Role of Metal 3D Printing to Increase Quality and Resource-efficiency in the Construction Sector

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Role of metal 3D printing to increase quality and resource-efficiency in the construction sector

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Abstract

Demand for the construction of new structures is increasing all over the world. Since the construction sector dominates the global carbon footprint, new construction methods are needed with reduced embodied carbon and high resource efficiency to realize a sustainable future. In this direction, metal additive manufacturing, also known as 3D printing, can be an opportunity. Many studies are underway to answer open questions about metal printed products and processes for high-tech industries. The construction sector must join the metal 3D printing research more actively to enrich the knowledge and experience on this technology and correctly adapt the process parameters suitable to the construction sector requirements. This paper states the opinion of a research group composed of academics and practitioners from Europe, US, Japan, and South Africa on how metal 3D printing can be a complementary tool/technology to conventional manufacturing to increase productivity rates and reduce the costs and CO_2 emissions in the construction industry.

Keywords:

Sustainable construction; additive manufacturing; resource-efficiency; European green deal; architectural design; standardization

Table of contents

1 Introduction

The construction sector dominates the global carbon footprint with a 40% share among all sectors (International Energy Agency and United Nations 2018). Half of this share is due to the CO_2 embodied in the building elements, and one third is covered by the structural system (Kaethner and Burridge 2012) (Figure 1.a.b). Since the operational energy emissions are dropping thanks to increased passive building design and decarbonization of electricity grids, the already large share of the structural system to the carbon footprint is expected to increase further (Arnold 2020), as the global population will grow by 2.5 billion by 2050. Estimates are that 230 billion square meters of new construction is needed to meet the demand for housing, workspace and more expansive infrastructure (London Energy Transformation Initiative 2020; International Energy Agency and United Nations 2017; 2019). Therefore, the operations involved in developing new structural systems can have a vital role in reducing global CO_2 emissions, material and energy consumption.

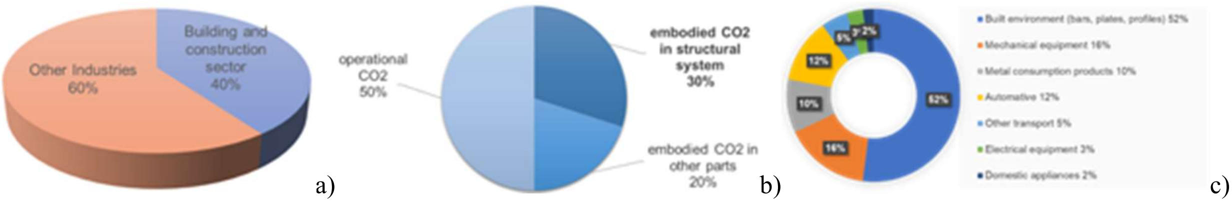


Figure 1. CO_2 by sector / built environment and share of steel construction applications. a) Global CO_2 consumption; b) Consumption within built environment (data from (Kaethner and Burridge 2012)); c) Global use of steel (data from (World Steel Association 2020))

52% of global steel is used for construction as reinforcement bars, plates and structural profiles (World Steel Association 2020) (Figure 1.c), and steel structural solutions generally involve substantial manhours, material waste, and high energy consumption related to the fabrication of joints for which a significant research effort is being made worldwide (Kanyilmaz 2019). A large source of CO_2 consumption and inefficiency of the traditional steel fabrication is related to the activities of joint fabrication (e.g., making of the holes, cutting of plates, post-weld heat treatments, accessibility issues for machines/operators, need for rat-holes when multiple welds concur to the same vertex, preheat issues and its control, the need of cleaning the weld from oxide patina before performing multiple layers, distortion induced by welding, dimension of the Heat Affected Zones). The consumption of energy could be reduced thanks to the possibility to produce complex parts in a single process.

Metal additive manufacturing (MAM), also known as metal 3D printing, is a relatively novel process of creating objects in layers by addition of melted metal powders or wires, which allows free-form geometries that can be customized locally to the internal stresses. MAM has seen wide adoption in aerospace and medical industries in the last decade, which is still growing (Debroy et al. 2018; DebRoy et al. 2019). The particular advantages for manufacturing of metal parts in the high-tech industries are the reduced lead time for parts and on-demand manufacturing including customization and optimization of parts on-demand, combining multiple components into one with less joins between them, and adding complexity with new features and designs that were not possible using traditional manufacturing tools. The main niches are for critical, high-value parts, with the economics and cost-benefit analysis discussed in more detail in (Leary 2021). A recent EU report (European Commission 2019a) places 3D printing as one of the five key technologies opening up opportunities and changing decades-old mechanisms for creating and distributing value in the Construction Community, and highlights that the skills agenda must be extended to the key industries such as construction. By exploiting the power of metal 3D printing, we can accelerate the transition of the steel construction sector toward a sustainable production of structural systems. Some research projects of metal 3D printing in the other sectors have already quantified the advantages (Horizon Europe Project, n.d.; Watson and Taminger 2018; Verhoef et al. 2018; Bekker and Verlinden 2018), and such benefits would be amplified in case of the construction sector, whose impact on the global energy and CO_2 consumption is the largest (International Energy Agency and United Nations 2018). The construction industry is actively demanding more efficient solutions that result in reduced costs and person-hours, and less energy consumption. Metal 3D printing would unleash the construction sector from the constraints of traditional manufacturing, and enable mass customization with increased production speed and quality, by placing materials where needed and using advanced digital tools for design and production.

Additive manufacturing of metals has witnessed an exponential increase in research activities especially in the last decade. As seen in Figure 2.a, the metal additive manufacturing research follows an exponential increase trend overall, where powder bed fusion techniques (PBF) have received the majority of attention. The directed energy deposition (DED) has received an increasing amount of interest from the mid 2000s, which peculiarly shows a similar trend to metal additive manufacturing for constructions. The metal 3D printing processes have exploited the design, software, calculation capabilities as well as reliable automation and energy sources in the last two decades, reaching a more mature state. The interest on the construction sector follows the overall maturity of the processes as well as the need for larger parts with shorter lead times. While not being one of the main end-users of the metal 3D printing processes, the construction sector appears to be one of the next drivers of these technologies. As shown in Figure 2.b the highest output comes from North America and Europe with considerable interest from Australia and South America. It can be perceived that the necessities in product innovation and improvements of material usage, and a reduced environmental impact in the construction sector in these parts of the globe are currently driving the research.

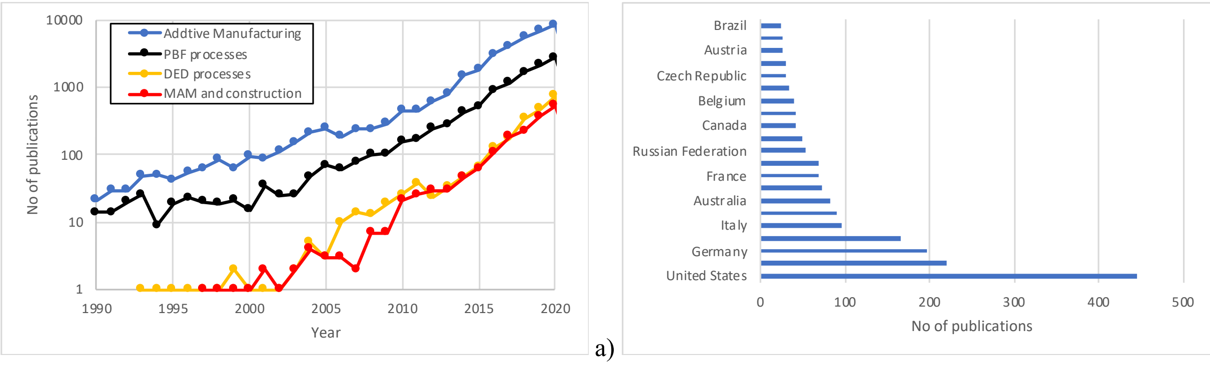


Figure 2. a) Number of additive manufacturing related articles in literature concerning PBF, DED processes and metal additive manufacturing for the construction sector. b) Top 20 countries in terms of publications in metal additive manufacturing in conjunction with the construction sector. Data gathered from Scopus (date of access 15 February 2021).

