A review of Industry 4.0 and additive manufacturing synergy

Mahyar Khorasani
School of Engineering, Royal Melbourne Institute of Technology, Melbourne, Australia
Jennifer Loy
School of Engineering, Deakin University, Geelong, Australia
Amir Hossein Ghasemi
Department of Mechanical Engineering, Shahid Rajaee Teacher Training University, Tehran, Iran
Elmira Sharabian
CSIRO Manufacturing, Clayton, Australia and School of Engineering, Royal Melbourne Institute of Technology, Melbourne, Australia
Martin Leary and Hamed Mirafzal
School of Engineering, Royal Melbourne Institute of Technology, Melbourne, Australia
Peter Cochrane
AI Centre Sentient Systems Research, EAST, University of Suffolk, Ipswich, UK
Bernard Rolfe
School of Engineering, Deakin University, Geelong, Australia, and
Ian Gibson
Fraunhofer Project Centre, Department of Design, Production and Management, University of Twente, Enschede, The Netherlands

Abstract

Purpose – This paper reviews the synergy of Industry 4.0 and additive manufacturing (AM) and discusses the integration of data-driven manufacturing systems and product service systems as a key component of the Industry 4.0 revolution. This paper aims to highlight the potential effects of Industry 4.0 on AM via tools such as digitalisation, data transfer, tagging technology, information in Industry 4.0 and intelligent features.

Design/methodology/approach – In successive phases of industrialisation, there has been a rise in the use of, and dependence on, data in manufacturing. In this review of Industry 4.0 and AM, the five pillars of success that could see the Internet of Things (IoT), artificial intelligence, robotics and materials science enabling new levels of interactivity and interdependence between suppliers, producers and users are discussed. The unique effects of AM capabilities, in particular mass customisation and light-weighting, combined with the integration of data and IoT in Industry 4.0, are studied for their potential to support higher efficiencies, greater utility and more ecologically friendly production. This research also illustrates how the digitalisation of manufacturing for Industry 4.0, through the use of IoT and AM, enables new business models and production practices.

Findings – The discussion illustrates the potential of combining IoT and AM to provide an escape from the constraints and limitations of conventional mass production whilst achieving economic and ecological savings. It should also be noted that this extends to the agile design and fabrication of increasingly complex parts enabled by simulations of complex production processes and operating systems. This paper also discusses the relationship between Industry 4.0 and AM with respect to improving the quality and robustness of product outcomes, based on real-time data/feedback.

Originality/value – This research shows how a combined approach to research into IoT and AM can create a step change in practice that alters the production and supply paradigm, potentially reducing the ecological impact of industrial systems and product life cycle. This paper demonstrates how the integration of Industry 4.0 and AM could reshape the future of manufacturing and discusses the challenges involved.

Keywords Digital integration, Industrial revolution, Internet of Things, Mass customisation, Product service systems, Agile production, Energy storage, Additive manufacturing, Industry 4.0

Paper type General review

1. Introduction

Industry 1.0 (approximately 1760) saw the migration from muscle and water power to the steam engine (Engelman, 2015; Kanji, 1990) with early automation spanning industries such as nail production, for the Royal Navy, to textile production for

The current issue and full text archive of this journal is available on Emerald Insight at: **https://www.emerald.com/insight/1355-2546.htm**

Rapid Prototyping Journal
© Emerald Publishing Limited [ISSN 1355-2546]
[DOI 10.1108/RPJ-08-2021-0194]

Received 7 August 2021
Revised 31 October 2021
19 January 2022
Accepted 8 February 2022

