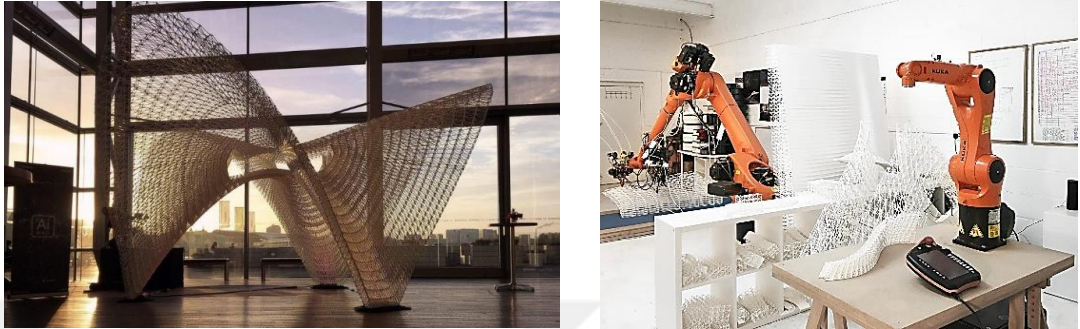


Fig 5.22: AI Build Pavilion (URL – 20)

The intricate structure took 15 days to print and half a day to assemble 48 pieces. (URL – 20)

5.2.2.7 Terraperforma - IAAC

The project combines a traditional material, unfired clay, with state of the art computational design tools and 3D printing technologies. Using clay as a construction material with performative capabilities was the main ambition of the project (Fig: 5.23).

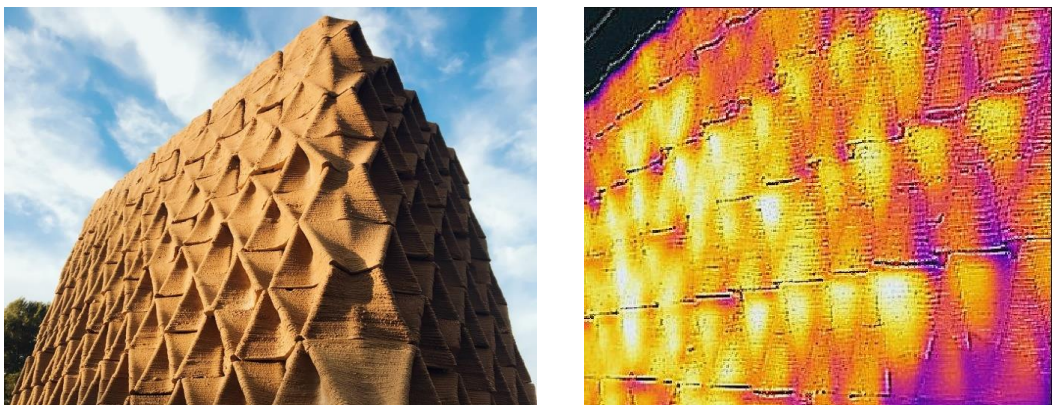


Fig 5.23: Performative 3D printed clay wall (URL – 21)

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. Due to logistical difficulties the structure is printed in modules ex situ and combined on site. (URL – 21)

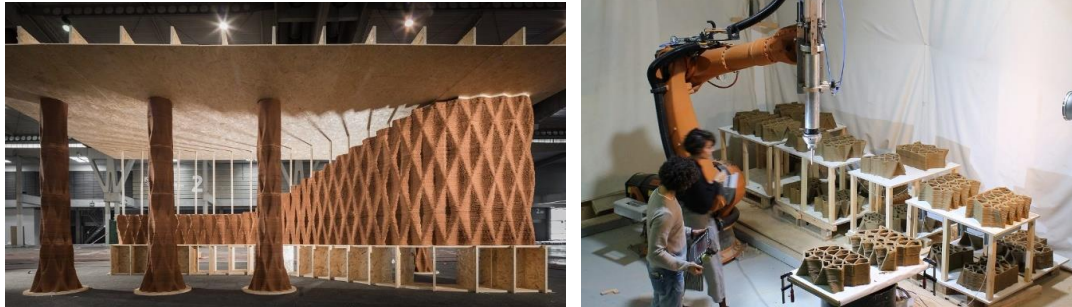


Fig 5.24: Barcelona Building Construmat, 2017 IAAC Pavilion (URL – 21)

In Barcelona Building Construmat, 2017 IAAC has built on site a pavilion using the blueprints of terraperforma in the course of four days to bring awareness to the possibilities on site manufacturing brings (Fig: 5.24).

5.2.2.8 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 (Fig: 5.25).

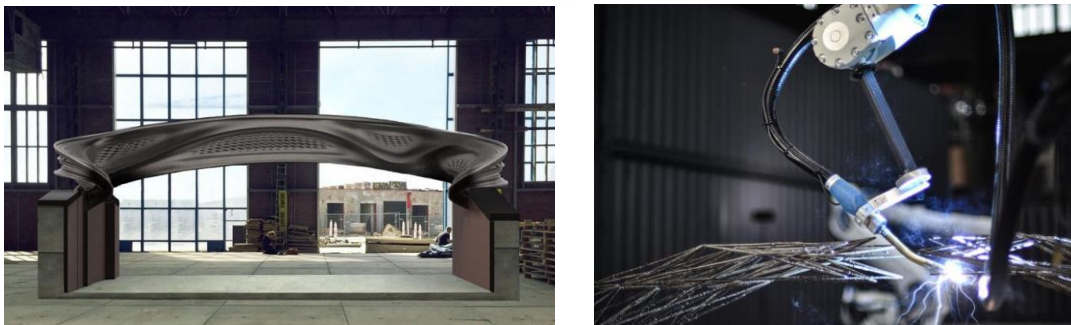


Fig 5.25: MX3D Metal Bridge (URL - 34)

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.