Despite the evident trend of growth and potentialities overseen, metal 3D printing still requires further developments to be fully exploited by the construction sector. The gaps in technology, process knowledge, design, and certification are the common issues to all sectors adopting the AM solutions, which have not been thoroughly investigated elsewhere to the authors' knowledge. This article discusses how metal 3D printing can be a complementary tool/technology to conventional manufacturing to reduce the lead times, the costs and CO_2 emissions of the construction industry. The discussion is aimed to identify the critical issues, which can be better addressed in future research activities and industrial practice.

2 General needs and requirements of the construction industry concerning metal 3D printing

The construction sector employs more than 12 million EU citizens (European Committee for Standardization 2021), and this sector as others, will soon have to undergo major changes towards digitalization and robotization, which will continuously bring changes to job profiles in the construction sector. Especially in the field of manufacturing, the current manual workforce procedures will be transformed into an industrialized design process (European Commission 2019b). The European Commission has highlighted the need to embrace the digital transformation by the community in a manifesto published by the European Construction Industry Federation (FIEC) in June 2018. In 2015, The Japanese government and the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) announced an initiative called the "i-construction" to enhance the productivity in construction and infrastructure industries utilizing ICT technologies.”. In South Africa, the government has established a commission for 4IR technologies (Presidential Commission on the Fourth Industrial Revolution 2020), making various recommendations, including digitalization of manufacturing and utilization of 3d printing for on-site manufacturing. Despite the good intentions, developing countries generally struggle with practical implementation of such recommendations due to the need for jobs and sustainability in the industry. The introduction of metal 3D printing can help in creating modern job types in the construction sector such as metal printing and robot operators, modern engineers and architects with new digital skills. Such new jobs will both protect the workers during the new industrial transition and enhance the safety and quality of their work-environment.

There is more than one possible adoption of AM in the construction industry, and therefore different potential niche areas of application. One of these is the new functionality in using the novel design freedom, to create improved metal parts for the construction industry. This involves finding better functional solutions to construction challenges, that make metal AM viable despite the higher cost involved in such parts. One potential example of this is in topology optimized resource-efficient joins or brackets, allowing significantly reduced mass and material waste with the same strength. More advanced examples include the incorporation of other functions into the same part (e.g. incorporating electronics into the part directly (Juhasz et al. 2020) allowing digital monitoring of the construction). Advanced manufacturing allows the incorporation of properties that were not possible using low-cost construction materials such as specifically designed porous structures for improved air-flow and thermal management, structures with vibration or shock absorption capabilities and more. All these examples deliver expensive solutions but with unique capabilities not yet available in traditional constructions. Another major benefit is the digital inventory and distributed manufacturing of metal AM with short lead times, reducing transportation costs and simplifying the supply chain, while allowing customization or modification from "standard" designs according to the local requirements.

Separately from the challenge of producing large dimensions for structures (although AM technology readiness level is increasing rapidly), the absence of specific design regulations and experience is currently considered by the construction industry itself to be the major barrier preventing widescale implementation of metal 3D printing. While the experimental validation costs for the qualification of high-tech industry products are justified by serial production, this is not feasible for relatively simple civil structures. Since they are not serially produced, testing efforts for each construction "product" would undermine the benefits. To place metal 3D printing in the mainstream of the EU construction sector within the next decade, the building codes and standards must be improved, and this requires the definition of specific metal 3D printing parameters (material, process) tailored for steel construction applications, the assessment of the metallurgical and mechanical properties of steel parts with case-compatible 3D printing methods, and the conception of specific methods to calculate the structural, economic and environmental impact of the new technology. Metal 3D printing can be best exploited alongside the common steel profiles produced with traditional methods; therefore the structural integrity of the printed parts with the conventional steel parts (joined by welding or bolting) must be quantified and enhanced. Despite the important role printed metals are expected to play in the near future, the available research only scratched the surface of these mentioned topics. This article aims to support further work in this topic by providing a state of the art and perspective.

3 Metal 3D printing material and process availability for large parts

The Metal 3D printing processes vary in terms of functional principles, feedstock types, geometrical capabilities, and size. Four significant issues are to be faced for the civil construction sectors in metal 3D printing:

- Material availability. The AM metals are not necessarily compatible with the civil construction requirements.
- Machine size restrictions. The machines are mainly made for small to medium sized products.
- High cost. Low productivity and expensive feedstocks increase the production costs.
- Finishing requirements. The produced parts may require post-processing and heat treatments for the surface finish and the mechanical properties.

The following paragraphs aim to provide the reader an overview of the technological readiness of the metal 3D printing processes from the civil construction perspective.

Criteria	LPBF	EBPBF	LMD	LMWD	WAAM	BJ	FDM
Materials	Construction steels not available	Construction steels not available	Construction steels not available	Construction steels not available	Construction steels available	Early stage	Early stage
Typical dimensions	300 x 300 x 300 mm^3	Ø250 mm x 400 mm	>1500 x 1500 x 1500 mm^3	>1500 x 1500 x 1500 mm^3	>1500 x 1500 x 1500 mm^3	400 x 250 x 250 mm^3	300 x 200 x 200 mm^3
Precision	High	High	Medium	Medium/Low	Low	High	High
Build rate	Low	Low	Medium	Medium	High	Medium/High	Low
Safety requirements	Laser and powder	Electron beam and powder	Laser and powder	Laser	Process glare	Powder	
Cost	+++	+++	+++	+++	+	++	++
Target	High value, aesthetics	High value, aesthetics	Large parts with geometrical flexibility	Large parts with geometrical flexibility	Large parts with geometrical flexibility	Small and aesthetic parts	Small and aesthetic parts

Table 1. A basic comparison of some of the main Metal 3D printing processes for use in the construction sector (Frazier 2014; B. Wu et al. 2018; Gu et al. 2012; Fayazfar et al. 2018; Motta, Demir, and Previtali 2018; Rane, Di Landro, and Strano 2019; Bai, Wagner, and Williams 2017)

Table 1 shows a generic view of the main metal 3D printing processes exploitable by the construction sector. Powder bed fusion (PBF) and directed energy deposition (DED) process families are the main techniques used for the production of metal parts, where fused deposition modelling (FDM) and binder jetting (BJ) alternatives are today being developed. FDM is now being adapted to metals by incorporating debinding and sintering phases. BJ is a highly promising AM process being developed with high build rates for metals that also requires debinding and sintering phases. The PBF (LPBF and EBPBF) and DED

(LMD, LMWD, WAAM) processes have been shown to possess adequate mechanical properties provided by low porosity levels (<0.5%) and tailored heat treatments developed over time. Arguably the most mature metal 3D printing process stands out as the laser powder bed fusion (LPBF) technique (Yadroitsev et al. 2021). A laser beam selectively melts the powder bed with adjacent melt tracks of the scanned geometry, repeated by layer. The process lends itself to highly detailed products and fine features mainly required by aerospace, tooling, medical, and energy sectors. The machine sizes and material availabilities are limited to the expectations of these driver sectors. Concerning the civil constructions, the use of low carbon steels is not readily available by conventional machine manufacturers, while the high end materials such as Ti-, Ni-, Al-alloys and stainless steels are among the most widely used ones (see Table 2). The material scarcity is both due to the limited process development required by the limited sectors but also due to the low processability of most of the conventional alloys during the fast cooling phase of the process. The electron beam powder bed fusion (EBPBF) variant operates under vacuum as the electrons require such conditions. EBPBF is today mainly used for Ti-alloys, where recent advancements have been made towards new Ni-, and Cu-alloys. In particular the construction steels are not amongst those already processed by the PBF processes (Fayazfar et al. 2018) with recent developments around similar chemical compositions (Aumayr et al. 2020).