retail. Manufacturing was further accelerated from 1870 to 1914 with the invention of electricity and the production line during Industry 2.0. This period also saw improved transport and communication links, with railroads eclipsing canal systems, and the invention of the telephone and wireless. Increased demand and shortened production cycles resulted in greater accuracy and speed during production (Engelman, 2015; Kanji, 1990; Adanur and Jayswal, 2021). However, the operational limitations of the fundamental technologies used during this period were finally overcome during the early digital era (circa 1970), when the computing power of Industry 3.0 (I3.0) began. The digitalisation of everything from logistics to machine accuracy, to production line control followed rapidly, with computers credited with improving consistency in product quality and performance whilst decreasing manufacturing lead times and costs (Rifkin, 2011; Blinder, 2006). This era was superseded in the next digital transition by an approach moving away from mass production towards mass customisation (MC) controlled by a digital thread of information, termed Industry 4.0. This era of complex digital connectivity relies on real-time data collection, analysis and communication tools and increasingly on new materials and new fabrication techniques, as well as the growing Internet of Things (IoT), robotics and artificial intelligence (AI) (Lee *et al.*, 2015; Suresh *et al.*, 2020; Wankhede and Vinodh, 2021).

Industry 4.0 has the potential to provide a first recognisable step towards efficient, managed and therefore more sustainable industries and societies. The use of additive manufacturing (AM) has expanded rapidly over the past three decades and could be increasingly integral to this transition. This is because it supports MC on a large scale. In the 1980s, early researchers developed the first machine in the lineage of AM with lasers used to selectively melt layers of polymer and metals (Sames *et al.*, 2016; Gardan, 2016). Based on Bourell's report (2016), the term AM was formally adopted in 2009 by the American Society of Testing Materials. Different AM processes were classified [10] based on the applied technology and the performance of the system and include vat photopolymerization, powder bed fusion (PBF), material extrusion (MEX), material jetting, binder jetting, sheet lamination and directed energy deposition (DED). The AM industry average annual growth rate, including all products and services, has been over 20% with estimated global revenues capping US$21bn (Wohlers, 2020) in 2020. As AM grows, so does the potential for the broader adoption of MC and more controlled use of resources with its implications for sustainability.

The supporting design, testing, assembly, shipping and maintenance technologies of AM have also evolved rapidly since 1990 when most applications centred on modelling and design for prototypes (Kruth *et al.*, 1998; Knuth, 1999; Boschetto *et al.*, 2021). As AM matured, with more users and applications, the overall quality, reliability and diversity have improved markedly with greater knowledge and better models of the pre-process, process and post-process cycles. In turn, this has seen improved lead times, customisation and personalisation of products with increases in the flexibility, adaptability, stability and sustainability of components. Subsequently, the time and cost of production have reduced to become fertile ground for new areas presented by Industry 4.0 (Thompson *et al.*, 2016; Tiwary *et al.*, 2021).

The chief objective of this research is to show how the synergy of AM and Industry 4.0 can change the direction of advanced manufacturing by improving production quality. This research also aims to explore how Industry 4.0 assists AM and, conversely, what is the impact of AM in Industry 4.0, considering the exclusive features of these two technologies. In this review paper, we consider the key elements of Industry 4.0 data creation, communication and management, followed by the information and intelligence that are inherently applied and created during this approach. We see the main pillars of Industry 4.0 as material science, robotics, AI and IoT, with cybersecurity, simulation techniques, communication tools and cloud technologies, big and small data and system integration as the primary review and discussion topics. We show how AM, through its capabilities – such as MC and light-weighting – combined with the integration of data and the IoT, can assist in the search for greater utility, higher rates of efficiency and ecologically friendly outcomes as part of the era of Industry 4.0. The uniqueness of this research is in discussing the visualization of available knowledge, through simulations and real-time monitoring of AM within Industry 4.0 which can improve automation and self-optimisation through closed-loop, responsive systems throughout the life cycle of product production and use.

2. Industry 4.0

Creating easily accessible information, on demand, during the full life cycle of components and products is both a key benefit and a challenge for Industry 4.0. Realising this ambition enables the continual of product design and performance subject to the statistics of "actual customer" use, greatly improved (predictive) maintenance and support cycles. The realisation of recovery, re-use, re-purposing and recycling (4R) that actually works and contributes significantly to the green economy and an easing of all critical production and marketing decision-making would involve the management of large amounts of dynamic data, as indicated by the continual cycle (Rojko, 2017) shown in Figure 1.