5.2.2.9 Hortus XL – University of Southern Denmark

The structure is designed to be a living sculpture receptive to human and non-human life. The sculpture is designed algorithmically, manufactured with extrusion based high resolution 3D printers. It contains colonies of photosynthetic cyanobacteria simulating the growth of substratum inspired by coral morphology (Fig: 5.26).



Fig 5.26: Hortus XL – Bio Sculpture (URL – 23)

EcoLogicStudio details the process behind the living sculpture as follows; The photosynthetic bacteria is injected on biogel into triangular units and will absorb the carbon dioxide and transform it into oxygen in a process that also creates biomass, useful for the production of bioplastic material and energy. (URL – 23) In the previous decade wall gardens were expected to be the answer to the air pollution in the cities. Nevertheless they proved to be rather difficult to maintain in an urban environment. This significance of the study is that Hortus XL project creates a viable option to replace the wall gardens in urban environments.

5.2.2.10 DFAB House /Mesh Mould – ETH Zurich

The project is apart of the ongoing research of Dfab House. The mesh mould is set out to adress find a solution to use combine formwork and reinforcement. They have first tested extruded polymer meshes as structural reinforcements. (Figure 5.27)



Fig 5.27: ETH Zurich Mesh Mould (URL – 24)

The study showed that the robotic fabrication of formwork and reinforcement can be effectively combined into one but the polymer meshes were load bearing only to a certain extent. (Hack, 2013)

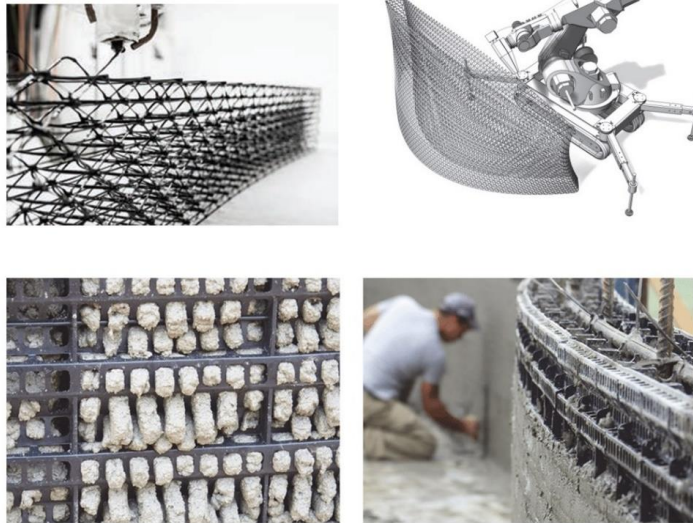


Fig 5.28: ETH Zurich Mesh Mould – Polymer Based (URL – 24)

The second half of the study worked on using rebars instead of polymer. The robotical placement of rebars in line with free form design required to innovation. A new robotical arm is developed which has to capacity to size rebars into small pieces and weld them into desired form. The innovative approach was a success, the reinforced wall was manufactured robotically from design to fabrication (Fig: 5.28).

This approach has the capacity to revolutionize construction sites as it merges rebaring, concrete pouring and formwork (Fig: 5.29). As per usual with any additive process it increases material use efficiency while lowering the waste.

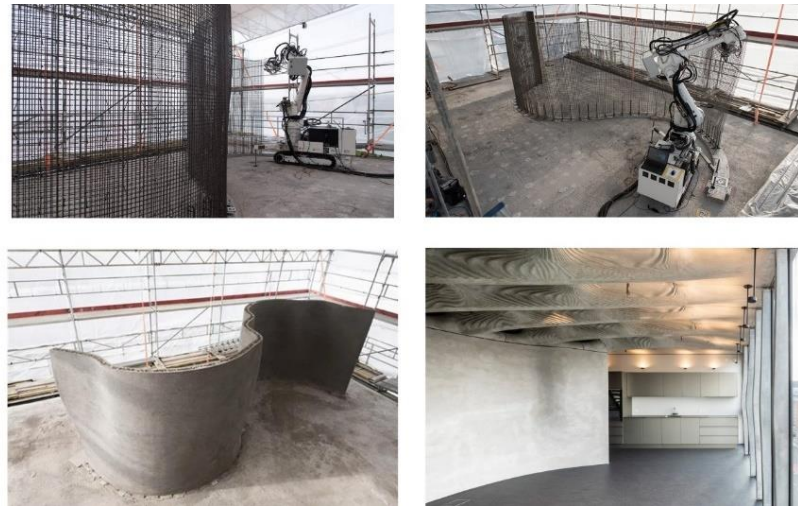


Fig 5.29: ETH Zurich Mesh Mould Several Stages (URL – 24)

5.3 Future Potentials and Challenges

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. Material wise recreating the properties of natural fibrous composites has already been in use in several industries but the morphological characteristics of biological structures have not been throughly exploited. 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 .

The methods and materials used to explore fibrous structures vary greatly. Menges' (2015) research mostly focuses on resin infused carbon fibres weaved by robotic arms. On the other hand Tamke et al (2014) shifts the focus on computer-controlled fabrication of elements to more natural living systems and experiments with core rattan (Fig: 5.30).

