The Sir Ian Dixon Scholarship

Additive Manufacture: Structural Freedom & Architectural Complexity

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Abstract

There are several challenges that the construction industry currently faces. Increasingly diminished skills in the labour force, more stringent health and safety requirements and more demanding construction programmes are driving the industry to seek alternative methods to build.

This research first examines the feasibility the use of Additive Manufacturing technologies in construction through literature review. This provides an overview of additive manufacture's current state of art and the benefits it can bring to the architect, design and the contractor. Alongside this, it highlights technical limitations that are preventing its use in projects today.

Through a collaborative approach, the case study provided a first part prototype for a complex architectural column. This proves the technologies capability to produce complex geometries at a relatively low cost compared to conventional processes

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1.0 Introduction

There are several challenges that the construction industry currently faces. Increasingly diminished skills in the labour force, more stringent health and safety requirements and more demanding construction programmes are driving the industry to seek alternative methods to build (Buswell et al., 2007). In fact, recent government legislation has called for a UK construction sector that leads the world in research and innovation, transformed by digital design and new technologies (HM Government, 2013). The manufacturing and automotive industries have pioneered the use of automation to combat problems in productivity, quality, safety, high cost and shortage of skilled labour. It is time for construction to follow suit.

Additive Manufacturing (or 3D printing) describes an array of automated manufacturing processes that all work on similar principles. Components can be manufactured directly from 3-dimensional CAD models in a lay-by-layer fashion, as opposed to subtractive manufacturing approaches. This allows the user to print a design of near infinite geometric complexity in one process, without human input and with negligible manufacturing waste. Thanks to recent developments in the technology, usable materials are not limited to polymers. Metal, glass, composite and most importantly concrete processes have, and are continuing to be developed.

There is an ever-increasing expectation for front-running architects to design innovative structures that explore the very limits of construction feasibility; not only in complexity, but also optimised for ease of manufacture and assembly during the construction phase of building (Buswell et al., 2008). Consequently, numerous design iterations are often required to ensure compliancy with manufacturability and resultant affordability to the end-user. Architects nowadays are presented with cost restrictions when considering the design of components. This can often correspond to components, walls and buildings being kept simple and standardised. Additive Manufacture (AM) provides a solution to standardisation through its ability of mass-customisation at no extra cost. Determining factors of cost are now limited to energy and material usage during production and print resolution. Conventionally, those architects who can afford to design shapes of complex geometries often find bespoke moulds and tooling results in high cost and unpredictable delays to the construction process (Gosselin et al., 2016). As innovative and complex structures and components present costly, time consuming, high risk problems to a contractor, these are overlooked at an early stage in design. The development of new, innovative manufacturing processes are slowly being recognised as a potential solution to this issue.

Historically, Additive Manufacture in construction has been associated with a cost-effective solution for the production of small-scale architectural models. Architects, such as Frank Ghery used this technique to help visualise complex conceptual designs for theoretical comprehension and analysis (Wong and Hernandez, 2012, Labonnote et al., 2016, Buswell et al., 2007). The development of large-scale AM processes, such as Contour Crafting, have been the focus of research in the construction sector and have sparked numerous research construction projects throughout the world. However, existing technological and legislative restrictions, coupled with a lack of trust throughout the construction sector prevents unfamiliar technologies, such as

Additive Manufacturing from producing smaller components, larger structures, or even entire buildings on site today.

The research conducted during the scholarship was split into two sections: Literature Review and Case Study. The literature review first provides an overview of Additive Manufacturing technologies. It then goes on to describe how it can provide benefits to the architect, design and subsequently the contractor on site. Finally, limitations that are preventing the technology's use currently are highlighted and specific issues are addressed with potential mitigating measures alongside the discussion of where Additive Manufacture will be used assuming these limitations are overcome.

The case study is titled: 3D Printing a Complex Column. Through a collaborative approach with main contractor Bouygues UK, leading architect Zaha Hadid Architects, and Additive Manufacturing specialist Ai-Build, the case study provides an indication of the potential capability of the technology. This is realised through design and manufacture of a 1st pass proof of concept, in which the designer and manufacturer looked to push the boundaries of design and the feasibility of manufacture. The column was printed in half scale with a view to continue the development of design and manufacturing process through means of advanced structural and computational optimisation tools. The eventual aim of the study is to manufacture a full-scale column, which can then be cast in high performance fibre reinforced concrete. Unfortunately, due to time and budget restrictions, it was not feasible to achieve this during the allocated research period. However, the deliverable achieved during the time does showcase the ability to cost-effectively manufacture a complex structure and is a testament to collaboration at an early stage in a design process being essential when using Additive Manufacturing technologies.

1.1 Aim

This research aims to investigate the viability of Additive Manufacture's use for innovative and complex structural components in buildings and the technology's potential to provide solutions to existing industry challenges. Through literature review, it aims to provide an overview of the technologies current state-of-art, how it can provide benefits to the architect, the contractor and design. It will also highlight how the technology can help to satisfy recent government legislation calling for more innovative and environmentally friendly construction methods. Through case study, the project will also investigate Additive Manufacture's ability to process a complex structural column that would otherwise be incredibly difficult and costly do to in a conventional method.

1.2 Objectives

Objectives of the research are as follows:

- To provide an overview of Additive Manufacturing technology
- To identify the benefits that additive manufacture could provide to the construction industry
- To identify Additive Manufacturing can benefit the architect, design and the contractor
- To highlight current technological restrictions that are preventing its use in buildings today
- To showcase the technologies capability to cost effectively print a complex structural column through case study
- To make recommendations, based upon literature review conclusions from case study findings

2.0 Part 1: Literature Review

2.1 What is Additive Manufacturing?

Additive Manufacturing (AM), known also as Freeform Fabrication, Rapid Prototyping, 3D printing, is defined as "a process of joining materials to make objects from 3D model data, usually layer upon layer…" (Frazier, 2014). It contrasts traditional subtractive manufacturing processes whereby undesired material is machined away from a "block" of material to form a final part. The term AM encompasses a large variety of manufacturing processes, which all operate on similar principles; additive processes where material is deposited in a layer-by-layer fashion until the final geometry of the part is formed.

Before a part can be printed, it needs to be described in such a way that a printer can understand. The first stage of any process is to convert the continuous geometry of a conventional computer model (CAD model) into a format that can be understood by AM machines. In order to achieve this, the CAD model needs to be described as multiple cross-sectional layers. This is achieved by a process similar to finite element analysis. The CAD model is approximated by thousands of small triangles, which are sliced into cross-sectional layers (Wong and Hernandez, 2012) thereby allowing the geometry of 3D model to be described as a collection of several cross-sectional layers. ***Figure 1*** below:

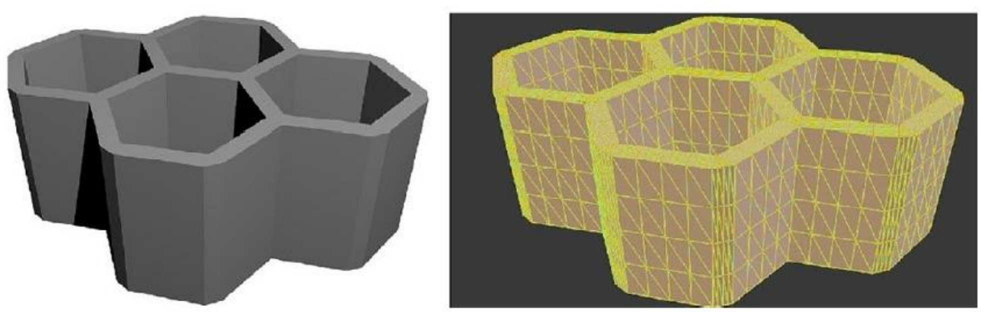


Figure 1: Showing the continuous 3D geometry of a CAD model being translated

These layers are subsequently translated into the machine tool paths (Buswell et al., 2008). The "printer" is then able to produce one layer of the part in accordance with the computer data. When the layer has been printed, the part itself is either dropped, or the printer head raised by a defined distance and the process is repeated over and over again until the correct number of layers are deposited, forming the desired physical 3D part.