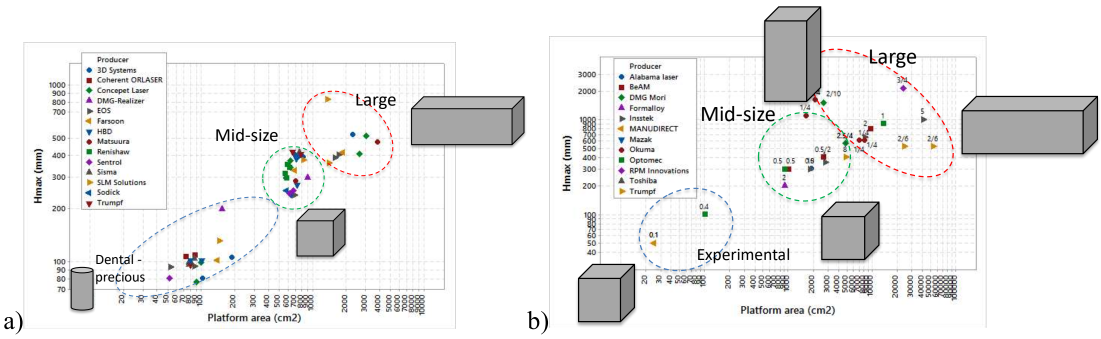


Figure 3. a) LPBF and b) LMD system dimensions and build volume geometries.

Material	Renishaw	EOS	SLM Solutions	3DS	Sisma	GE Concept Laser	Applications
Stainless steel	316L	316L, CX, GP1, PH1, 17-4PH	316L, 15-5, 17-4PH	316L, 17-4 PH	316L	316L, 17-4 PH,91RW	Food, biomedical, consumer
Ni-alloys	In625, In718	In625, In718, Hastelloy X, In939	In625, In718,In939, Hastelloy X	In718, In625	Hastelloy X	In625, In718	Energy, motorsport
Al-alloy	AlSi10Mg	AlSi10Mg	AlSi10Mg, AlSi7Mg0.6, AlSi9Cu3	AlSi12, AlSi10Mg, AlSi7Mg0.6	AlSi12, AlSi10Mg	AlSi10Mg, AlSi7Mg	Lightweight, aerospace, aviation
CoCr-alloy	CoCrMo	CoCrMo	CoCrMo	CoCrMo	CoCrMo	CoCrW	Dental, biomedical
Ti-alloys	Ti6Al4V	Ti6Al4V, CP Ti	Ti6Al4V, CP Ti, TA15	Ti6Al4V, CP Ti	Ti6Al4V	Ti6Al4V, CP Ti, Ti5Al5V5Mo3Cr, Ti6Al2Sn4Zr2Mo	Biomedical, lightweight, aerospace
Tool steel	Maraging 18Ni300	Maraging 18Ni300, 1.2709	H13, Maraging 18Ni300, Invar36, 1.2709	Maraging 18Ni300, 1.2709	Maraging 18Ni300	Maraging 18Ni300	Tooling, aerospace, automotive
General purpose steels		20MnCr5					General purpose engineering applications
Cu-alloys		99.6% pure Cu	CuSn10, CuNi2SiCr		Bronze		Energy, heat exchange
Precious					Au, Ag, Pt		Jewellery, design
Tungsten		W1					Energy, nuclear

Table 2. Material availability by some of the main LPBF system providers declared in their websites.

Concerning the producible part sizes, Figure 3.a provides a perspective comparing some of the industrial LPBF machines in terms of the build platform area and build height. It can be seen that the most common machine size is a cubic shape with approximately 300 mm length at all dimensions. More specialized systems go over 800 mm build height but an overall increase in the build volume is not easily scalable. This is due to the issues in managing the large amount of powder that has to be stored on the machine silo, in the powder bed but also recycled throughout the process. Such conditions generate safety issues as well concerning explosivity especially when highly reactive metals such as Ti and Al are concerned. Moreover, a larger build volume requires a higher number of laser sources to match with the build time requirements. The laser scan path management, the thermal load on the machine structure, and the conjunction points of the different lasers are among the factors that increase the machine design complexity. Despite such difficulties large system concepts emerge. The GE Atlas project provides a powder bed with 1100 x 1100 x 300 mm^3 build volume. The Adira Tiled Laser Melting system is composed of a 1000 x 1000 x 500 mm^3 build volume and a mobile scanner head over the entire build platform (Additive Manufacturing Media 2018). The custom made LPBF system of Aerosud provides a build volume of 2000 x 600 x 600 mm^3. The recently announced SLM Solutions NXG XII 600 will operate with simultaneously working 12 laser sources on a 600x600x600 mm^3 build volume (SLM Solutions 2020). While these are important technological demonstrations, each system is destined to a high-end application to work with expensive Ti-, Ni, and Al-alloys.

Concerning the DED processes, different process solutions emerge as a function of the energy source and the feedstock type used. Electric arcs, lasers, and electron beams can be employed as the heat sources while powder or wire feedstocks are used. The union of powder and laser corresponds to the laser metal deposition (LMD) process, which appears to be the most widely available one in terms of the commercial machine types. The powder feedstock is blown through a coaxial nozzle via a carrier gas into a melt pool opened by the laser beam. The material availability is highly dependent on the end-user's experience as standard material types are scarcer in this case. Figure 3.b provides the overview of machine dimensions concerning commercially available systems. LMD systems can be larger as a powder bed is not required, while robotic and cartesian systems can be employed to manipulate the deposition head. Hence, the machine size depends on the laser and powder safety requirements and automation capacity (size of robot arm). Wire feedstocks in DED provide a safer operating and stocking conditions as opposed to powder feedstocks and they can reduce the material cost and improve productivity. So far electron beams, lasers and arcs have been used in combination with wire feedstocks. The Sciaky EBAM 300 system uses an electron beam in a vacuum build chamber of 7620 x 2743 x 3353 mm^3 to deposit wires with higher deposition rates (Skiaky Inc 2021). However, the operating costs are a better fit for high value components used especially in aerospace. The laser metal wire deposition (LMWD) technique uses a laser beam to melt the wire feedstock, where coaxial deposition systems have been commercialized too. The material availability of LMWD is still limited as the process development is still underway for new alloys. On the other hand the wire and arc additive manufacturing (WAAM) process is the evolution of highly automatized arc welding processes (MIG metal inert gas or TIG tungsten inert gas). WAAM exploits the recent advancements in process automation, path programming and the existing material availability in welding consumables (B. Wu et al. 2018). Therefore WAAM can intrinsically produce parts in construction steels (Rodrigues et al. 2020; Dirisu et al. 2019). The size and the geometrical complexity of the WAAM produced parts depends on the machine configuration, which commonly is based on the single end-user's preferences.