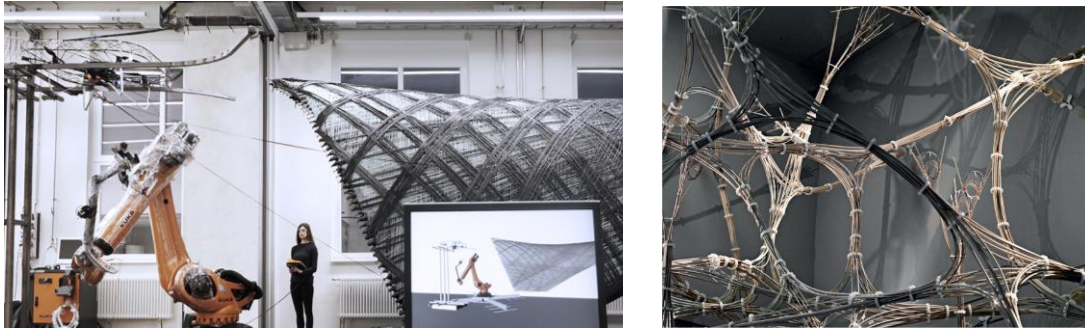


Fig 5.30: a. ICD/ITKE Research Pav. 2016-17(URL – 25) b. The Rise (Tamke et al., 2014)

The studies selected in the following section are all sharing a common theme of tectonic systems based not on representation but on material properties and on fabrication constraints. As argued in previous chapters the technological shift allows the designers to explore beyond mass manufactured material and production systems and enables them to replicate the optimisation phenomenon observed in nature. The current researches on computational tectonics show that the structures found in nature prove to be most topologically optimised structures. (Menges, 2015; Snooks, 2012; Oxman, 2013; Tamke, 2014)

5.3.1 ProtoHouse – Softkill Design

London based architecture firm Softkill Design has designed a conceptual house influenced from bone growth. They have used an algorithm imitating bone growth to deposit material to the areas where the most stress is. This approach created a fibrous structure rather than a solid envelope (Fig: 5.31).



Fig 5.31: Proto House 1.0 (URL – 26)

The fibrous material creates a porous environment allowing the environmental factors to penetrate (Fig: 5.32). They have generated a solution in which the waterproofing is done on the inside rather than the outside.

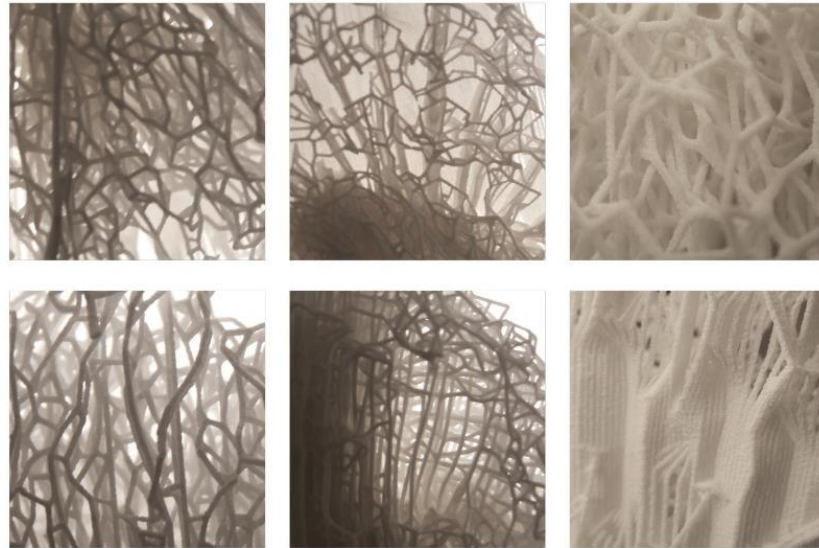


Fig 5.32: Fibrous Design Detail (URL – 26)

Proto House 1.0 is 3D printed in 1/33 scale in 31 sections using selective laser sintering technology. (URL – 25) ProtoHouse 2.0, a 4x8 meter building, improves the first design and will be 3D printed in seven large pieces also with SLS technology.

5.3.2 Fiberbots – Neri Oxman

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 (Fig: 5.33). In her seminal work she has observed that the silkworms are in a way working like a multi-axis 3D multi-material printer depositing silk fibre. (Oxman, 2014)



Fig 5.33: Silk Pavilion and its details – MIT (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 fibreglass filament around themselves.” (Kayser, 2018) The experiment’s innovative approach comprised of 16 robots. The robots are identical, working simultaneously depositing fibreglass to fabricate self-supporting composite tubes (Fig: 5.34).

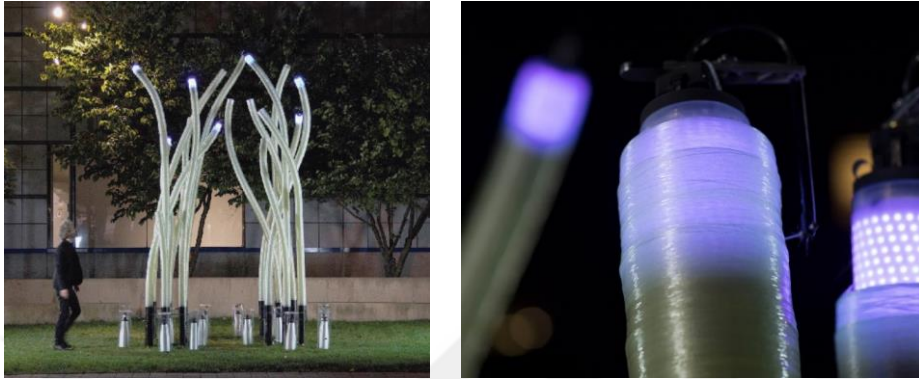


Fig 5.34: Fiberbots – MIT (URL -27)

The robots feed a mixture of fibreglass 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 fibreglass is used in this study, for further studies smart fibres made of natural materials are being developed.