Figure 2 provides an illustration of a typical AM process:

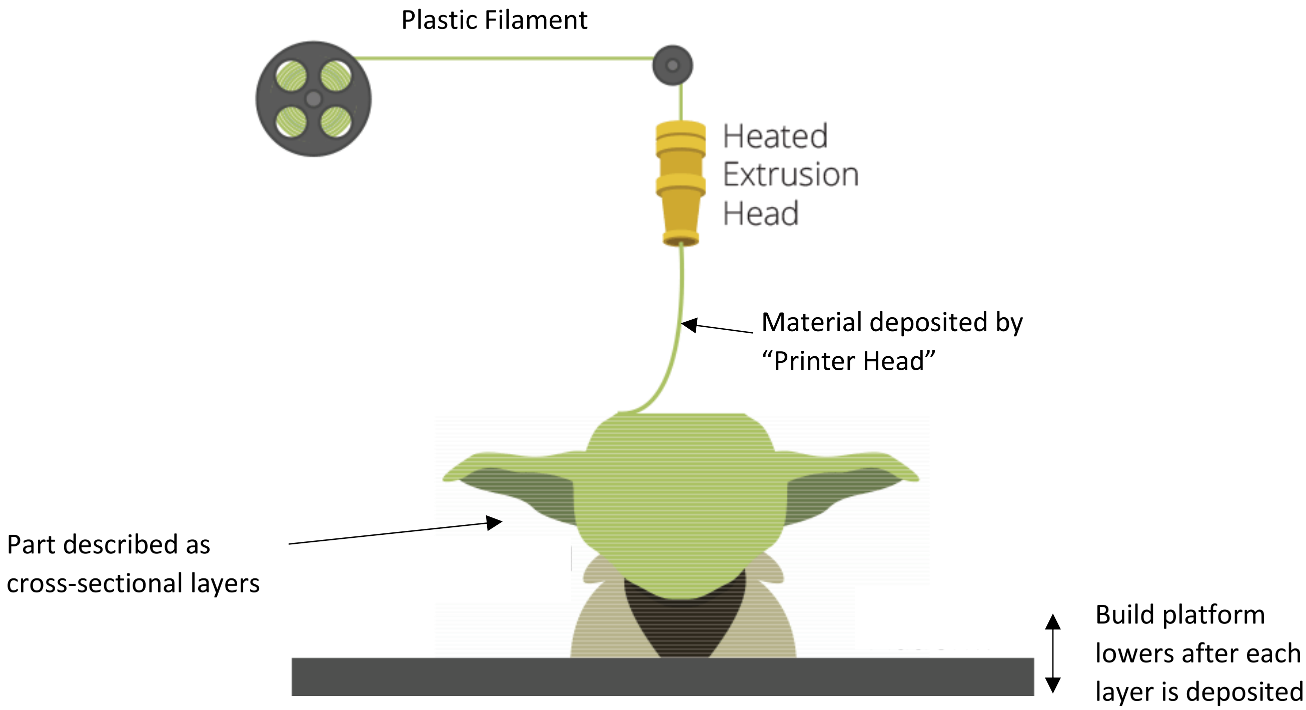


Figure 2: Illustration of a typical AM process

The distance in between individual layers of a part often determines what is known as the print resolution. Here, a smaller layer thickness, corresponds to a higher print resolution and subsequently a better material finish (Gao et al., 2015) and vice versa. Whilst, objects with higher print resolution provide a better surface finish, they take longer to print and consequently cost significantly more. An example of contrasting print resolutions can be found in ***Figure 3*** below:

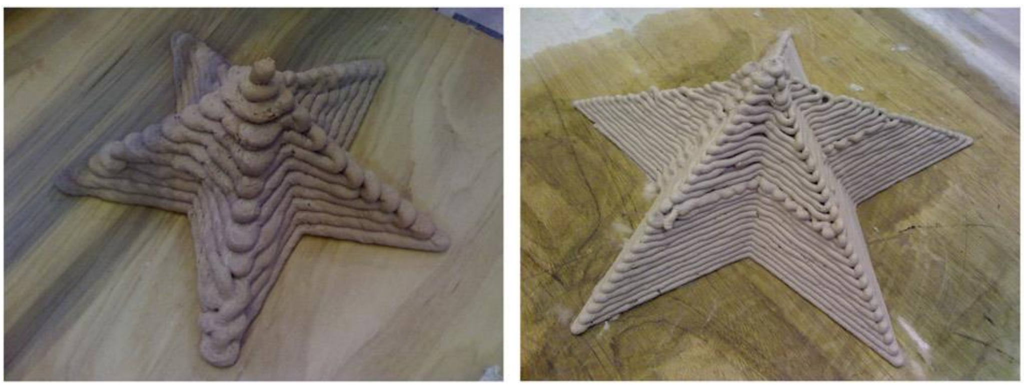


Figure 3: Showing the difference between a higher and lower print resolution

AM processes aren't exactly a recent revelation; they were visualised as early as the 1890s where it was used to form moulds for topographical relief maps. However, the development of other technologies, such as computer aided design (CAD), computer-aided manufacturing (CAM) and computer numerical control (CNC) has allowed for rapid development of new AM processes during the 1980s and 1990s (Wong and Hernandez, 2012). Today there are a plethora of named processes that operate differently and can use different materials. Additive manufacturing processes can be split into 7 main catagories. A summary of these can be found in ***Table 1***:

Table 1: Showing the 7 categories of Additive Manufacturing processes along with example processes

Additive Manufacturing Category	Short Explanation	Example of Process Name	Print Material
Binder Jetting	Liquid binder and powder based material selectively deposited and combined in layer by layer fashion	Binder Jetting	Metal, Ceramics
Directed Energy Deposition	Focused thermal energy (can be a laser) fuses materials by melting them as they are deposited	Laser Metal Deposition	Metal
Material Extrusion	Material is selectively deposited through a nozzle or printer head	Contour Crafting, 3DGP	Concrete, Glass
Material Jetting	Material selectively deposited onto surface where required. This is then cured with UV light	Polyjet	Polymer
Powder bed Fusion	Bed of metal powder is melted into desired layer shape often by a concentrated source of thermal energy	Selective Laser Melting	Metal
Vat Photopolymerisation	Liquid polymer resin deposited in layer and UV light cures resin where required	Stereolithography	Polymer
Sheet Lamination	Sheets of material, representing build layers are deposited and subsequently welded using ultrasonic welding technologies	Ultrasonic Additive Manufacturing	Metal

Whilst AM processes vary in the ways they deposit material and the materials they use, they each operate on a similar layer-by-layer principle. This enables nearly any shape of near infinite geometric complexity to be produced in **one process**. Whilst there are few manufacturing limitations, such as printing overhangs, Additive Manufacture is not comparable to any other process. It can still produce what 8 different manufacturing processes in a production line can, in one. This massive leap in manufacturing capability can unlock the doors to the designer's imagination, allows for mass customization and could solve the problems to multiple industries in the future with no extra manufacturing cost. For clarity, a short description of AM can be found online at: https://www.youtube.com/watch?v=l0SXlkrmzyw.

In Berman's 3D Printing: The Industrial Revolution, 2012, he proposed that AM will undergo a three-phase evolution throughout its history:

1. AM uses are largely limited to producing small-scale prototypes and casting inserts as the mechanical properties of the parts are insufficient for structural purposes (Bourell et al., 2009).
2. Sometimes known as 'direct digital manufacturing' AM uses expand to creating finished goods as processes are refined.
3. 3-D printers are made available to the end user. Customers will download their desired products, which will have the capacity to be made customisable. They will be able to print the parts when and where they are required.