For this paper, the selected methodology involves reviewing the critical features of Industry 4.0, which comprise of data transfer, tagging technology mounts, information management in Industry 4.0, and intelligent features. The exclusive features of AM, such as its use in MC and light-weighting, and the benefits of this feature for Industry 4.0 are reviewed. The role of digitalisation and the IoT in the optimisation of AM processes is also discussed to shed a light on the effects of Industry 4.0 on AM and to show how AM can enhance Industry 4.0.

2.1 Data transfer

The Industry 4.0 data spectrum is broad and convoluted with the IoT and associated cyber-physical systems (CPS) including components, sub-systems, systems and products, with integrated sensors and actuators (Routray *et al.*, 2020). This gives rise to: big data; small data; clouds; multi-mode communication; cybersecurity challenges; and man–machine interface issues. CPS is a term to define coordination and combination between the computational (soft) and physical

Figure 1 (A) Cycles for Industry 4.0. (B) General overview of Industry 4.0

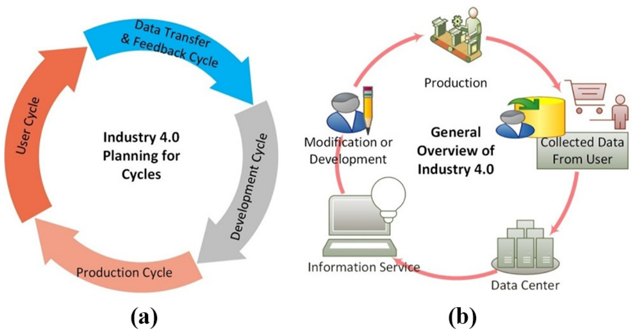
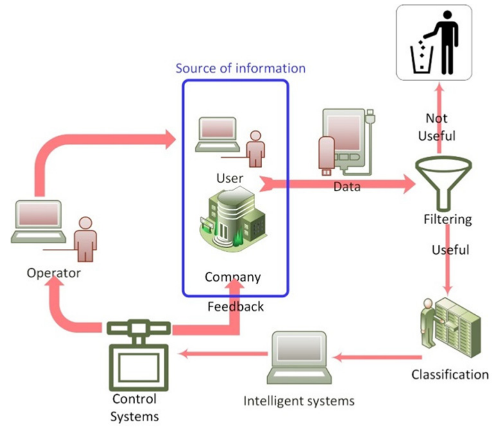


Figure 2 Circulation of data/information in Industry 4.0



(hard) elements of systems (Elhoone *et al.*, 2020). It is at the core of Industry 4.0 and targets continuous improvements in reliability, functionality, performance and efficiency. In this context, the key challenge of cybersecurity is to ensure the safe, secure and accurate sharing of dynamic data throughout supply chains (Aslan, 2020). This need demands an integrated knowledge of data creation, communication, networking and monitoring (Elhoone *et al.*, 2020). Virtual box is an effective way for companies to estimate and recognise the manufacturing life of parts for possible maintenance before they break and shut the system down. This is achieved by analysing information from sensors in real time and leads to a self-optimisation of the process that should improve the quality of data transfer and lead to reduced downtime and maintenance costs (Chen and Zhou, 2021; Hussin *et al.*, 2021).

The vast choice of fixed, near-field and mobile communications technologies available provide for data rates in the bit/s to Mbit/s as inferred for modern vehicles that are rapidly mutating to self-contained mobile clouds serving hundreds of sensors and actuators (Kanagachidambaresan *et al.*, 2020; Qin *et al.*, 2021; Renteria *et al.*, 2021). In this situation, paralleled by home and office appliances along with many industrial plants and service industries, almost nothing connects directly to the internet via fixed-line or mobile connection as all information is aggregated and analysed locally prior to network connection when required (Lasi *et al.*, 2014; Singh *et al.*, 2021).

From this most obvious set of examples and statements, it is axiomatic that the data formats, processing and modes of communication are going to be many and complex, and the need for stability and reliability has to be assured by the autonomy of devices and sub-networks. To this end, a substantial array of communication technologies culminating in 5G technology provides industrial-grade connections on the move (Peraković *et al.*, 2020; Cvitić, 2020). However, at this time it is impossible to chart all the tagging, tracking, sensor, actuator, devices, products and facilities, their control parameter/performance data and analysis variants (Figure 2). Paper records ("Travellers") itemised every important operation in the production chain and recorded who had done what at every key point in the process. More recently, these paper records have largely been replaced by barcodes, QR codes, electronic tags and data embedded in the product chips.