An important factor concerning the part cost is related to the low productivity of the metal 3D printing processes. In PBF systems for a single beam source the productivity is <0.5 kg/h for steels. The productivity issue is mainly tackled by increasing the number of beam sources. In LPBF, commercial systems with up to 12 sources have been introduced. With DED processes the productivity relies both on the power available and the material feed rates. For LMD and LMWD up to 1 kg/h can be potentially exploited. WAAM can reach between 5 to 10 kg/h build rates, giving it a significant advantage.

The post-processing phase can also be an important limitation to the process. As the productivity increases the feature resolution is decreased as a rule of the thumb. The complexity of the component produced can generate the post-processing phase more difficult. The organic forms, undercuts, internal channels achievable via PBF processes require non-conventional finishing operations such as abrasive flow jet or electrochemical machining increasing the final cost of the product (Anilli, Demir, and Previtali 2018). The DED produced parts are characterized by irregular surfaces with high surface roughness (Bruzzo et al. 2021). Combined with the large size their finishing operation may be best fit to be carried out during the deposition phase in a hybrid manufacturing scheme. Heat treatments are often required to remove the internal stresses and improve mechanical performance (C. Tan et al. 2018; Aboulkhair et al. 2016). For BJ and FDM the sintering phase in a furnace is mandatory to achieve the final densification. For PBF products, heat treatment can be mostly required to avoid part distortions as they are released from the baseplate. The large DED products are also difficult to manage for possible heat treatments. Opportunities of tailored deposition strategies should be sought for minimizing if not eliminating the internal stresses during the deposition process.

Finally, as shown in Figure 3, today's metal 3D printing means should be evaluated as a function of the targeted application. From this point of view, aesthetics, function, time to market, maintenance, assembly and disassembly of the components should also be analysed along with the other metrics. The value, which is different from the cost is much harder to quantify, involving the life cycle assessment and the use of the resources.

The future trends in metal 3D printing equipment will presumably move towards a consolidation phase in the upcoming years in the most developed processes such as LPBF. The expansion towards very large machines will continue however will also be limited to the safety and productivity issues. The construction sector can better exploit existing design flexibility and reduce production costs by increasing productivity rates and utilizing cheaper feedstocks. New concepts for large area processing by laser beam shaping in LPBF development, however at laboratory scale (Matthews et al. 2017; Zavala-Arredondo, Groom, and Mumtaz 2018). The DED systems will move towards more standardized architectures improving usability and settling of design rules for the processes. These factors can be better exploited to integrate these relatively less developed processes to a complete digital platform and integrate with the design and calculation tools of the construction sector (Smith et al. 2016). Newer metal 3D printing processes namely BJ and FDM will be further explored enhancing the process and material knowledge base allowing to allocate them better in the applications of the construction sector. Overall for all processes, the future holds the development of process monitoring and control systems, which will ensure product quality (Grasso and Colosimo 2017). With ensured quality, the variability in the static and fatigue properties could be reduced between products, build jobs, and also machines. This would be exploited by the construction sector by reduced safety margins in the design phase. Multi-material processing and high temperature preheating systems are also under development, which can open up to newer functions through novel materials with gradient properties (Caprio et al. 2020; Scaramuccia et al. 2020; Wei et al. 2018; Yan, Chen, and Liou 2020).

4 Structural Integrity and Fatigue aspects

One of the major difficulties of metal additive manufacturing is the inconsistent mechanical behaviour of the parts produced using this technology being highly dependent on various factors such as microstructural differences of the material, possible defect types within the produced parts, surface roughness effects, residual stresses, and more. Due to the rapid cooling rates, thermal reheating during the AM process and directional solidification, metallic components produced via additive manufacturing represent microstructures and three-dimensional multiscale architectures that are different from their cast and wrought conventional counterparts (Gorsse et al. 2017)(S.M.J. Razavi and Berto 2019). AM metals commonly have fine grains and anisotropic microstructures elongated along the printing direction. Internal porosities are among the distinguishing bulk microstructural features of metallic components fabricated by metal 3D printing (Sanaei and Fatemi 2021). These porosities can be classified into two major categories of gas pores and lack of fusion. While gas pores normally form during solidification of metals and can be entrapped from surrounding gas, lack of fusion defects develop due to the low energy density of the heat source (i.e., laser, electron beam, electric arc) leading to insufficient melting bonding between the melted layers. As a result of the layer-wise nature of AM technology and partially melted powders (in case of powder-based metal 3D printing), AM components commonly have high surface roughness in as-built condition. During the AM process, the appearance of the large thermal gradients in the neighbourhood of the melt pool, rapid and uneven cooling of the melted material, and repetition of this process leads to localized residual stresses in the AM components. These residual stresses are reported to be detrimental to the mechanical properties of the produced parts and can possibly result in warping or cracking of the AM part during or after the fabrication process.

The mentioned factors (i.e. anisotropic microstructures, internal porosity, surface roughness, residual stress) directly influence the structural integrity of the AM parts, and therefore numerous research studies have focused on tailoring the process parameters, quality control efforts, non-destructive testing in-process and inspection of final parts, and post-processing of the parts to remove and mitigate many of the defects causing detrimental failures (Maleki et al. 2021)(Bagherifard et al. 2018). The common goal in most of these research studies in the literature is to improve the mechanical properties of AM parts to have comparable mechanical behaviour with the components produced by the conventional techniques.

In general, the quasi-static mechanical properties of AM metallic components are on par with their wrought counterparts and depending on the process and post process conditions often even exceeding them. The higher strength of AM metals is mostly correlated with the finer microstructural features compared to their wrought counterparts. On the other hand, as a result of presence of brittle phases or internal defects, AM parts can experience lower ductility (A. du Plessis, Yadroitsava, and Yadroitsev 2020).

Dealing with the structural integrity of AM components and structures, the major concern is focused on fatigue loading. Fatigue failure has a local nature meaning that the presence of any geometrical discontinuities can raise the stress level in the part resulting in fatigue failure initiation in the vicinity of these discontinuities (Santecchia et al. 2016). In this scenario, the effect of surface roughness and internal defects in the AM parts would be intensified making them more susceptible to fatigue failure (S. M.J. Razavi et al. 2018; S.M.J. Razavi et al. 2018; Seyed Mohammad Javad Razavi et al. 2021). Hence, a comprehensive understanding of the fatigue failure mechanisms and their dependency to the material microstructure, internal defects, and surface roughness is a vital task to enhance the durability of AM components and structures (Berto, Razavi, and Torgersen 2018).

On the other hand, the mechanical behaviour of AM parts under static and fatigue loading is reported to be closely related to the input geometry of the component in a way that any change in geometry of part can alter the manufacturing strategy and consequently the microstructure, surface condition, residual stresses and internal porosities (Liu and Shin 2019)(Herzog et al. 2016). For the specific case of MAM for the construction industry the structural components are significantly larger than the parts studied by high-tech industries, and this change of scale needs to be widely studied. The data from the literature shows that the microstructures of the AM metallic materials are highly dependent on the scale or thickness of the fabricated part. In this scenario, as reported in (Hrabe and Quinn 2013; X. Tan et al. 2015; Toh et al. 2016; S. M.J. Razavi, Van Hooreweder, and Berto 2020), larger and thicker parts show larger microstructures, lower hardness and higher ductility compared to thinner or smaller parts produced with the same process parameters (see Figure 4). This dependency has only been studied in the lab scale and there is a large knowledge gap for exploring the scale effect of construction applications. The scale-effect research is still at its early stage because MAM bulky parts are expensive, lots of residual stresses occurs, and the crack growth is hardly predictable. The high costs and the great research still needed can be supported by peculiar projects looking for resource-efficient solutions for applications where traditional design is extremely expensive, unsafe or even unfeasible.