5.3.3 Mars Utopia – IDEA Architecture Office

Over the years several people from different backgrounds have proposed multitude of projects to inhabit Mars including Norman Foster and Elon Musk. Nevertheless a project by a Spanish architect garnered great interest both from NASA and the European Space Agency. Spanish architect Alberto Villanueva proposes to use Martian soil and the fungus mycelium to print atmosphere forming towers.

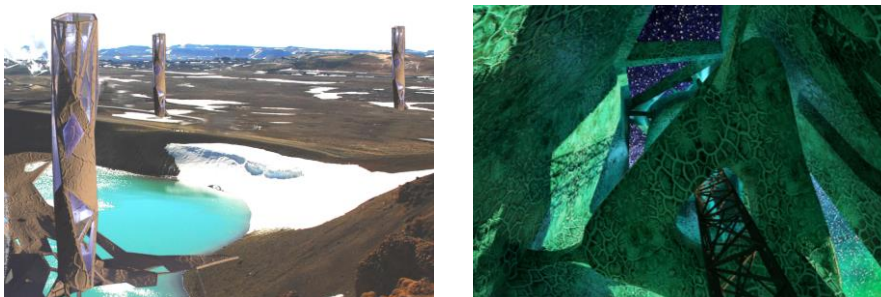


Fig 5.35: Mars Utopia (URL -28)

To sum up the project there are three stages to reach the inhabitation stage;

1. Free the underground frozen water by 3D printed metal structures using ferrous elements found in Martian soil.
2. Use the energy generated by electromagnetic fields to melt the ice and draw it to the surface, creating a system of water-filled craters and lakes in about 4 to 6 months.
3. 3D print first stage of atmosphere-building towers with epoxy resin and the fungus mycelium,

After the first three stages are completed the mycelium takes charge of the project. The fibrous structure of mycelium draws water from lakes, grows organically and has excellent structural capabilities and most importantly converts carbon dioxide into oxygen. Approximately in two years, the atmosphere is expected to be inhabitable for humans (Fig: 5.35).

This project uses all the advantages of 3D printing in one project. The 3D printers would function in inhabitable environments where no man can work and build structures with materials found on site in a short space of time.

5.4 Recommendations for further Research

Industrial revolution triggered an age of significant economic and social change around the world. On one hand it elevated the quality of life and created an abundant wealth for the early adapters on the other hand it has triggered a never before seen destruction of natural resources to the point of extinction. The age we are living in marks another revolution sometimes called the The Fourth Industrial Revolution. Defined by the Encyclopedia of Britannica the Fourth Industrial Revolution, stemming from the Third Industrial Revolution (also called the Digital Revolution) as “the convergence of digital, biological, and physical innovation” . As the digital and the physical worlds merge, it opens up new opportunities both for business and for society enabling new ways of thinking to incorporate sustainability.

The following examples are right at the intersection of digital, biological, and physical innovation which I believe very much represents the future therefore determine today's

research subjects. I will name a few of these projects without going into detail just to give a better understanding of the subject.

One of these researches that is merging materiality and AM that leads to a practical application. The Bioreceptive Facade Panels supported by *Engineering and Physical Sciences Research Council (EPSRC)* of UK and developed by BiotA lab, based in University College London’s Bartlett School of Architecture. They explore new materials coupled with new geometries that can foster the growth of cryptograms, lichens and mosses. The bioreceptive concrete panels they are working on targets the increasing air pollution in urban areas by integrating vegetation and other photosynthetic systems onto surfaces like facades and walls while at the same time carrying insulating properties. (Fig 5.36)

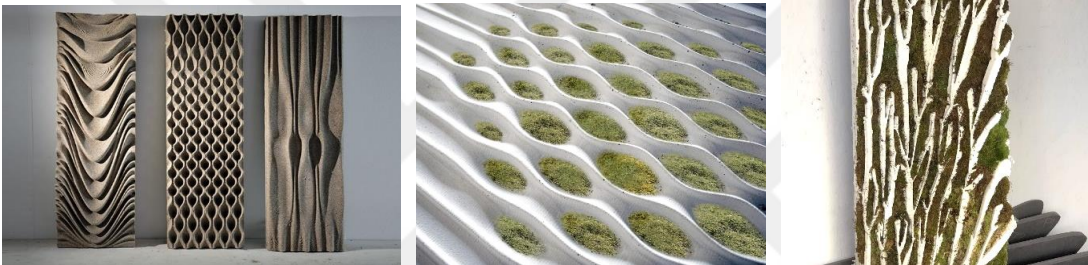


Fig 5.36: Bioreceptive Facade Panels by Bartlett School of Architecture (URL - 31)

Another research that integrates a biological approach is the Living Seawall, developed in collaboration with the Sydney Institute of Marine Science and Reef Design Lab, and sponsored by Volvo. The concrete tiles reinforced with recycled plastic and cast form a 3D printed mold aim to combat ocean plastic pollution by creating an artificial habitat for marine life attracting organisms that filter out pollutants. (Fig 5.37) The follow up to the research prove that the method used was succesful in recreating an artificial habitat.



Fig 5.37: The Living Seawall (URL - 32)

A designer from the Netherlands, Eric Klarenbeek, just as suggested in “ Mars Utopia Project” uses mycelium (mushroom roots) to make objects. He has developed a system to directly 3D print mycelium infused straws. Nevertheless without a formwork it becomes very hard to control the growth process. As a solution he 3D prints a very thin outer shell with bioplastic as the formwork and places the mycelium infused straw into the plastic shell, and allows it to continue to grow. In a couple of days it becomes structurally solid yet a very lightweight object. Several studies are conducted on the use of mycelium in different structural outlets. Already several large scale companies (i.e. Ikea, Stella McCartney Dell etc.) are investing in mycelium based products to develop more sustainable brands (Fig: 5.38).