Additive Manufacture has already surpassed its 1st evolutionary stage where it has been used to quickly and cost effectively to produce small prototypes enabling the designer a physical representation of a final design. It has even reached its 2nd evolutionary phase with the dental and medical industries using the technology to print personalised casts, bone replacements and dental inserts. It has already been shown that AM technologies are far more cost-effective for fabricating low-volumes (<10,000 part batch volumes) of customised features (Gao et al., 2015) and today 85% of Orthodontists in the US are using its customisable benefits (Buswell et al., 2007). The ability to produce parts of infinitely geometric complexity mean that AM has now been widely recognizes as one of the most promising techniques in the design of high performance automotive, aircraft and aerospace structures (Zhu et al., 2015). This is because designs can now be tailored to their exact use and considerations need not be made for manufacturability and associated affordability. A previous concern of Berman was that the mechanical properties for parts are insufficient for structural purposes. However, GE aviation has even predicted that by 2025, over 20% of new aviation products will incorporate the use of AM in some form (Alhart, 2017). It has even been cited by Gartner as "one of the five emerging technology trends that are believed to impact business significantly during the period 2014-2019" (Prentice, 2017) with expected sales to reach over $100B per year by 2020 (Materials KTN 2012).

The benefits of AM are not limited to its ability to unlock restrictions on the manufacturability of complex designs. AM has the ability to simplify the supply chain and increase efficiency and responsiveness in demand fulfilment (Huang et al., 2013) through its ability to produce parts-on-demand. Berman's 3rd evolutionary phase describes the stage AM is at today. However, it is inferred that he is targeting a domestic end user. It is more than reasonable to hypothesise customers downloading their customised part in an industrial setting. The ease of mobility of a 3D printer can enable the manufacture of parts wherever desired. Consequently, it is not unfathomable to imagine a scenario where replacement turbine blades could be printed for F23-B fighter aeroplane engines in live war zones when parts fail or bespoke complex façades printed for a building on a live construction site.

Aside from futuristic visualisations, how can AM really benefit construction? How can it allow benefit the architect? How can it help a contractor become more profitable and more appealing to a client? How can it even improve building functionality and make the sector become more environmentally friendly?

2.2 Additive Manufacture in Construction

2.2.1 Brief History

Additive Manufacture's history lies largely with high value adding sectors, such the Automotive, Aerospace & Medical because of high capital investment requirements and high material costs. Up until a few years ago, its uses in construction were largely limited to producing architectural models. Architects, such as Frank Ghery (Labonnote et al., 2016, Buswell et al., 2007), used this technique to help produce physical representations of complex conceptual designs for theoretical comprehension and analysis (Wong and Hernandez, 2012). More recently, concrete AM processes have been the predominant focus of research in the construction industry. Developments of pioneering AM processes such as Contour crafting, d-Shape, Freeform construction and Concrete Printing have opened the doors to larger-scale building applications (Lim et al., 2012). These processes all use a material that construction is incredibly familiar with: concrete! Consequently, projects have progressed from small-scale prototyping to larger building components and even entire structures. Projects such as "3D print canal house" in Amsterdam (Hager et al., 2016), WinSum Company's 5 storey building, ApisCor's affordable housing project and the MX3D bridge have not only proven large-scale additive manufacture's viability but have also demonstrated its capability to produce parts-on-demand. These have shown how AM can drastically reduce a project's carbon footprint through nearly eliminating building waste and minimising transportation costs. Whilst this sounds like it could be expensive, WinSun Company buildings in China printed their 5 storey building entirely from large-scale 3D printing processes at a cost of circa $5,000 (Hager et al., 2016).

2.2.2 Additive Manufacture & Architecture

There is an ever increasing expectation for front-running architects to design innovative structures that explore the very limits of construction feasibility (Buswell et al., 2008). Complex structures largely require multiple energy intensive processes to manufacture. Consequently non-repetitive, intricate and complex designs are either costly, time consuming or impossible to manufacture conventionally. Architects nowadays are also presented with cost restrictions when considering the design of components. Those who can afford to produce complex designs do so by producing one-off moulds and formworks, often resulting in large amounts of waste material and unpredictable delays to the construction process (Gosselin et al., 2016). As a result, generally components, walls and even entire buildings' designs are kept simple. It could even be stipulated that general cost and manufacturing restrictions have led to standardisation and subsequent stagnation in the design of the majority of buildings we see today. Those 'flagship' projects that do push the boundaries of design are often produced with a very low consideration for budget, and are often well over programme.

Previous to AM's existence, a major consideration during a design stages was both a design's suitability for a desired function and whether it was cost-effective and even feasible to be produced. Consequently, manufacturability shortcomings inhibited an architect's ability to design to their imagination. However, the inherent flexibility of AM manufacturing capabilities provides the architect with individualization and contextualization to design whatever component and subsequent architectural "space" that they like. Usually, cost of production rises in conjunction with complexity of design. This can easily be attributed to the more processes, more complex tooling/molds or highly-skilled labour expertise required to construct it (Gao et al., 2015) on top of any associated risk. However, with Additive Manufacture, no molds are required, no tooling is required and processes are completely automated. Complexity can be manufactured at no extra cost.

A process that provides the ability to manufacture intricate, complex designs at no extra cost would encourage designers to create bespoke, innovative and optimised architectural and structural designs (Labonnote et al.,2016). In the art sector, artists such as Nick Ervinck, have already proven the technologies worth by adopting AM to process innovative contemporary sculptures. Its ability to process "…sculptures that are on the edge of the physical and digital realm in terms of architecture" (Franky, 2010) enables the designer "…freedom of design" and will encourage more abstract, innovative designs in the future. An example of Ervinck's work can be seen below:

Figure 4: Additive Manufactured Sculpture by Nick Ervinck

More recently, architects such as Foster + Partners, Zaha Hadid Architects, DUS Architects and Universe Architecture have taken interest in AM for the ability to remove manufacturability as a design constraint. Whilst interest is gathering, it is highlighted in Foster + Partners investigation into the design potential for large scale additive manufactured components that a major obstacle for the technology to be used industrially is the ability of the processes to print at full scale. However, since 2009, the development of AM construction processes and have proven this is an obstacle easily overcome.

2.2.3 Additive Manufacturing and Design

The manufacturing capabilities of AM definitely has the ability to change the way that designers approach the design of components, or even entire buildings. Consequently, it is of paramount importance to consider that the way we design will need to be adjusted in order maximise AM's capability and to respond to such drastic changes in manufacturability. Not only that, but Ding, L et al., 2014 stipulated that conventional design approaches in construction are not currently suitable for automated technologies and rightly so; generic construction processes are not automated. A standard design process often needs to first assess part functionality and its requirements, but then must consider cost, feasibility of manufacture and most importantly (in construction) the practicality of assembly. From a commercial perspective, this is the preferred route; ultimately the client wants to maximise the aesthetic value of a component and the contractor/"deliverer" wants to do it for as cheap as possible. Research, conducted by Vayre et al., 2012 has been performed to determine a suitable design process, aimed at maximising the AM's capabilities. A 4 stage design process was proposed:

1. Analyse part specification
2. Produce several rough shapes
3. Optimize shapes in relation to the specifications and manufacturing restrictions
4. Propose design

During stage 2, Vayre suggested that removing an experienced designer who is familiar more with conventional design processes would encourage more innovative, less conventional design proposals. However, designers must ensure that the shapes would perform as per the part requirements. This, in turn can make a designer more appealing to a client. To make best use of AM's capability, it is important to synergise expertise across the entire process from design concept through to build. Collaboration with manufacturing engineers, designers, architects and engineers is of paramount importance from an early stage during this design process (Labonnote et al., 2016).

Aside from enabling a more abstract and complex aesthetic creations, the designer has the ability to improve a part's functionality through optimisation at no extra design cost, which represents stage 3 of Vayre's model. The predominant interest of this literature review is structural optimisation, as this would be most applicable to the case study.