The data recorded represents the "small-data" element of product design and manufacture to be subsumed into the whole and largely unaddressed throughout the product life (Dastbaz and Cochrane, 2019). At a component level, Travellers can detail all the materials and processes, with the more complex, valuable and expensive items detailing ownership history, usage and performance with time. By improving the technology in Industry 4.0, the growth of consumer usage and preference reporting creep into information technology and communications (ITC) through apps and voice-activated devices is observed (Simion and Géraud-Stewart, 2020). The implications here are significant, for the first time it may be possible to automate the operational technology, such as an AM machine centre. Including, for example, powder handling systems, as well as assembly processes of a complete vehicle without any direct human intervention (Gibson *et al.*, 2021b, Li *et al.*, 2021). Similar features are also emerging in the medical, prosthetic and ITC sectors.

2.2 Tagging technology mounts

At a base level, every component, sub-system, system and product might present a bar/QR code for ease of identification and certification (Abdelrahim and Abdelaly, 2020). These can use adhesive, rivet/screw-on or spray-on technologies at extremely low costs to be easily read by machines or humans. However, building on this base are more sophisticated Travellers that electronically integrate all base information including all the raw material sourcing, processing, production, supply, installation, logistics, ownership and usage history. Clearly, as this inventory grows, then so does the complexity of the tagging technology, but even at the extreme, it represents only a fractional cost (Mittal *et al.*, 2018) of the system. The current spectrum of tagging technologies and mounting options is presented in Table 1. During the next industrial cycle (Industry 5.0), we might see smart materials with memory, processing and new technology that has written directly into the material/component structure.

Today, low-cost chip tagging takes three basic forms: a wired or radio frequency (RF) addressable surface mount chip, a portion of the space integrated into the component/sub-system electronics and more recently, RF chips integrated into the

Table 1 Depth and breadth of tagging and the base IoT core by technology and production phase

Item	Memory	Processing	Component	Subsystem	System	Product	Mount
Bar/QR code	✓	×	✓	✓	✓	✓	S
RFID passive	✓	×	✓	✓	×	✓	S/E
RFID active	✓	✓	✓	✓	×	✓	S/E
Sensor RF/wired	✓	✓	×	✓	✓	✓	I
Activator RF/wired	✓	✓	×	✓	✓	✓	I
CPU/data Aggregator	✓	✓	×	×	✓	✓	I

Notes: S: Surface mount, E: Embedded mount, I: Integrated mount

material during early fabrication. These also can be integrated into the build plates for different AM processes such as PBF, DED and MEX, to capture the thermal information for further monitoring and process control. In complex products, the networking of these tags with some central controller/aggregator might be considered to form an independent mini cloud (Mezghani *et al.*, 2021; Fang *et al.*, 2021).

2.3 Information in Industry 4.0

All of the above concepts and observations can extend to a myriad of current appliances, devices, tools, homes, offices and many other active and passive possessions. It is envisaged a world of big and small data used in the management of all resources to realise economies and societies could be far greener and planet friendly than hitherto. It might also be envisaged that Industry 4.0 will see planet-wide communication dominated by machine-to-machine (M2M) communication supporting big and small data with predictive analytics and data consistency in the computer-aided X process chain (Dastbaz and Cochrane, 2019).

The traditional manual (by hand-setup) of production lines a stage and machine at a time is gradually surrendering to local and remote programming through technologies, such as AM, numerical control (NC) and computer NC (CNC) (Kief *et al.*, 2017; Khorasani *et al.*, 2021a). This obviates prolonged/tedious setups and rigging times demanding expert staff that liaise M2M along a complete production line. The introduction of automated cycles regulates data transfer between different lines, plants and stages of developed cycles. M2M has evolved to facilitate and satisfy this need and now sees continual refinement with production more or less continuously adaptive. However, consistent and continually refined data has to be acquired to account for wear and tear, drift and also includes laser scanning path and nozzle optimisation, machine maintenance and repair in different AM processes. This illustrates a major distinguishing factor between Industry 4.0 and previous revolutions (Jeon *et al.*, 2020).