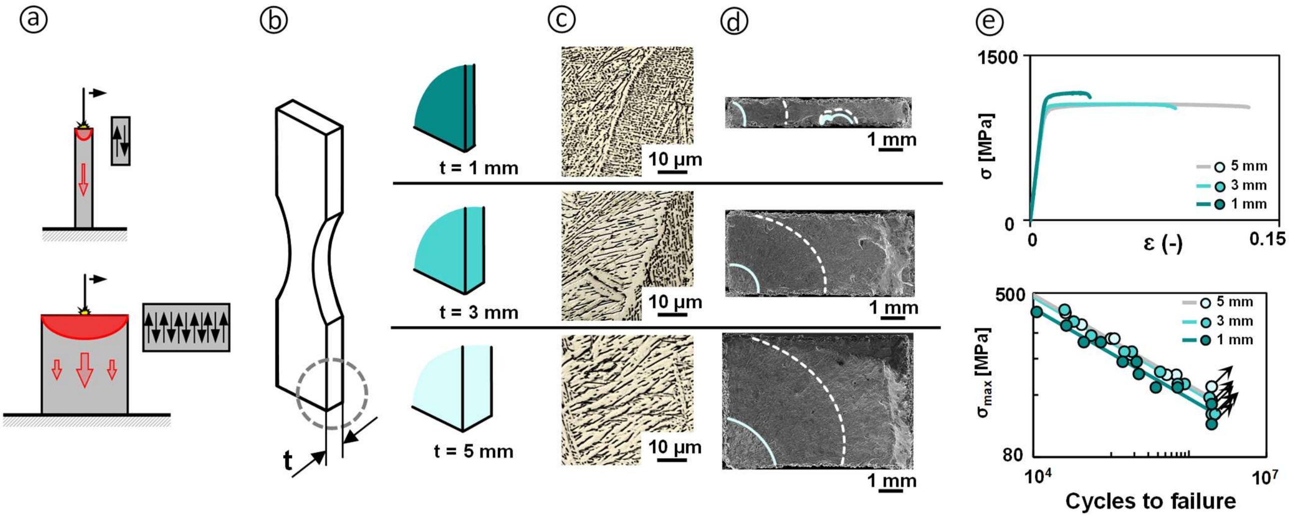


Figure 4. The dependency of mechanical behaviour of Ti-6Al-4V alloy to the thickness of the produced parts. (a) the thermal gradient in the specimens with different build thickness; thicker parts are reported to experience a higher average temperature during the fabrication. (b) the geometry of the produced parts. (c) the thickness dependent microstructure of the fabricated material. increasing the build thickness of the part has resulted in coarsening of the microstructure. (d) fatigue fracture surface of the tested specimens. Larger area of stable crack growth can be seen for the thicker parts with lower surface to volume ratio. (e) mechanical properties of the tested specimens under quasi-static and fatigue loading. Significantly higher ductility (elongation at failure) was obtained for the thicker parts of 5mm thickness. These parts also revealed higher fatigue endurance (S. M.J. Razavi, Van Hooreweder, and Berto 2020).

In the specific case of large and complex civil structures the fluctuating, time-dependent wind loads or the load applied by the fluid flow to the bridge structures can be categorized as variable amplitude fatigue loading conditions (Lorenzon, Antonello, and Berto 2018). As one of the main goals for design of large structures, weight optimization techniques have been proposed and used in the past (Dogan and Ozyuksel Ciftcioglu 2020; Cicconi et al. 2016; Wennhage 2003; Mojolic, Hulea, and Pârv 2015). Due to the high flexibility of AM in producing geometrically optimized parts, one of the advantages of using this technology in construction would be the weight reduction of the structure. At the same time, the weight optimized structures are more prone to high-cycle wind-induced fatigue collapse, making this topic a complex case of finding the perfect link between the design, printability, and mechanical performance and durability.

According to the published research in this field, the quality assurance and fatigue assessment of geometrically complex AM components cannot yet be precisely accomplished due to an absence of advanced practices which can incorporate the effect of the microstructural features (grains and internal defects), surface condition, residual stresses, and complex loading conditions to effectively model specific mechanical behaviour of AM materials.

To date, evaluation of the quality assurance of AM components has been the topic of numerous articles evaluating the effect of process parameters on the microstructure of resulting material, geometrical accuracy, and mechanical behaviour of the AM parts. Besides, limited attempts have been made to assess the mechanical behaviour of geometrically complex AM parts using the available theoretical models developed for components and structures produced by conventional techniques. Nevertheless, to the best of the authors' knowledge, no specific design and failure assessment criteria has been yet in place considering stress concentration arising from geometrical discontinuities in AM parts and their interaction with the complex loading conditions in various scales of the components and structures.

Reflecting all the mentioned challenges regarding the use of AM for fabrication of large and geometrically complex structures, a mechanistic knowledge of mechanical strength and failure modes of these parts under specific loading conditions is of great importance for developing a design protocol and failure prediction tool which are expected to be highly demanded in the near future.

5 The exploitation of metal 3D printing for innovative design

In terms of strength, reliability, formability and ductility, steel has much better properties than other construction materials, making it an indispensable material in the modern construction industry. Even when metal AM is adopted as a production method, and some severe issues need to be solved, such as material anisotropy and defect generation specific to the printing process, the potential superiority of the material would not be shaken. On the other hand, the cost-effectiveness of metal 3D printing (e.g., the unit cost per weight) may be inferior to other construction materials and technologies. Therefore, a favourable use of metal 3D printing for building is in printing components (e.g., nodes) where freedom of shape, strength and reliability are expected, and where the production through traditional techniques would be difficult (Galjaard et al. 2015). This is in contrast to 3d concrete printing (3DCP) which is often used to build walls that bear forces with the whole plane. 3DCP is a technology seeing huge growth in the construction sector at present and metal 3D printing might benefit from this development, in the context of improved adoption of digital design and manufacturing, automation and new design approaches being adopted in the construction industry (Anton du Plessis et al. 2021; Mechtcherine et al. 2020).

Leaving the material issues of Metal 3D printing to another section, what could be the preferred approach to deploy this challenging concept of the metal 3D printing node in actual buildings? We have to focus on the technical aspects of a structural joint: quality, cost efficiency, lead time, aesthetics, digital readiness, and customizability. Metal 3D printing nodes give advantages that are not reached by other techniques (Figure 5). Traditionally assembled joints are economical and have sufficient customizability, especially for small cross-section parts, but they are often not aesthetic. On the other hand, cast steel offers high quality and pleasing aesthetics but requires long lead times due to highly specialized manufacturers, its shape customizability is subject to the mould, and its cost to the mould amortisation.

Another advantage in line with building design is the digital connection between the additive manufacturing process and computer-aided engineering processes (e.g., AI-based engineering process). The full integration with building information modelling (BIM) allows the collaboration between the structural design and all the production phases (e.g., production scheduling, logistic, cost and time estimation and long term management). Indeed, the design process includes the geometry definition and production and assembling needs, giving the designer more responsibilities and greater design opportunities (C. Buchanan and Gardner 2019). Metal 3D printing allows for a drastic increase in the number and breadth of design attempts, expanding the nature of architectural design (Figure 6). Nevertheless, a suitable design workflow is still missing. When a provocatively designed work that takes full advantage of this feature will emerge, the exploitation of metal 3D printing would enter a novel dissemination phase.