Fig 5.38: 3D printed mycelium infused straw, 3D printed outershell and mushrooms growing from the mycelium and straw filled shell (URL - 33)

The above examples are all influenced by biomimicry and due to their complex forms, they are manufactured with AM technologies. One of the most studied subjects under biomimicry is the optimisation and the load response of forms found in natural systems. As human bodies are one of the best examples of several optimisation processes it is only natural for architectural researchers to get inspiration from a much faster developing science such as bio-engineering.

I would presume the bio-engineered scaffolds are a great example of merging man made and natural. They are already used in a wide range of clinical applications, one their most common uses is bone reconstruction. With the advancements in bioengineering and AM technologies, the 3D printed materials are infiltrated with bone marrow cells which develop into human bone cells.

While researching AM technologies and analysing several case studies I have come to realise that further research based on the concept of bioscaffolding seems to be most promising subject due to being right at the intersection of digital, biological, and

physical innovation. Experimenting with different designs and materials both for the scaffold and the material introduced to it seem to carry a significant value. Another reason for me to be interested on the subject is that in one of the classes in my master studies led by Prof. Dr. Gülen Çağdaş and Dr. Ethem Gürer, I have come to observe a natural “formation” phenomenon on a given scaffold. Though the research was limited in its scope still it was a step in the right direction. In this research two scaffold materials were experimented with. First, a perforated plastic material was kept in a copper sulfate saturated solution and in the second one, a wood based material encased with cotton threads was kept in the solution. As a result copper sulfate crystal formation was observed on the scaffolds. In both cases the formation increased the rigidity of scaffold material and created a surface like structure (Fig 5.39).

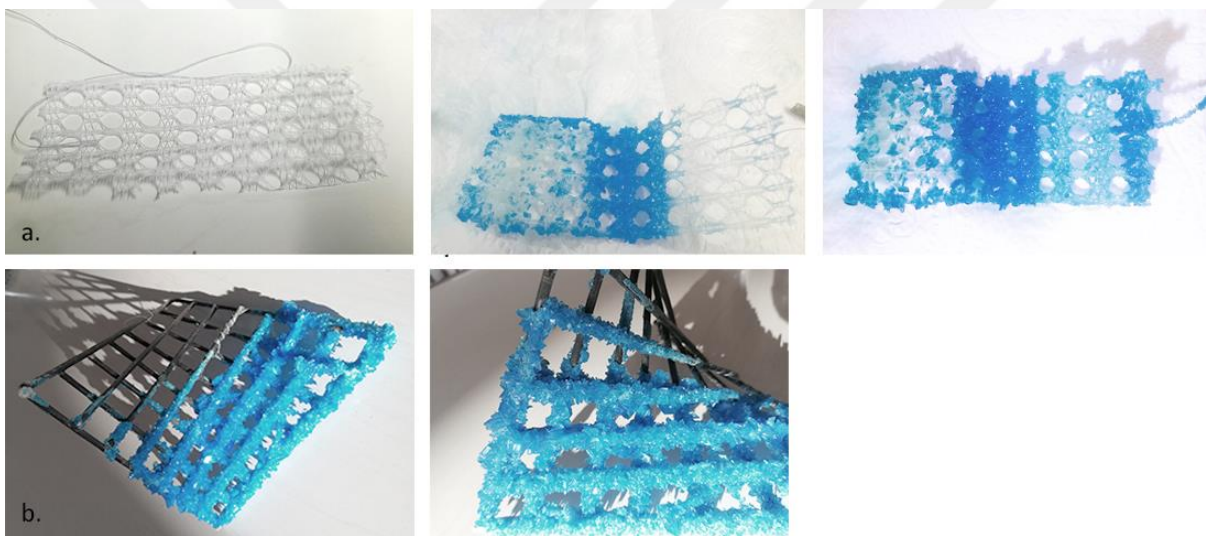


Fig 5.39: Copper sulfate crystal formation a. Plastic scaffold b. Wood based scaffold with cotton threads (Provided by the author)

In scope of this thesis further research could not be conducted due to limitations in time, budget and available technologies. In order to better observe the advantages and disadvantages of the technologies mentioned through out the thesis I have contacted several leading companies to learn the available technologies at hand. Almost all the major 3D printing service providers have very limited scope of the materials and technologies. The most commonly found technologies were FDM with mostly plastic based materials, SLS (MJF- a similar powder based technology) with mostly plastic based materials, SLA with resin and MSLS with metal based materials. (MSLS was being outsourced and they wouldn't tell where they were outsourcing from). An additional technology of voxeljet using sand as the main material seemed to be

available in one of the companies only to be revealed later on that they are outsourcing it from Germany with long due dates and a very high price tag.

From the readily available technologies I was able to get only plastic and resin based 3D prints. The technologies used are SLA, a technology based on photopolymerization, MJF a technology based on material jetting and FDM a technology based on material extrusion.

The chosen form served two purposes. The main purpose is that the form had overhangs. Overhangs are problematic due to layered manufacturing system in a gravitational environment. Only the powder based systems do not need any additional support since powder itself is supporting the structure. Additionally, the form printed with SLA technology is very brittle due to material's properties while the other forms are less fragile. The structure printed with MJF has the most seamless surface due to powder bed technology. On the other hand because supporting structures are used on SLA and FDM methods the surface quality is not comparable to MJF method. Finally FDM method has the lowest resolution based on layers.