2.4 Intelligent features

The Industry 4.0 spectrum of sensors, actuators, smart and “dumb” (non-active) tagging and the IoT presents us with an almost organic network of connected materials, components and sub-assemblies through to complete products that may be fixed or mobile (Schütze *et al.*, 2018). Each represents some semblance of autonomous “intelligence” realised by processing, memory, networking and connections to and interactions with the physical and virtual environments (Figure 3). To date, a full understanding of the implications has not only been elusive, it remains beyond the powers of modelling on anything other than a small and constrained scale (Parpala *et al.*, 2021; Cerda-Avila *et al.*, 2021).

Industry 4.0 software-orientated architecture is integrated by the IoT dumb and smart electronic devices to afford real-time access to production data and the development and use cycle (Lasi *et al.*, 2014). This configuration ensures quality and reliability whilst reducing lead time, production costs, waste and maintenance and is embeddable in AM machine centres. However, the simplified depiction belies many hidden and sophisticated trade-offs and adaptations with M2M and line-to-line and plant-to-plant learning on a continual basis.

3. Exclusive features of additive manufacturing to enhance Industry 4.0

3.1 Mass customisation

The term MC describes the contradictory production methods of realising mass production of customised components. Customisation implies that the customer can be involved in the design process to some degree. The earlier the customer is involved in the production design, the higher the degree of customisation is possible (Leary, 2019; Li *et al.*, 2021). It is argued that MC can be successfully implemented if customisability is merged with standardised processes that lead to high part variety options[46]. With the aforementioned benefits of AM technology in MC, the performance of Industry 4.0 can significantly improve. Figure 4 shows the unique capability of AM in MC. Figure 4(A) and (B) show the linear grading for size and density in X and Y directions, respectively. Figure 4(C) and (D) show that the AM capability is not limited to the production of linear-gradient materials. The grading can be sinusoidal with changes that can adapt to design for AM specifications (Mostafa *et al.*, 2021; Hooshmand *et al.*, 2021).

When the customers have a choice to select and create their products, it allows them to purchase products specific to their needs and preferences. MC is a marketing and manufacturing approach that supports the personalisation of products. It revolves around the needs of the customer, and in AM is based on innovations in technology since the 1970s (Gibson *et al.*, 2021e, Veetil *et al.*, 2021; Khorasani *et al.*, 2019c). Performing MC in conventional manufacturing is difficult because of both the geometrical limitations of established manufacturing techniques and the high cost of tooling. Creating bespoke tooling for MC is rarely cost-effective, even for value-added applications. However, AM provides a solution to these challenges by coupling computer-aided design and