Tsavdaridis et al., 2014 highlighted that there are 3 different types of structural optimisation: shape, size and topology. Structural topology optimisation is considered to be the most general of the three and is deemed to be a suitable optimisation tool for AM (Ponche et al., 2014). It provides a way of calculating an ideal redistribution of material inside a design space (Reinhard et al., 2011) and is necessary for establishing optimised lattice and hierarchical structures. This has already greatly benefited both the automotive and aerospace industries where light weight, high performance components are required. Lattice and honey-comb structures, seen in ***Figure 5***, are defined as complex material structures that are much easier to produce using AM than conventional methods. They provide a combination of high strength properties and low density. Moreover, these structures have been shown to improve the strength-to-weight ratio of a part by up to 228% (Reinhart et al., 2011, Reeves et al., 2012). In a modern era, where government legislation is calling for significant reductions in the environmental impact of buildings, Tsavdaridis et al., 2014 argues that optimising every part of a building must be a major consideration for the future

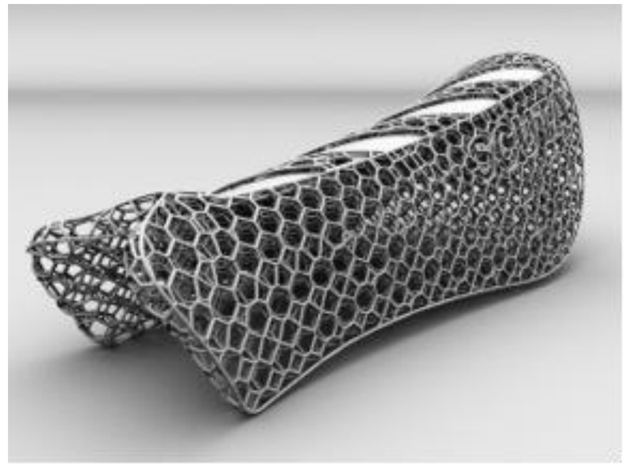


Figure 5: Honeycomb Structure

The ability to optimise structures through use of Additive Manufacture can have a significant impact on the carbon footprint of buildings. Optimisation, and subsequent reduction in material would not only result in less material being used, but would further reduce the total weight of a building considerably. This would result in a far less extensive foundation system, a lower carbon footprint and potentially, a lower cost and less transportation emissions. Concrete is the 2nd most widely used material in the world, and the 1st in construction. The production of concrete contributes to 5% of the of annual anthropogenic global CO_2 production (Crow et al., 2008) and up to 40% of global industrial particulate emissions (Rehan et al., 2005). Whilst most of the carbon emissions originate from the production of cement for the de-carbonization of limestone (Rehan et al., 2005), it is important to note that there are a wide range of issues that contribute to issues across concrete's life cycle. Reinforced concrete has even more associated sustainability issues, which can be attributed to the extract, production and manufacture of the steel reinforcement bars. In December 2015, 195 countries committed to reducing their carbon emissions drastically by 2020. Included in this cohort was China – cement's largest exporter (Soule et el., 2002), who committed to reducing
their carbon emissions by 40-45% per gross domestic product. This global commitment has driven research for innovative alternatives to existing materials and for industrial decarbonisation strategies across the construction sector. In the UK, reports like The Concrete Industry Sustainability Performance Report (Porrit, J., 2009) are helping to identify the ways in which the construction sector can proactively tackle the sustainability issues associated with the production of concrete. These include: reducing CO_2 emissions associated with production, developing more sustainable and innovative products and construction processes. Consequently, the ability to

affordably print optimised structures using Additive Manufacturing processes could help the industry work towards satisfying our global commitments to drive down carbon emissions.

Outside of environmental benefits, reductions in material usage may encourage the utilisation of higher performing, more expensive materials at a cost neutral basis. These material savings could even encourage investment into the development of new, sustainable and undiscovered material compounds for use in construction (Labonnote et al., 2016) at a cost neutral basis.

In order to optimize component designs efficiently, a predecessor to the processing stage is the computer modelling stage of the design process, where the optimization itself occurs. Several papers have also highlighted the importance of the relationship between data processing, data consumption, computer modelling and processing power requirements. Buswell et al., 2008 highlighted the importance of no errors during the tessellation algorithms used in converting conventional 3D CAD models to the STL file. Whist STL data format is understood by most AM machines (Buswell et al., 2007), newer and more efficient data formats are currently under development. Vayre et al., 2012 argued that existing 3D-CAD software does not have the capability to consider inherent differences in the mechanical and thermal properties, which AM materials demonstrate when compared to materials produced using conventional processes. CAD software is also not completely capable of supporting models of complex geometries, now feasible due to AM's flexibility, as they can require tens and hundreds of thousands of features often manifesting itself as incredibly large data files (Gibson et al., 2010). Consequently, it is essential that software used for optimization is developed and refined to ensure that AM can be used to full potential by designers (Vayre et al., 2012). This is where the BIM (Building Information Modelling) comes into play.

As of 2016, the UK government have required a fully collaborative 3D BIM with all project information and asset information, documentation and data being electronic. They have recognised that the procurement of construction services and asset management can gain the end user significant savings in capital and operation cost, increased value and carbon performance through the use of an open database of sharable asset information (*Government Construction Strategy 2016-2020)*. Using BIM as a design tool and synergizing it with AM during early design stages provides endless benefits to the design process, especially when considering the design and incorporation of incredibly complex geometries. A standard STL file (readable by a printer) can only describe the 3D geometry information of an object itself, whereas BIM describes all information about the geometry of the space the object lies in, its interaction with others, manufacture information and the individual characteristics of the object (material properties, colour etc). This can all be subsequently transmitted to the printer during construction and circumnavigates CAD software's inability to cope with the huge quantities of data required for manufacture. Most BIM tools already have the capability to export into a print readable format and has proven so by streamlining the production of architectural models (Bogue, R., 2013). On top of this, BIM can significantly assist design changes, reduce the time of remodeling and reprinting products during the production stage. Redesigned components are automatically imported into the model to ascertain whether they align with their surroundings and their feasibility of being printed (Wu et al., 2016). In other words the future is- “BIM are the brains and AM is the brawn”.

Synergy between BIM and AM, alongside inherent flexibility of AM opens up new possibilities in applying DfMA (Design for Manufacture and Assembly). DfMA refines building processes through ensuring that considerations are made for the manufacturability and assembly of a component during early design stages – it’s not just about designing, it’s about building too. This is becoming an increasingly important feature at the design stage where there are significant gains to be made in efficiency through off-site prefabrication, standardisation and creating economies of scale throughout the supply chain. Standardisation often plants the seed of “repeatability” in the end user’s head. However, with AM’s capabilities there is no need to standardise – it is possible to print complex, non-repeatable objects off-site, which enables the designer more freedom at no extra cost. Pre-fabrication using AM processes also means that quality can be controlled substantially better before items arrive on site.

Even though numerous advantages can be cited as a result of AM, a fundamental principle of construction engineering is experience. Not only do AM processes need to prove their worth, design practices need to be more adaptive to new innovative projects and take risks. Companies, such as Skanska, Burro Happold, Arup, Foster & Partners and Bouygues Construction are taking steps to develop construction processes and incorporate them into builds. Whilst it will be a while before designers make AM large step towards succeeding traditional construction processes during early design stages (Lindemann et al., 2013), it’s hard to argue that the unification of the digital design process (through BIM) and digital manufacturing processes (through AM) is the future of the construction industry.

2.2.4 Additive Manufacture & The Contractor

As a whole, the construction industry currently faces challenging problems. Increasingly diminished skills in the labour force, more stringent health and safety requirements and clients’ expectations for shorter and consequently more demanding construction programmes are driving the industry towards automation (Buswell et al., 2007). These issues, coupled with the evolution of architectural design, mean that contractors are often found promising the delivery of complex projects in unrealistic timeframes and to unachievable budgets. From the contractor’s perspective, it goes without saying - increased complexity represents higher cost. This manifests itself in several ways: increasing risk in human error, health and safety accidents, budget overspend, programme overrun, increasing cost to build and increased logistical complexity. USA and Japan have pioneered automation technologies to tackle problems such as low productivity, quality, safety, high cost and shortage of skilled labour (Ding et al., 2014). Construction methods have largely remained the same and have veered away from automation. However, aside from social implications, which will not be discussed, automated processes, such as Additive Manufacturing when refined and developed will be a more sensible to a contractor in order to prevent any potential financial and litigation penalties associated with Health & Safety.