Fig 5.40: a. Structure printed with SLA tech. b. Structure printed with MJF tech. c. Structure printed with FDM tech. (Provided by the author)

The second purpose of the form was its structural properties. It is a magnified replica of human bone structure. While the porous structure of the bone densifies at the stress lines it is also supported by crystals forming in the cavities. A simple stress experiment conducted on the structure made out of TPU material with elastic properties encased in different materials (i.e. crystal, mycelium etc.) can be an introductory step for the bio-scaffold studies. In order for the project to be fully sustainable the scaffold material (i.e. clay, wood etc.) should also be experimented with. (Fig 5.40)

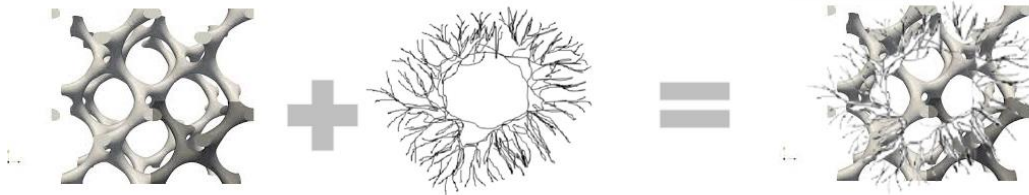


Fig. 5.41: Optimised structural scaffold coupled with formation material (By the author)

The design of the experimentation process starts with form definition. The form of structure determines the ideal componental structure for its purpose. The structure could be a load bearing structure requiring the scaffold design and the chosen infill material to have optimised structural properties working in union. The structure could also be tested for surface formation in which case a more light weight formation design is required. In both cases FEM analysis will help determine the necessary structural capabilities (Fig: 5.42).

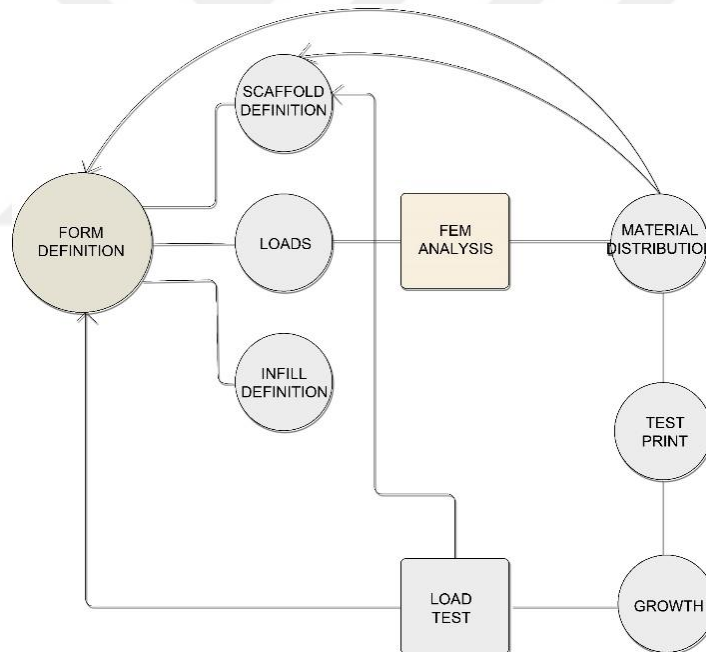


Fig. 5.42: Schematic representation of the potential experiment (By the author)

Below two possible scenarios are explored. The first one has a more dense scaffold structure mimicing a bone under an electron microscope. The infill of structure will first fill the cavities of the scaffold then will penetrate the negative space creating a load bearing capacity. The second scenario has a more loose scaffold structure to test the surface forming capabilities (Fig: 5.43).

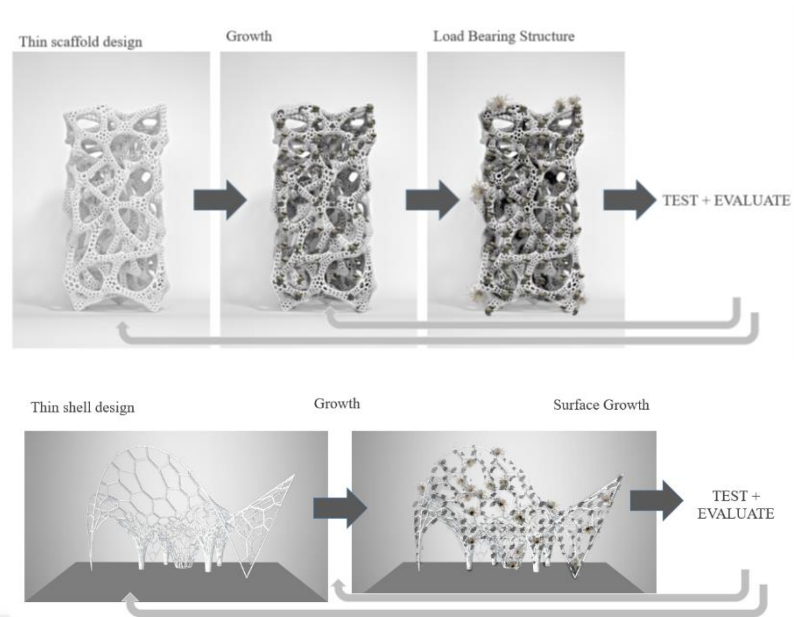


Fig. 5.43: Two experiments; a. 3D printed scaffold with formation to test load bearing capabilities. b. 3D printed structure with formation to test surface forming capabilities (By the author)

These experiments would likely be adding to the literature on man made structures and natural formation discussions. The 3D manufacturing processes coupled with natural formation would especially be useful in generating sustainable self forming structures where it is difficult for humans to work.