	 Assembled node	 Cast steel node	 3D printed node
Quality		✓	
Cost efficiency	✓		
Lead time	✓		
Aesthetics		✓	✓
Digital readiness			✓
Customizability	Customizable especially in case of small sections	Depends on moulds condition	High customizable, but depends on printability

Figure 5. Pros and cons of traditional and 3D-printed structural nodes.

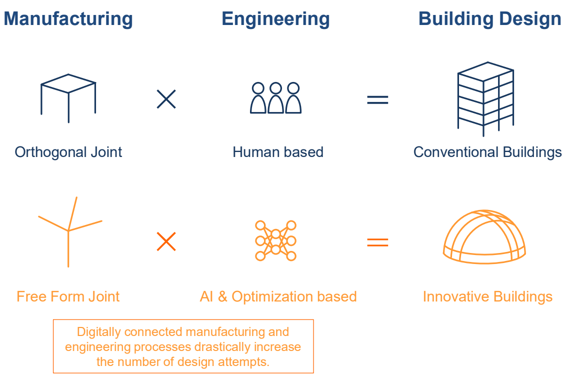
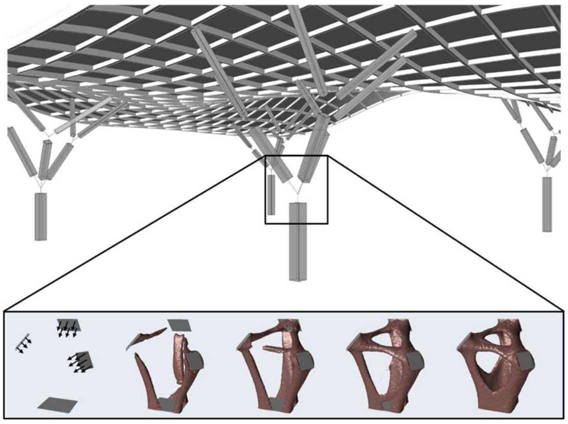


Figure 6. Relation diagrams of manufacturing, engineering, and building design.

Takenaka developed an advantageous metal 3D printing node based on aesthetic, customisation, amortisation costs, and digital readiness. The concept of free-form nodes using metal 3D printing technology was presented by the Japanese construction company Takenaka Corporation, in collaboration with the Amsterdam-based start-up MX3D (Figure 7a)(MX3D 2019). The joint is composed of multiple branches attached from arbitrary angles to a lower column (Figure 7b). The companies generated the structural node by topology optimization considering the assumed loads, and the 3D printing using WAAM technology with duplex stainless steel wires (Figure 7a).

a)



b)

Figure 7. a) Topology optimized and additively manufactured free form structural node (MX3D 2019). b) Topology optimization process of nodes integrated with overall structural planning.

6 Design opportunities employing different Metal 3D printing processes

Many aspects of the steel construction sector are standardised, for example, there are standard dimensions for hot-finished profiles and standard joint details. Furthermore, prismatic sections and simple details are typically favoured to minimise fabrication costs. Such an approach is efficient, economical and facilitates ease of design and construction but does not, in general, minimise material use, wastage or embodied energy. A recent study concluded that the average utilisation of steel in structures is less than 50% (Moynihan and Allwood 2014). A significant potential advantage of using additive manufacturing in construction is that material can be placed in the optimal configuration to resist the applied loading without the penalty of excessive fabrication costs associated with manual operations and bespoke geometries. Hence, close to optimal utilisation of the material could be achieved. In addition to geometric optimisation, there is also greater scope for harnessing the benefits of (I) mixed material properties (e.g., higher strength material in heavily stressed regions and lower strength material where ductility demands are greater (C. Buchanan and Gardner 2019)), (II) anisotropy (e.g., orientating the print layer direction such that the stiffness of the structure is maximised (Pinelopi Kyvelou et al. 2020)), and (III) thermal prestressing (e.g., using a scanning strategy that results in residual stresses that are opposite in a sense to the stresses that will arise from the subsequent application of load (C. Buchanan and Gardner 2019)).

The landmark MX3D bridge has shown that it is possible to additively manufacture, using WAAM, 308LSi austenitic stainless steel elements on a scale that allows meaningful use in construction. It has also been shown, following a comprehensive program of physical testing (Gardner et al. 2020) (Figure 8), and numerical modelling, that the required structural performance to satisfy the demands of ultimate limit state loading specified in design standards can be achieved.


a)

b)

Figure 8. Physical testing of the additively manufactured MX3D bridge. a) Vertical load testing; b) horizontal load testing

The steel construction industry frequently uses steel tubular elements to build high performance and architecturally appealing structures. Thanks to high multidirectional axial and bending inertia, they are an excellent choice to achieve high strength with minimum weight (Duarte et al. 2017). In addition, steel tubular frames require less corrosion and fire protection than other frames types with similar mechanical properties (Kanyilmaz et al. 2020). For tubular structures, one of the main issues is the local buckling of compression members, which are widely used in the construction industry as columns, in trusses and as bracing elements (Ruizhi Zhang et al. 2020). On this basis, recent works have demonstrated the feasibility and significant benefits derived through the structural optimisation of tubular elements, additively manufactured at a smaller scale using powder bed fusion (R. Zhang, Gardner, et al. 2021). In the studied scenario, the axial load bearing capacity of optimised 'Aster' and 'wavy' shells were assessed relative to a reference circular shell of essentially the same volume. The tested geometries are shown in Figure 9. Increases in capacity of up to about 40% were observed experimentally, while ever greater benefits, with further geometrical refinement, were predicted numerically (Figure 10) (R. Zhang, Gardner, et al. 2021).

a) b) c)

Figure 9. Reference circular shell and optimised Aster and wavy shells additively manufactured by powder bed fusion (R. Zhang, Gardner, et al. 2021). a) Circular shell; b) aster shell; c) wavy shell

a) b) c)

Figure 10. Numerical simulations of shells demonstrating potential capacity gains achieved through geometrical refinement (R. Zhang, Gardner, et al. 2021). a) Circular shell; b) aster shell; c) wavy shell

For the wider application of metal additive manufacturing, the construction sector needs greater confidence, further precedents, more emphasis on physical testing and advanced numerical simulations, and the establishment of authoritative design guidance. For the latter, greater knowledge is needed about the fundamental materials and geometrical properties of metal additively manufactured components, and about the variability and dependence on process parameters thereof. Research in this direction has already begun (Pinelopi Kyvelou et al. 2020; Laghi et al. 2020; Laghi, Tonelli, et al. 2021; R. Zhang, Buchanan, et al. 2021; Silvestru et al. 2021; Laghi, Palermo, et al. 2021), but substantially more is still needed. A relevant study on properties assessment of metal additively manufactured components applied laser scanning to obtain statistical data on the geometric variability of WAAM samples (Figure 11). Despite advances in robotics and materials which are currently outpacing structural design standards, another aspect that needs to be studied is the applicability of existing structural design rules, and the required modifications for application to additively manufactured products. The initial research presented by Kyvelou et al. (P. Kyvelou et al. 2021) concluded that, provided the weakening effect of the surface undulations that are characteristic of as-built WAAM material, existing plate buckling design rules are generally appropriate for application to WAAM elements. While some initial research towards the development of structural design rules has commenced (P. Kyvelou et al. 2021)(Craig Buchanan et al. 2017), the long-term behaviour of additively manufactured components is largely unknown (P. Wu, Wang, and Wang 2016), and significantly more work is required. One approach to optimally utilize the complexity offered by additive manufacturing is to use biomimetic design principles as reviewed in (Anton du Plessis et al. 2019), leading to organic and cellular designs minimizing material use and optimizing functional performance.