The development of new manufacturing processes are slowly being recognised as a potential solution to alleviating restrictions that are making innovative and challenging projects less appealing. In fact, the British government has recently called for a more environmentally friendly UK construction industry that leads the world in research and innovation, transformed by digital design and new technologies (HM Government, 2013). The government is also calling for leaner and more modern methods of construction whereby constructions minimise waste of materials, time and effort in order to generate the maximum possible amount of value throughout a build. This is known as Lean Construction. It has already been discussed how Additive Manufacturing produces hardly any material waste – only the amount of material that is required is printed. This could have a substantial effect on the total amount of construction waste produced throughout an entire build. Another large benefit of Additive Manufacturing printers to the contractor is that they are incredibly mobile and can be transported directly to live construction sites or to warehouses very nearby. As a result, parts can be printed as and when they are needed on site, or can be printed close to site if a more controlled print environment is required. This significantly simplifies the supply chain and nearly eliminating the risk of damage to parts during transportation, the need for storage on site, the need for packaging and the potential risks associated with parts not being delivered in accordance with a construction programme. Another use for Additive Manufacture is the production of bespoke formwork for complex facades, which are often incredibly costly to manufacture conventionally and are often scrapped after their use. The removal and production of formwork for more intricate designs often represents a large cost to the contractor which can be significantly reduced as a result. Contractors also have the opportunity to become more environmentally friendly throughout the construction process by employing Additive Manufacturing processes during the build process. By reducing packaging and transportation requirements, it is possible to significantly reduce the carbon footprint of parts across the entire life-cycle of a building element. Applying this across an entire building would result in significant reductions in the environmental impact of a building. Not only that but AM processes lend themselves to the ability to adapt and develop materials so that recyclable materials can be used to print. However, more research would be required into the performance of these to enable certification and ensure quality to the end user.

2.2.5 So, why is the Construction Industry not using Additive Manufacture now?

Whilst there are clear advantages associated with the use AM technologies, there are several technical challenges that currently prevent it from being seriously considered in both the design stage of components and on sites.

- ***Understanding material behavior:*** Frazier et al., 2014 cited that material processed by AM often experience complex thermal cycles, which make predictions of material behavior more complicated to understand. On top of this, the relationship between print layers require further understanding, particularly in concrete. More research is therefore required for each desired material in order to understand and predict material failure and the mechanical characteristics.
- ***Lack of engineering materials available:*** Wong and Hernandez (2014) discussed how at present there is a distinct lack of available engineering materials, which can be produced using AM technologies. However, reduction in material usage for components (due to optimsation) enable the development of other construction materials, which are suited to their final use.
- ***Evolution of software:*** Buswell et al., 2012 highlighted how there is a clear need for CAD modelling and simulation programs to catch up with the drastic change in manufacturing capability. Efforts are required develop software that
- ***Certification and Qualification:*** Part certification and qualification are two major barriers to a parts-on-demand visualization coming into fruition (Frazier et al., 2014). This is particularly challenging when considering onsite fabrication where the environment for each print will be different. To ensure client satisfaction coupled with an insurers, systems must be developed to ensure the quality of a print. A suggested method of overcoming this issue would be to use BIM to verify designs through live simulation. This can help identify and rectify design issues in advance of a print and could bypass the requirement for certification
- ***Part repeatability:*** Huang et al., 2013 discussed inconsistency between repeating parts as a major barrier to overcome. On top of this, reducing the variance of mechanical properties between parts is of major concern to the AM industry and in situ monitoring techniques must be employed to overcome this.
- ***Printing Speed vs Print Resolution***: A higher print resolution results in a better surface finish. The higher the print resolution, the smaller the layer thickness and consequently the longer the build time (Gao et al., 2016). Research must be conducted to decrease print time with increasing print resolutions through print path optimisation.
- ***Single Material Manufacturing***: Ott et al., 2010 highlighted that a huge restriction of AM is single material manufacturing. Consequently, he introduced the appertaining process model, which allows the production of multi-material structures. Whilst multi-material AM technologies are being developed, uncertainty of behaviour between material interfaces

limits their use in current live projects and up-and-coming designs (Gao et al., 2016). BIMAC provides good foundation. E.g using cement based materials for walls and plastics for window frames (Ding et al., 2014)

- ***Reliability:*** Buswell et al., 2008 concluded that the real challenge from a processing perspective would be to ensure that a 'build' is successful on the first attempt to avoid unnecessary surplus cost. In situ monitoring can be used to compensate for any errors in prints.
- ***Contractual Interpretation:*** As a body of case law develops, there will be an unavoidable degree of uncertainty on parties' rights, duties and contractual interpretation.
- ***Tests and Standardisation***: There is currently a distinct lack of agreeable processes, machinery and verification protocols to ensure compliance to specifications and guarantee the integrity of prints. Development of procedures are required to address this. Alongside this, standardised material testing procedures are required to be developed for any onsite printing

3.0 Part 2: Case Study – Printing a Complex Column

3.1 Case Study Aim:

The aim of the case study is to manufacture a proof-of-concept building component, which showcases Additive manufacturing's capabilities. It also aims to prove that the technology can manufacture an incredibly complex shape cost effectively and in one single process. This demonstrates qualities often associated with 3D printing when compared to existing conventional manufacturing processes.

3.2 Objective

The objectives of the case study were to:

- Affordably print a complex architectural component, which pushed the boundaries of design, feasibility manufacturing and showcases Additive Manufacturing's future potential.
- Challenged and subsequently enabled the development of Ai-Build's technology and software

Future objectives for the continuation of this project are highlighted in the ***Future Research*** section of the case study.

3.3 Producing the Complex Structural Column

3.3.1 Collaboration

In order to achieve the aim of the case study (highlighted in section 3.1 Case Study Aim), it was incredibly important to collaborate with industry professionals from a very early stage in the process. As is highlighted in the literature review section of the report, it is imperative to synergise expertise from manufacturing professionals, designers and engineers in order to maximise Additive Manufacture's capabilities fully. Consequently, the most important part step for the success of the case study, was to collaborate with other companies to achieve the case study aim.

Ai Build, an emerging additive manufacturing company, who are developing 3D printing technologies for large-scale objects, were contacted and immediately registered their interest in collaborating. Their interest in developing large-scale processes technologies, focusing predominantly on the construction sector, made them the perfect partners. For future information on their company, please visit www.ai-build.co.uk. Leading architect, Zaha Hadid Architects, who have close ties with Ai Build also agreed to help design the component with the potential for future development moving beyond the designated timeframe for this research. An example of previous collaboration between Zaha Hadid Architects and Ai-build can be seen below:

Figure 6: A thallus experimental structure in Milan designed by Zaha Hadid Architects

In February 2017 a meeting was arranged with Ai Build visit to their factory in Leighton Industrial estate. During the meeting, a short tour of the facilities took place and the company's long and short term visions were presented. The process that Ai Build uses to produce their objects is a polymer-based extrusion process using a 6-axis industrial robot (shown below), which provide incredible flexibility and enable a larger-scale print when compared to normal 3D machines. The robot that was used during the production of the prototype is shown below:

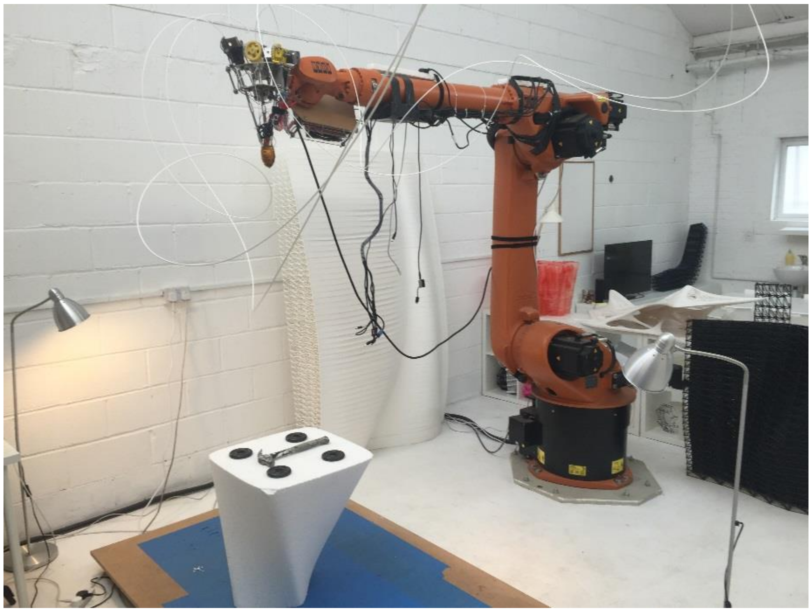


Figure 7: Showing the AM robot used for the processing.