6. CONCLUSION

6.1 Explicit benefits and challenges of AM technologies in AEC

AM technologies in the construction industry offers a positive outlook for the future. Some of the previously mentioned key advantages of AM in AEC can be summarized in three points; i. Design Freedom and Complexity, ii. Environmental and economic gains iii. Cost and time reduction.

- i. As AM in AEC develops designers will not be limited to repetitive and rigid designs. Complex geometries will more readily be applicable. Furthermore as the rift between design and production lifts, design making process will better be informed by both materials and the processes of production allowing for more optimized products. The design optimization process will bring a project a specific solution set therefore creating a highly customized design.
- ii. AM will lower costs in terms of labour, time and material. Since it is a highly automated process labour costs will significantly drop. As human factor is eliminated it will further lower the costs by increasing the time wise efficiency. Furthermore both due to the nature of the technology and the above mentioned design and topological optimisation processes material cost reduction will be an added benefit.
- iii. Last but not least the potential environmental benefits are further added value of the process itself. The use of recyclable and natural materials and the increased efficiency in material use does not only benefit the environment but also low costs can help build more sustainable and affordable structures in less developed countries.

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

- i. As of 2019 the largest 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.
- ii. 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 automatize the fabrication process. As of 2019 the automatized 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.
- iii. Another challenge is the slow adaptation of AEC industry to the technological advances. Unfortunately all of the three professions in AEC, architects, engineers and builders by and large resist to technological advances until they become inevitable. Today there aren't many reliable statistical studies on economic benefits of AM therefore it becomes really hard to legitimize the initial investment both economically and time wise.
- iv. Though AM technologies are around since the 80's the regulations on AM materials and technologies for rapid prototyping and other small scale applications has been in effect only since 2009. If we take into account that the large scale AM applications has seen a rise only in the last decade it would be natural to assume that there are not building codes and regulations regarding construction scale processes making it difficult to penetrate the market.

6.2 Final Assessment

Additive manufacturing (AM) processes are seen as the 4th industrial revolution. This thesis tried to explore the current state of AM and specifically AM in large scale structures through literature reviews and case studies. Throughout the thesis several

classifications are attempted to be made to better understand the technologies and processes and therefore better position the latest developments in a very diverse and much disputed subject.

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.

As mentioned throughout the thesis the developments in computational tools redefines the roles of the architect, engineer and the builder. The rigid distribution of roles between each profession starts to blur. The architect can no longer impose a form on a material. Now it is a two way road between design, material and making, each informing the other.

However in order for an architect to be an active participant in the newly defined cyber physical environment, the least she/he can do is to be equipped with computational tools, such as topological optimization, form-finding and other computational design techniques. On the other hand in order to utilize any of the above tools she/he needs to be understanding the underlying geometrical and physical constraints and material properties.

On one hand architects have lost some of their design freedom with the industrial mass produced standard materials on the other hand this process created a rift between professions and catapulted the architect into an all knowing creator position. The new developments are somewhat taking some of their god like powers but giving an ability to design with extraordinary tools but most importantly also enable them to bring more innovative designs into life with more ease.

The section on future potentials tries to explore the intersection of architecture and making from a more biomimetic perspective. I 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 my opinion the greatest opportunities lie in the fact that it enables the architects/designers to explore new ways of thinking and designing.



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APPENDICES

APPENDIX A: Advantage/Significance and Disadvantages of Case Studies

APPENDIX B: Comparative Analysis of Case Studies



Table A.1: Advantage/Significance and Disadvantages of Case Studies

No.	Project Name	Project Owner/Year	Advantages/Significance	Disadvantages/Further Improvement
1	Deep Facade	ETH Zurich /2018	. First cast metal in 3d printed mould	
2	Organic Column	XtreeE/2017	. Load bearing column	. Limited load bearing capacity . High material waste due to formwork
3	Concrete Formwork	AI Build /2017	. Allows complex geometries	. Limited load bearing capacity . High material waste due to formwork
4	DFab House - Smart Slab	ETH Zurich /2018	. Allows complex geometries .Geometry optimization .Multiple methods combined .Load bearing	.Ex situ .High material waste due to formwork
5	MIT Foam Formwork	MIT/2015	.Insulation and concrete pouring in one solution .In situ .Insulation and concrete pouring in	.Limited load bearing capacity .Single nozzle, two stage manufacturing
6	Yhnova	Nantes Digital Sci. Lab. and Research/2018	one solution .Multiple nozzle .In situ	.Limited load bearing capacity .Manual work
7	Arup 3d Print Joints	Arup	.Highly optimized	
8	The Radiolaria Pavilion	D Shape & Shiro Studio /2009	.First large scale 3d print	.Powder bed technology low efficiency
9	Apis Cor House	Apis Cor/2017	.First large scale habitable 3d print	.Limited load bearing capacity .Manual work
10	Mini Builders	IAAC / 2014	.Multiple axis small robots .Swarm printing	.Limited load bearing capacity .Manual work
11	3D-printed Canal House	Dus Architects / 2013 (Unbuilt)	.Highly sustainable solutions .Hybrid systems	.Not much info publicly available
12	Saltygloo	Emerging Objects & Univ. of California Berkeley /2013	.Local material use	.Limited load bearing capacity .Manual work
13	Bloom	Emerging Objects & Univ. of California Berkeley /2015	.Local material use	.Limited load bearing capacity .Manual work
14	Load-Responsive Cellular Envelopes	Politecnico di Milano / 2017	.Optimised .Load responsive	.Early experimental stage
15	Munich Deutsches Museum Facade	Technical University of Munich / 2018 (Unbuilt)	.Use form for shade .Air pockets as insulation	.Early experimental stage
16	Daedalus Pavilion	Ai Build /2016	.AI use	
17	Terraperforma	IAAC /2017	.Local material use .Air pockets as insulation	.Early experimental stage
18	The Metal Bridge	MX3D/2018	.First 3D printed metal structure	.Highly expensive
19	Hortus XL	University of Southern Denmark /2018	.Incorporation of oxygen inducing material	.Early experimental stage
20	DFab House-Mesh Mould	ETH Zurich/2018	.Highly automated process .Load bearing	.Ex situ