Figure 3 Industry 4.0 landscape from data to intelligence

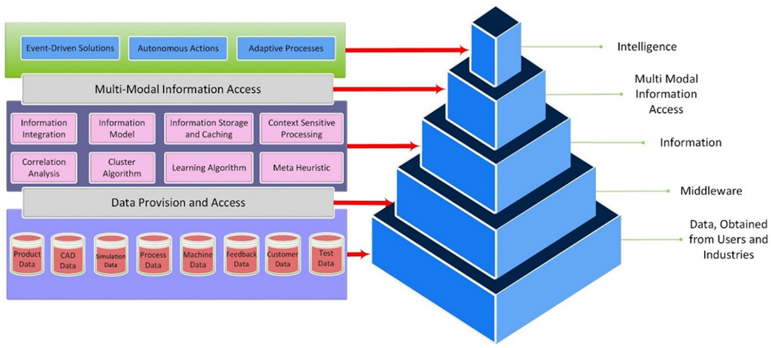
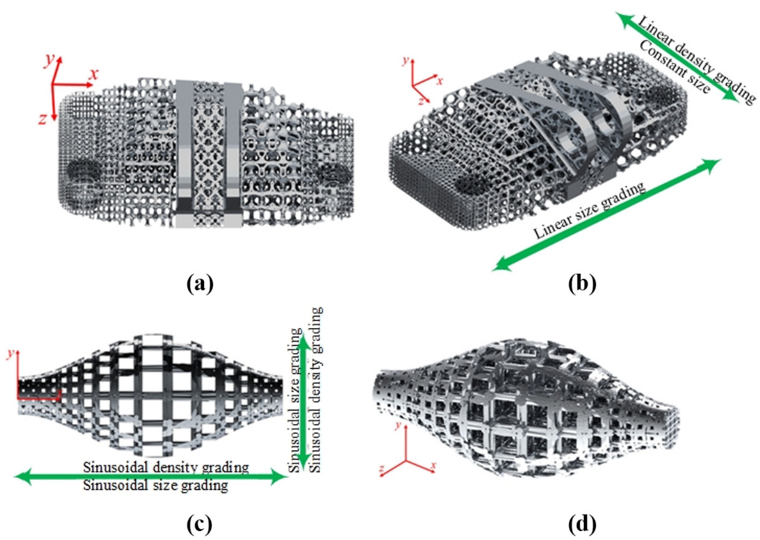


Figure 4 (A and B) Linear grading for size and density in *X* and *Y* directions. (C and D) Sinusoidal density and size grading for size and density in *X* and *Y* directions



Source: Mostafa *et al.* (2021)

manufacturing (CAD-CAM) processes in techniques that did not require unique tooling for each iteration of a design. A Bain survey (2018a) of more than 1000 online cases showed that around 30% of the sellers prefer to have a customisation option and suggests this proportion will increase in the coming years. AM MC enables greater geometrical complexity as well as customisation (where the customer is able to select features) and product personalisation (based on personal scan data, such as for ortheses, for example). Another advantage of MC is helping companies to improve their production time and time-to-market.

3.1.1 Additive manufacturing mass customisation

In conventional manufacturing systems, MC needs more consideration and care, even where it is possible for it to be used. Between each step and within the single process, the tool must be changed or the next batch must be set up, which increases the production time and subsequently the cost of the process (Obreja *et al.*, 2013). In contrast, AM does not require tool or mould changes, workpiece setup or shifting from the one-to-another stage (like milling or drilling) which means it eliminates much of the time and cost associated with production changeover (Gibson *et al.*, 2021a; Khorasani *et al.*, 2019a; Khorasani *et al.*, 2019b). In AM, 3D designs are modelled, converted to an STL file and then sliced and printed. Nowadays, by improving the technology the speed of AM processes is increasing and in some technologies, such as with strip cladding or for multi-jet fusion, the production speed is comparable with conventional manufacturing.

There are particular industries that are already benefiting from the customisation facility of AM, also known as 3D printing, such as dentistry, medical implants and device manufacturing, and the transport industry, including automotive, bicycle and motorcycle production (Guanghui *et al.*, 2020; Lyons, 2014). For example, SmarTech (2018b), Khorasani *et al.* (2020c) and Khorasani *et al.* (2020b) reported huge growth in the 3D printing dental market, from $780m in 2018 to $3.1bn in 2020, as dentists can create some of the most personalized products through 3D printing. These include implants, orthodontic models, crowns, bridges, dentures and even surgical tools. The footwear industry is another high-profile example that exploits AM MC to make personalised innersoles and shoe soles, with the market expected to achieve a $430bn stake by 2024 (Wohlers, 2020; Wohlers, 2019).

3.1.2 Benefits of mass customisation in Industry 4.0 through 3D printing

AM reduces the cost of production through the removal of tooling, by decreasing the number of production stages and potentially the need for an expert operator, although a technical specialisation in AM still needs to be universally realised. Other benefits of AM MC are efficiencies in the design iteration and prototyping before the product is ready for the market. AM compresses workflow and, in the majority of cases, can produce complex parts in a single production process, avoiding the cost of assemblies. Moreover, AM provides an inventory and distribution cost reduction during production, storage and shipping by MC and digitisation of inventory and logistical postponement processes (Gibson *et al.*, 2021d).