3.4 Case Study Layout

For the purpose of this year's research, the case study was split into two sections:

1.0 Concept Design Development
- Convey design intent to design team and agree on a design, which tests capabilities of technology.

2.0 Proof of Concept Print
- Print the Concept design in ½ scale to provide Bouygues UK, Zaha Hadid Architects & Ai Build with a platform to enter design development stage

Further stages of research would be required to take this design through to a full scale concrete column (These are highlighted in the **Future Research** sections). However, this is not a feasible achievement due to time and budget restrictions. The intention is to continue the project further following completion of the scholarship's research period. A summary of the work carried out can be found below.

3.4.1 Concept Design Development

The architectural inspiration for the design was chosen to be based on natural forms, dendriform architecture and complex patterns. An aspect of nature that is particularly interesting and relevant to Additive Manufacturing's capabilities is how plants strategically distribute weight exactly where needed for structural purposes. This aligns with a structural optimisation technique called Topological Optimisation, whereby computational generative tools are used to minimise the weight required to perform equivalent structural purposes through the strategic redistribution of material. A perfect example of this in nature is how the majority of a trees weight is positioned at the bottom and reduces towards the top. This is because trees are often subjected to shear forces from wind and the most structural integrity is required at its roots and towards the lower end to cope with this. Topological optimisation is often incredible hard to manufacture conventionally simply because of the abstract shape which is often generated. As mentioned in the literature review, Additive Manufacture's capabilities provide an easily method of producing geometrically complex shapes at no extra cost. Therefore for the purpose of this research, it was decided that in order to showcase the technologies capabilities, this would be the focus area of the design.

Upon deciding the inspiration for the design, a column was chosen to be the building component that would be printed. Designs from the selected areas of architecture were chosen and conveyed to the designer. Examples of some can be seen below:

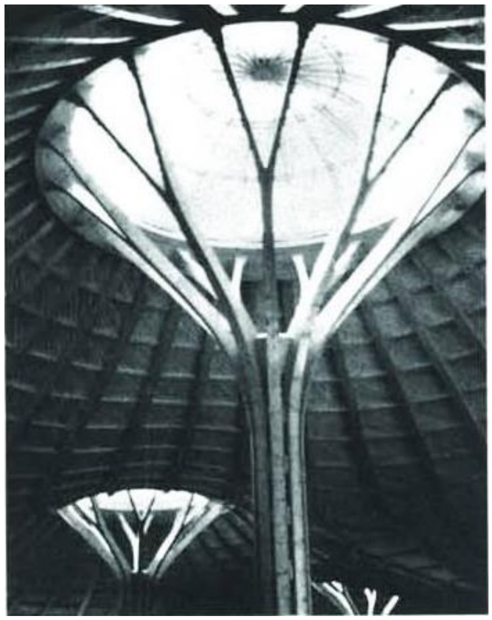


Figure 8: Inspiration for the column design

The architect, which had the most influence over the design was the architect Felix Candela. Candela valued methods of construction as integral to his designs and coupled that with intentions of sourcing local materials with a focus on sustainability. The most influential piece of his to this project was the Candela Column, seen below:

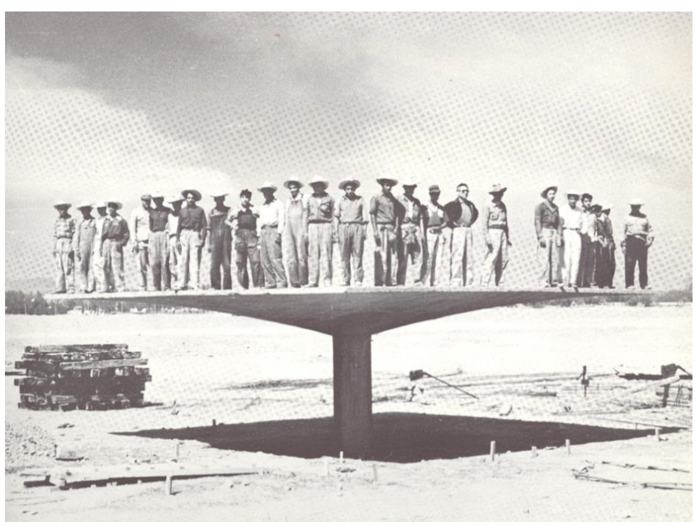


Figure 9: The Candela Column - Vallejo Mexico, 1953

The 1st iteration of the column prototype was designed by Michail Desyllas (Zaha Hadid Architects, Ai Build). As a first test, the team pushed the boundaries of design coupled with Ai

Build's manufacturing capabilities to see whether it was feasible to be manufactured. As a company, Ai Build are always looking to take on complex designs to help develop their technologies, so this was a perfect project for them. Several "test" prints were undertaken by the team to optimise tooling path and ensure a quality finish on the first prototype print. The 1st iteration design reflected the design intent perfectly and provided enough complexity to test the manufacturing capabilities of Additive Manufacture. This can be found below in ***Figures* 10 & 11**:

Figure 10: 1st Pass Design of the column

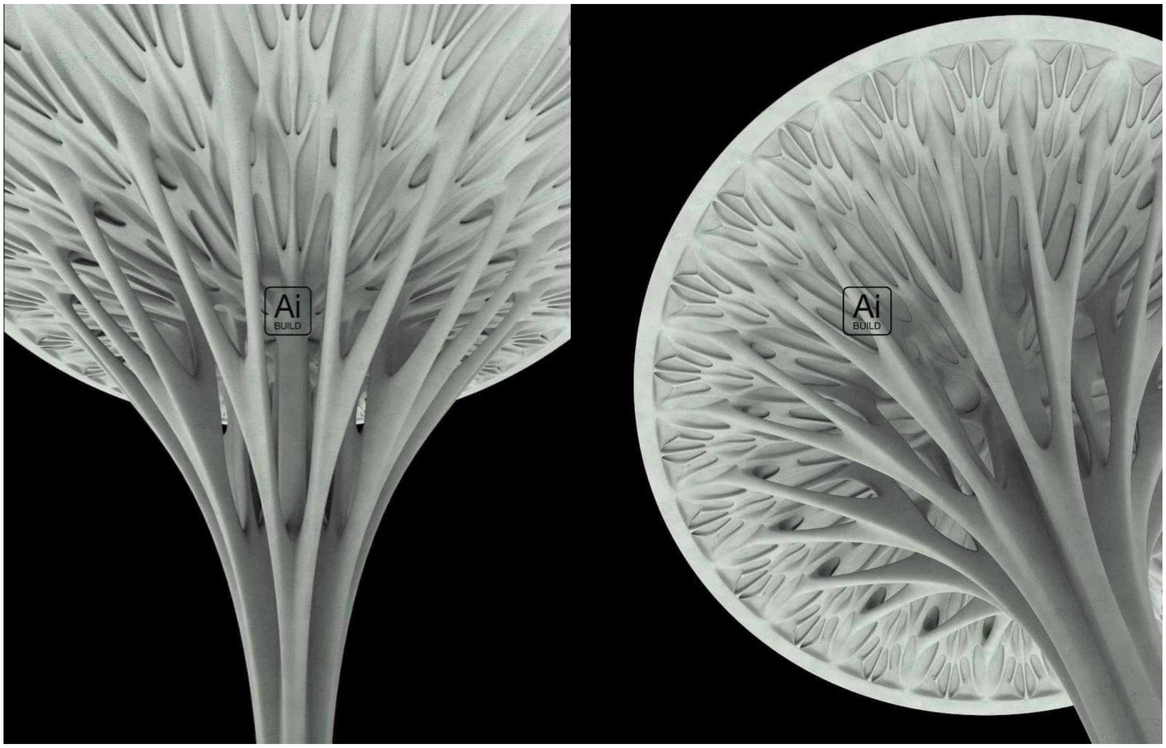


Figure 11: 1st Pass Design of the Column

3.4.2 Proof of Concept Print

It was decided that the print of the 1st iteration design would be produced at half-scale for cost and speed purposes. The diameter of the head of the column at half scale is 1m with the printed height standing at 1.2m high. After further design development is carried out, the final column is going to be printed at full scale (2.5m tall and 2m head circumference).