Table B.1: Comparative Analysis of Case Studies






	1	2	3	4	5
Name	DeepI Facade	Organic Column	Concrete Formwork	DFab House - Smart Slab	MIT Foam Formwork
Illustration					
Project Owner/ Year	ETH Zurich /2018	XtreeE/2017	AI Build /2017	ETH Zurich /2018	MIT/2015
Country	Switzerland	France	UK	Switzerland	USA
Project Type	Facade	Structure	Structure	Structure	Structure
Intervention Type	Indirect (Mould)	Indirect	Indirect (Mould)	Indirect (Mould)	Indirect/Direct
Scale	Module	Module	Module	Module	Monolith
Fabrication Location	Ex situ	Ex situ	Ex Situ	Ex Situ	In situ
Material	Mould: Sand Cast: Metal	Mould: Concrete Fina product: Cement Comp.	Mould : PLA Final product: Cement Comp.	Mould : Sand Final product: Cement Comp.	Mould: Foam Fina product: Cement Comp.
Technology	Binder Jetting	Material Extrusion	Material Extrusion	Binder Jetting	Material Extrusion
Rebar - Reinforcement	No	No	No	Yes*	Yes
Significance	First cast metal in 3d printed mould	Column	Freeform formwork	Hybrid processes	Foam as formwork and insulation

Table B.1: Comparative Analysis of Case Studies (continued)






	6	7	8	9	10
Name	Yhnova	Arup 3d Print Joints	The Radiolaria Pavilion	Apis Cor House	Mini Builders
Illustration					
Project Owner/ Year	Nantes Digital Sci. Lab. and Research/2018	Arup	D Shape & Shiro Studio /2009	Apis Cor/2017	IAAC / 2014
Country	France	UK	Italy	Russia	Spain
Project Type	Structure	Joint	Pavilion	Structure	Pavilion
Intervention Type	Indirect/Direct	Direct	Direct	Direct	Direct
Scale	Monolith	Component	Monolith	Monolith	Module
Fabrication Location	In situ	Ex situ	In situ	In situ	In situ
Material	Mould: Foam Final product: Cement Comp.	Metal	Inorganic binder Artificial sandstone	Cement composite	Cement composite
Technology	Material Extrusion	Binder Jetting	Binder Jetting	Material Extrusion	Material Extrusion
Reinforcement	Yes	-	No	Yes	No
Significance	Foam as formwork and insulation	Digitally optimized and manufactured	First 3d printed monolith large scale structure	First 3d printed house Contour crafting	Swarm of small robots

Table B.1: Comparative Analysis of Case Studies (continued)




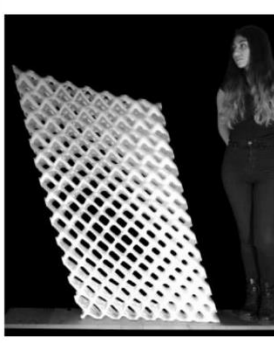






	11	12	13	14	15
Name	3D-printed Canal House	Saltygloo	Bloom	Load-Responsive Cellular Envelopes	Munich Deutsches Museum Facade
Illustration					
Project Owner/ Year	Dus Architects / 2013 (Unbuilt)	Emerging Objects & Univ. of California Berkeley /2013	Emerging Objects & Univ. of California Berkeley /2015	Politecnico di Milano / 2017	Technical University of Munich / 2018 (Unbuilt)
Country	Netherlands	USA	USA	Italy	Germany
Project Type	Structure	Pavilion	Pavilion	Facade	Facade
Intervention Type	Direct	Direct	Direct	Direct	
Scale	Monolith	Component	Module	Component	Module
Fabrication Location	In situ	Ex situ	Ex Situ	Ex situ	Ex situ
Material	Bio-based printing materials	Salt	Cement composite	Fiber Reinforced Plastics	Polycarbonate
Technology	Material Extrusion	Binder Jetting	Binder Jetting	Material Extrusion	Material Extrusion
Reinforcement	-	Yes	No	No	No
Significance	One of earliest and most hyped large scale project	All locally sourced natural material	Component Based	Load-Responsive	Air filled cavities for insulation Form used for Shading

Table B.1: Comparative Analysis of Case Studies (continued)

	16	17	18	19	20
Name	Daedalus Pavilion	Terraperforma	The Metal Bridge	Hortus XL	DFab House-Mesh Mould
Illustration					
Project Owner/ Year	Ai Build /2016	IAAC /2017	MX3D/2018	University of Southern Denmark /2018	ETH Zurich/2018
	Netherlands	Spain	Netherlands	UK	Switzerland
Project Type	Pavilion	Structure	Structure	Installation	Structure
Intervention Type	Direct	Direct	Direct	Direct	Direct
Scale	Module	Component	Module	Module	Module
Fabrication Location	Ex situ	In situ	Ex situ	Ex situ	Ex Situ
Material	Polymer	Clay	Metal	Polymer	Cement composite
Technology	Material Extrusion	Material Extrusion	Directed Energy Deposit.	Material Extrusion	-
Reinforcement	No	No	-	No	Yes
Significance	Ai and 3d print technologies explored	Performative wall design prototype Closed air cavities as an insulator	First printed large scale metal structure	Living facade	Hybrid processes

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