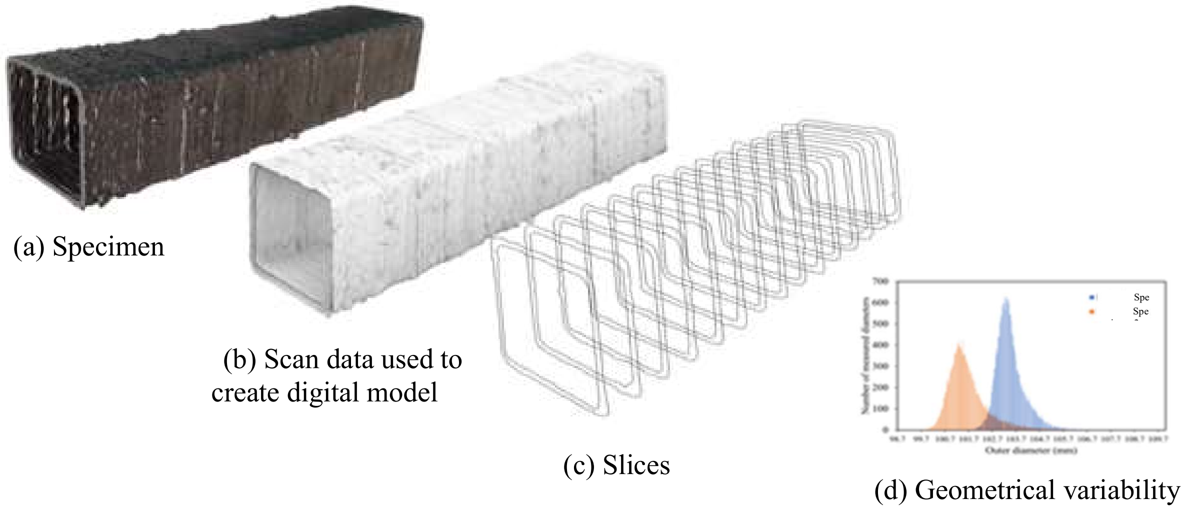


Figure 11. Laser scanning to obtain geometrical data on WAAM samples (P. Kyvelou et al. 2021)

Additive manufacturing is likely to complement, rather than replace, existing production methods (e.g., hot-rolling and cold-forming) in construction. It is therefore foreseen that, while further prestigious structures will continue to emerge, the largest volume of additive manufactured elements will be in hybrid applications, such as hot-rolled steel members with additively manufactured joints and details, and in strengthening and repair. Designers will have to be increasingly accustomed with Design for Manufacturing and Assembly (DfMA), i.e. designing and optimising a component with the manufacturing process in mind, giving due consideration to a range of constraints. An example of an optimised joint between an I-section beam and a square hollow section column is shown in Figure 12. Another example of complementing traditional manufacturing with metal AM has been studying (Kanyilmaz et al. 2020)(Chierici, Berto, and Kanyilmaz 2021) a design solution for tubular steel structures having complex geometries. The aim is to reduce the design and assembling costs and increase the resource-efficiency of structures with many dissimilar complex joints.

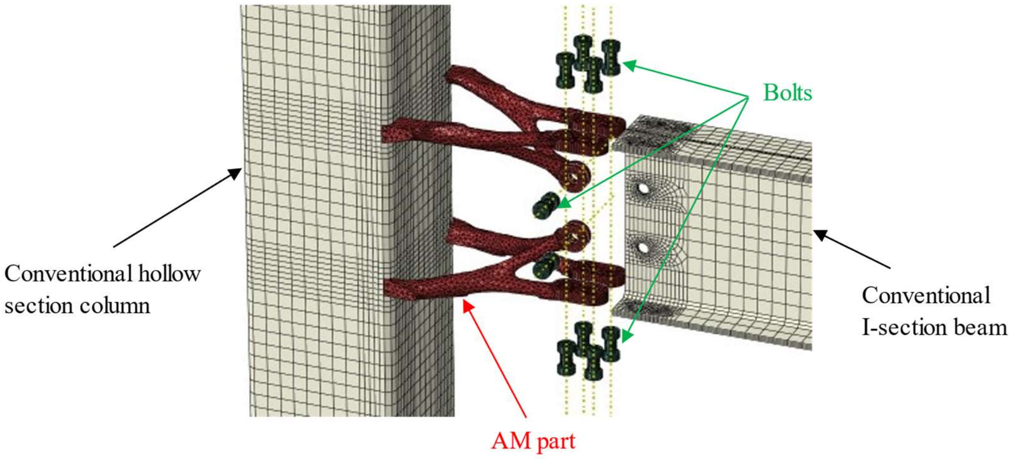


Figure 12. Example of an optimised joint between an I-section beam and a square hollow section column

The geometrical advantages of metal AM would allow to build each node as unique and optimised to its internal stresses. (Figure 13a). This design approach prevents from assembling several separately manufactured parts, and from specifically designing internal stiffeners for each hollow joint. In addition, the joining between the conventional components and the printed node has been designing as a butt-joint to simplify the joints verifications and assembling (Figure 13b). The current study focuses on the suitability of the printed steel to welded (Figure 13c) and bolted joints, and on the behaviour of medium printed components which can show differences with respect to the most studied small components from the high-tech fields (Figure 13c).

Overall, although there are clear challenges ahead for the wider application of metal additive manufacturing in construction, initial signs are positive and there are clear potential benefits.

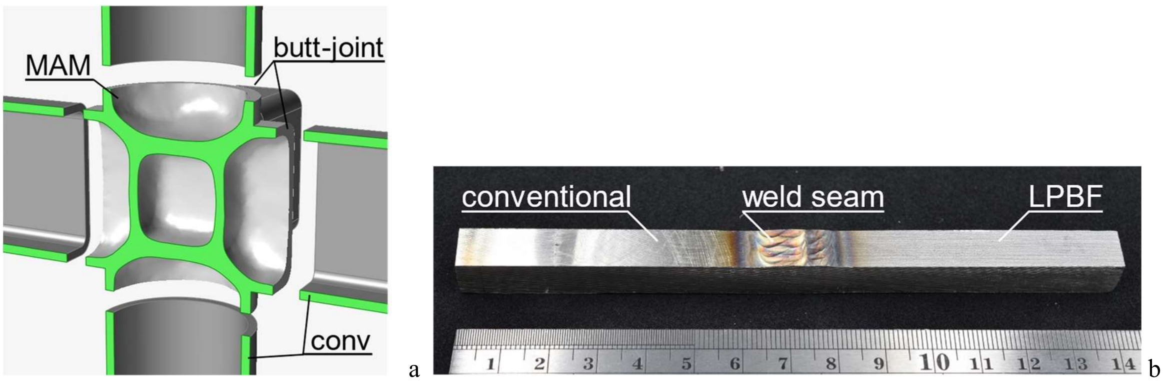


Figure 13. a) Joint design for a simple assembling (butt joint) with node geometry optimised to the internal stresses. b) Samples for the study of welding traditionally with additively manufactured SS316L, having suitable dimensions and joining techniques for the construction sector (marker in cm).

7 Regulation and certification forecast for Metal 3D printing in the construction industry

The global construction industry is one of the most lucrative and competitive. To successfully introduce new technologies, construction firms must choose qualified technologies that meet stringent safety and sustainability requirements, and are flexible enough to respond to evolving needs. Adopting any new technology without proper risk assessment could lead to risks of using substandard ('non-conforming') products or materials or using them incorrectly ('non-complying'). Robust qualification and certification methodology could mitigate these risks.