The Additive manufacturing process, which Ai-Build used, uses a polymer-based process using a material called PLA. Consequently, the prototype's material is polymer. It is important to note that the final material of the column would not be plastic and intentions of material development are discussed in the ***Future Research*** section of the paper. The 1st iteration design can be found in the below image:

Figure 12: Showing the 1st pass design print at half scale

The total print time of the prototype was 26 hours and it was printed in one continuous process.

3.5 Future Research

Further research is required to complete the column in full scale and in concrete. A stage-by-stage breakdown of required works can be seen below:.

1.0 1st Stage Design Development (incl. Structural Optimisation)

The next focus area is to begin to consider how the column integrates with the slabs and determine the final function of the column (i.e whether it is an architectural feature or a repetitive column used within a single building. By setting mechanical parameters for its function, structural optimisation will be carried out to determine exactly where material is required. This may have significant implications on the aesthetics of the design.

- Collaborative efforts with Bouygues UK structural engineers, Zaha Hadid Architects CODE department and AI Build manufacturing experts enables mechanical testing.

2.0 Computer Analysis

Ascertaining implications of column shape and performance on slab thickness is another consideration that will be investigated by structural engineers at Bouygues UK through computer analysis. Another consideration for the design development stage would also be the final material used. This information would need to be applied for meaningful and significant structural analysis

- Bouygues UK to undertake mechanical and material analysis to enable any required design development

3.0 2nd Stage Design Development (incl. Structural Optimisation)

Having determined implications of column shape and performance, a final optimisation process can be carried out to determine the final design. It is important to note that design intent should not be superseded by any iterative computational generative design processes.

- Collaborative efforts with Bouygues UK structural engineers, Zaha Hadid Architects CODE department and Ai Build manufacturing experts helps realise feasible final print

4.0 Testing/Optimising Final Print

- Ai build to optimise and test final print to minimise print time and maximum surface finish.

5.0 Final Print at full scale

Having completed said analysis, further design development through collaborative efforts would enable a final design to be agreed. This can then be passed onto Ai Build for manufacture in full scale.

- Ai Build to carry out final print

6.0 Cast Print in 2nd Material

The final stage, somewhat ambitious for the original scope, is to cast the final design in full scale. This would be carried out through further 3rd party collaboration. By using a thermoplastic polymer, it is possible to create a “negative” mould for the column instead of printing in the final material, concrete. Ai Build are specialists in PLA printing and further development of concrete printing processes are required to achieve the desired level of detail. When the mould has set, the plastic can then be melted enabling the concrete to be cast. Melting the plastic mould also means that the mould material could be re-used, thereby creating next to no process waste. Whilst creating a mould does means the intent is not to use Additive Manufacturing to print the column in the final material, a cost comparison can be carried out between conventional casting techniques and Additive Manufacturing to determine which solution is more economical for creating bespoke, complex moulds for more abstract designs. As previously mentioned, further development of concrete processes would be required to achieve the intricacies and surface finish of the case study design.

4.0 Conclusion

There are several challenges that the construction industry currently faces. Increasingly diminished skills in the labour force, more stringent health and safety requirements and more demanding construction programmes are driving the industry towards automation. Alongside this, there is an expanding demand for architects to design innovative structures that explore the very limits of construction feasibility. Complex structures/components largely require multiple energy intensive processes for manufacture. Consequently these bespoke, intricate and complex designs are usually costly, time consuming and are often overlooked at an early stage in design. The government legislation is also calling for contractors employ more environmentally friendly construction methods to reduce the impact the sector has on the global ecosystem. The development of new, innovative manufacturing processes is slowly being recognised as one potential solution to these issues. Additive Manufacturing describes an ever-growing number of manufacturing processes, which all work on the same principle. It provides the possibility for automation and unlocks restrictions on manufacturability. Its additive nature provides a feasible method of processing geometrically complex structures in one process whilst producing a negligible amount of waste and through the lack of required tooling and moulds, it provides the user the ability to produce non-repetitive parts at no extra cost. The technology has already proven invaluable in processing non-repetitive parts in the medical, dental, high performance automotive and aerospace sectors and has been cited as one of the most promising technologies to revolutionise manufacture.

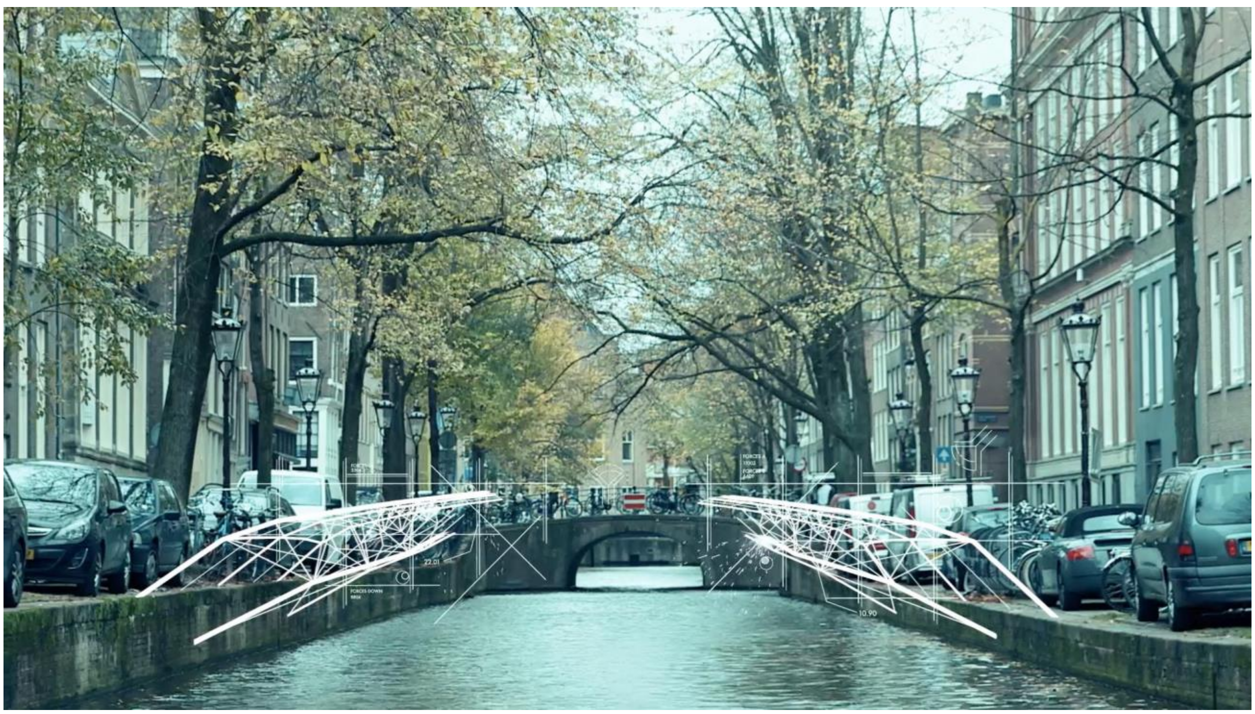
In the construction sector, Additive Manufacturing applications used to be limited to producing architectural models, which enable a physical representation of an architects design. In the past, a large concern for its use in buildings was the lack of sufficient material properties in printed parts that are required to comply with building regulations coupled with a large limitation on the size of prints. However, through extensive research, materials and processes have been developed that are currently being used in pioneering projects across the globe. Two few brief examples of pioneering projects can be found below:

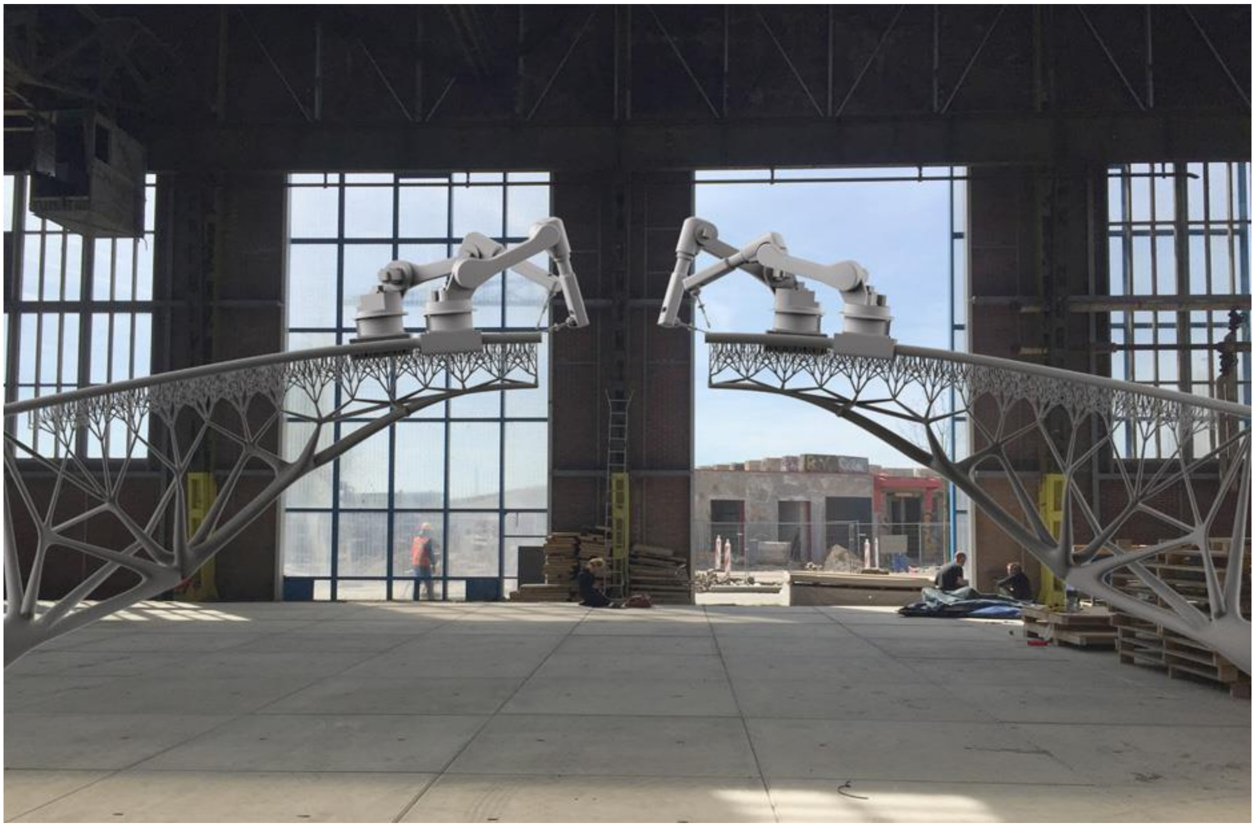
4.1 Apis Cor – Affordable Housing

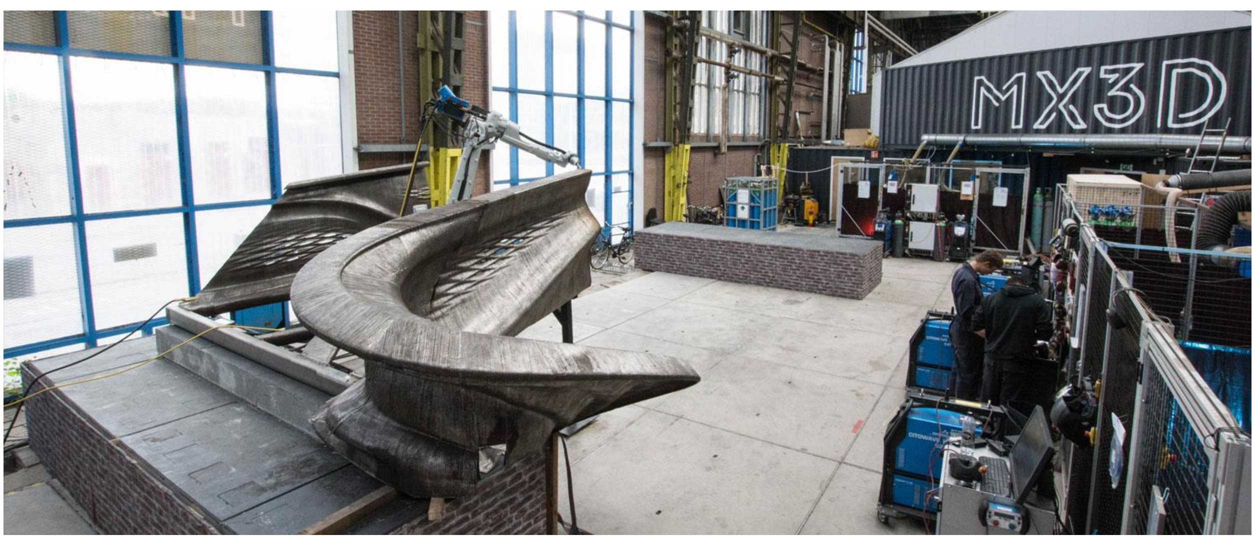
Apis Cor, based in San-Francisco, have developed a 3D printing concrete technology that has test printed a 400ft^2 house for less than $10,000. The entire building was printed in concrete with operatives placing fibre reinforced concrete in between the build layers, spraying insulation into the structure, installing the window frames and painting it bright yellow in around 24 hours. The printer itself uses 8kW of power to operate- as much as 5 electrical teapots working simultaneously. 2 operatives were required to complete the build and there was negligible construction waste. Pictures of the build can be seen below:

4.2 MX3D Bridge

The MX3D Bridge is currently a project being undertaken by a Dutch company, who are printing a large scale functional pedestrian steel bridge in Amsterdam. In order to achieve this, a 3D welding technology, developed by the architect, has been used. The original vision of the project was to print the bridge in situ, with robots printing supports for themselves as the bridge progressed. However, several unknown factors, such as the integrity of the canal walls meant the design needed to be adapted and the bridge had to be printed in the MX3D factory before being transported to the canal for its installation. This project really does provide an insight into the potential of large scale metal 3D printing's capabilities and stokes the fire for thought into where we could see this technology in the future. Pictures can be seen below:






MX3D

Through its ability for mass-customisation at no extra cost, Additive Manufacturing provides an architect with the ability to individualise and contextualise designs, therefore enabling a freedom of design without needing much consideration for standardisation, manufacturability and affordability. Design processes need to be adapted to align with the potential paradigm shift in manufacturing ability. Therefore, a major consideration for the incorporation of Additive Manufacturing in design is removing the expert from early concept designs to promote innovation and an early involvement from architects, designers, manufacturing experts and the contractor. Optimising parts improves the efficiency of a design and can be applied to several aspects of the performance of an object (structural, thermal and acoustic to name a few). The optimisation of parts was previously considered to be unnecessary in construction. This can largely be attributed to the complexity of optimised parts, which would otherwise be incredibly costly and difficult to manufacture coupled with the fact that optimised parts would be non-repetitive as it is rare that a parts throughout buildings have exactly the same requirements to optimise to. Additive Manufacturing's ability to produce any optimised structure means that there is a substantial argument to optimise every aspect of a building in the future. Alongside the development of design processes and to allow the processing of more complex computer models, a development in computer technology is required to deal with the vast amount of computer data and information required to fully incorporate Additive Manufacturing designs in buildings. It is incredible important to synergise the ability of BIM to carry a diverse selection of information about a part with the new manufacturing abilities of Additive Manufacturing to gain the most out of the technology. From a contractor's perspective, the mobility of printers simplifies the supply chain through just-in-time manufacture therefore reducing the congestion on sites, necessary packaging and eliminating and risk associated with the transportation of materials. Not only that, but employing automated manufacturing processes can help reduce health and safety risks, combat lack of high-skilled labour and significantly increase production levels.

Even though there are numerous advantages that Additive Manufacturing could bring to the construction sector for the design phase and construction phase of a building, there are several technical challenges that are preventing it from being used on sites today, namely; repeatability, precision, speed, legislation, certification and opinion. However, with the appropriate research, investment and "push" from the industry it is more than feasible that these obstacles can be overcome and we can reap the rewards of the multiple advantages of this innovative manufacturing process.

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