3D printing is an emerging technology with large potential but is not yet been widely adopted as an alternative manufacturing process to produce certified components for the construction industry. One of the main concerns about the adoption of 3D printing is long term safety, instability of the 3D printed buildings were commonly raised by manufacturers and the construction industry. It is important that the materials used to print the building blocks are going to be sturdy to withstand sustained loading and environmental effects. Hence the materials, process and printed products would require demonstrating compliance with applicable construction products regulations. For example, any construction product within the European Economic Area (EEA) must comply with the EU Construction Products Regulation (CPR), also known as the Construction Products Regulation. This law states that all products traded or sold in Europe must bear a CE mark, when a harmonized standard exists for this product. It does not necessarily mean that a product will be suitable for all end uses, but it does indicate that the product is consistent with its Declaration of Performance (DoP), as made by the manufacturer (SGS, n.d.).

The manufacturer of the 3D printed products that requires CE-marking or equivalent is ultimately responsible for the product to meet all requirements. In general manufacturers need to work with a Notified Body (NoBo) or an equivalent certification service provider for guidance, testing and conformity assessment services to achieve compliance. Currently there is no unified or standardised qualification of certification pathway for products made by 3D printing for construction industry. However, many regulatory certification bodies already developed specific certification pathway for those industries which already adopted 3D printing (e.g., aerospace, defence, maritime and oil & gas), and the construction industry can benefit from them.

Qualification is a process to demonstrate the ability to fulfil specified requirements that may involve specification review, design verification, feedstock material, manufacturing process, elaborate product testing and inspection, document preparation, and documenting the compliance in the form of a qualification certificate. It is often a one-time exercise that helps in ensuring the manufacturer's familiarity with specified requirements and its compliance. Qualification may be carried out to qualify personnel, equipment, products, processes or systems.

Certification is an act or process to assure a component complies with agreed/qualified parameters, and standard, or specific requirements and documenting the compliance in the form of a certificate. Possible requirements for specific components may involve unscheduled survey of manufacturing process, inspection of products, verification of traceability, witnessing of test specimens, verification of compliance to requirements, etc. It is a repetitive exercise to certify the conformity of a single product, a product batch or series of product batches. The type of certification often depends on the criticality of the component which in turn defines the involvement of certification requirements and activities.

DNV has developed and published a Class Guideline, DNVGL-CG-0197 (DNV-GL 2017), for additive manufacturing qualification and certification process for materials and components to facilitate the adoption of AM in Oil & Gas and maritime industries. DNVGL-CG-0197 proposed different types of generic qualification and certification requirements for AM that include the following important elements 1) Equipment Qualification / Calibration Certification; 2) Procedure and Facility Qualification; 3) Personnel Qualification / Endorsement; 4) Design Process Qualification; 5) Specifications and Design Review; 6) Powders / Materials Qualification; 7) Inspection and Certification Services; 8) Witness Audits; 9) Laboratory Testing. Table 3 provides the outline of compliance framework for qualifying and certifying 3D products.

Based on the experience from Oil & Gas and maritime industries, the authors propose the following qualification and certification framework for 3D printed products in the construction industry. It would help building trust and confidence in printing products as well as guide the manufacturers to comply with construction industry regulations. The certification pathway for the construction industry can be related to three phases of development of new technology as suggested below:

- Phase 1: Procedure qualification phase, where manufacturers demonstrate proof of concept to prove that they have feasible technology or products.
- Phase 2: Factory Production Control (FPC) Certification phase, where the manufacturers or end users design or manufacturing capabilities and process controls are assessed to determine if the manufacturer can produce specific grades or types of materials that conform to the relevant regulations.
- Phase 3: Certification phase, where manufacturers or end users require certificates for materials or products from regular production, either as individual parts or in batches, depending on the certification requirement of those parts.

The current existing certification documents for additive manufacturing used in other industries (Moroni, Petrò, and Shao 2020) can be adopted in the construction industry as the technology will bring more aid than harm. Adoption can be encouraged by further developing specific standards for the construction industry. Table 4 provides an overview of suggested activities to support qualification and quality control activities of AM parts production.

Stage	Compliance requirement	Example work scope
Design	Design Assessment/Verification	Check constructors design, drawings, calculations and specifications with applicable codes, standards, legal requirements (legislation) and purchase specification to assure safety, functionality and comfort for the users
Material selection	Material specifications	The conformity of the various products in accordance with construction requirements and relevant standards
Qualification including type testing	Validation of design, material, process, part and personnel	The qualification process ensures that the specified method, by which the parts are processed, is able to meet the qualifying criteria in a repeated manner in order to be identified as qualified.
Factory Production Control (FPC) Certification	Vendor Surveillance	A successful audit to check production and quality control procedures and inspection methods of products
Product inspection and certification		Witnessing destructive and Non-destructive Testing and Examinations (NDT/NDE) - Technical inspection in the workshop or on-site

Table 3. Suggested compliance framework for qualifying and certifying 3D products

AM activity	Typical qualification and/or quality control activity
Design	Design Assessment Requirements Specification FE calculations Regulations & codes Design Approval
Materials	Material handling procedures Facility audits Approved process Approved equipment Approved consumables
Pre-processing	Design file and cyber security Build layout with orientation, support structures & test specimens Software/firmware version Computational simulation of manufacturing process
3D Printing / Manufacturing	Build parameters Equipment Machine calibrations Consumables Operating procedures In-situ process monitoring and data- acquisition Approved cleaning and handling procedures
Post-processing	Removal from AM system & support structures Handling & recycle unfused powder (if applicable) Cleaning routines Heat treatment procedures etc. Final machining (if applicable) Maintenance & calibration records
Testing and Inspection	Instruments with required accuracy Calibrated equipment and instruments Approved testing and Inspection procedures
Verification /Certification	Periodical and unscheduled audits and compliance check for process control and equipment's, essential accessories and facilities

Table 4. Detailed activities to support qualification and/or quality control activity of AM parts production

8 Conclusions

This paper states the opinion of a research group composed of academics and practitioners from Europe, US, Japan, and South Africa on how metal 3D printing can be a complementary tool/technology to conventional manufacturing to reduce CO_2 emissions, increase the resource-efficiency and workspace safety of the construction industry. We presented the current experimental use of metal 3D printing for small and complex components that allow to meet the dimension limits of metal printers and how these parts can be advantageous in the construction industry. We discussed how the use of printed metal components with structural roles pose the issue of the dependency of the mechanical properties and imperfections on the printing parameters, requiring specific structural integrity assessment for both static and cyclic loads. The construction sector researchers are studying various metal 3D printing processes (e.g., wire arc additive manufacturing, laser metal deposition, laser and electron beam powder bed fusion) to outline the applicability limits for each of them. The current research also focuses on the change of scale effects from the components used in the high-tech fields (magnification factor: 10), the need for certification processes, and design rules to guarantee a safer and easier design. The construction sector needs also reliable joining techniques to assemble printed components with conventional ones, and current studies are towards the compatibility of printed components for manual welding and bolted connections.

The digital nature of metal 3D printing can expand the architectural design, by increasing the number and breadth of design attempts. Despite the challenges and the recent first attempts at the use of metal 3D printing in the construction sector, this topic is attracting both academics and industrial researchers not only from the construction sector. Indeed, filling the gap for metal 3D printing in the construction sector would enhance the overall knowledge about metal 3D printing and open new opportunities in all fields.

Acknowledgements

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List of tables

List of figures