Finally, AM MC is a driver for the creation of a customer interface for feature selection that provides a platform for a changing business model where the relationship between producer and consumer is enhanced. This provides a platform for the collection of consumer feedback and other additional data that can feed future product development decisions. Consumer preferences and trends can be tracked in real time, helping to enhance planning and marketing (Reeves *et al.*, 2011).

3.2 Light-weighting

The introduction of 3D printers enabled a focus on light-weighting that aims to use less material whilst achieving better performance in a product. Topology optimisation provides the foundation for this practice. Computer simulation and analysis tools are vital to this process because of the complexity of the structural geometries now possible with plastics, metals, ceramics and composites using AM. High-precision layering allows for unique shapes and features to be produced that would be impossible to produce with conventional milling, drilling, turning, shaping, casting, grinding, etc. In the automotive, cycling, motorcycle and medical and aerospace industries, lighter parts significantly improve the performance-to-weight ratio (Gibson *et al.*, 2021e, Schmitt and Kim, 2021) and therefore the light-weighting potential of AM is of particular interest. Figure 5 shows MC in design and manufacturing that was performed based on customer inputs for (A) aerospace joint clamp and (B) airbus 320 flight nacelle hinge bracket.

Complex internal geometries, such as those used in conformal cooling, and the complexity possible in the structures themselves, such as with lattice structures, are both possible with AM (Wang *et al.*, 2016; Puerta *et al.*, 2021; Azar *et al.*, 2021). These examples are difficult – or impossible – to achieve using conventional manufacturing processes and provide significant drivers for the adoption of AM. There are countless options for the size and shape of lattice cells, which can vary continuously throughout a part to reduce material use or change characteristics through a single part, potentially improving mechanical and thermal properties to suit a particular application. These mimic biological structures, such as bone, that also use varied lattice/cellular structures. In general, such structures can improve the strength/performance-to-weight ratio over "machined from solid" (Nagesha *et al.*, 2020; Khorasani *et al.*, 2020d; Khorasani *et al.*, 2021b). Figure 6, for example, shows conformal versus conventional cooling for injection moulding which can easily be obtained by AM.

Another example is in the design and manufacturer of heat exchangers, which are traditionally made by precision machining of internal channels into a solid block of metal. Figure 7 shows the Conflux AM technologies for heat exchangers using copper and steel. These typically realise a threefold thermal performance, a one-third of pressure drop and a 22% weight reduction compared to conventional manufacturing systems.

3.3 Additive manufacturing and the Internet of Things in optimisation

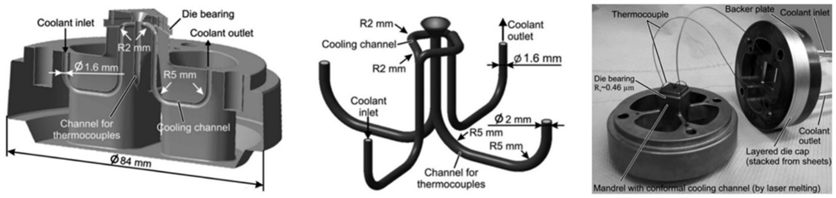
The IoT within Industry 4.0 is based on networked processing and the embedding of "memory" into each "Thing" associated with the IoT. This axiomatically leads to an autonomous operation that facilitates continual adjustment and improvement in production processes and tolerances (Rossit *et al.*, 2019). Therefore, it provides the basis for the maintenance/improvement of a system's robustness based on real-time data/feedback. Low latency wireless systems, such as local bluetooth and WiFi, plus externalised 5G, have an

Figure 5 Optimised design for 3D printing

(a) (b)

Notes: (a) Steel node designed by R&D of Arup company (Shapiro *et al.,* 2016) and (b) airbus 320 flight nacelle hinge bracket redesigned by electro optical systems and the Airbus Group Innovations of Filton, Bristol (Tomlin and Meyer, 2011; Meng *et al.,* 2020)

Figure 6 Design of the AM, longitudinal section through the plane of supply of the thermocouples (A) and geometry of the channels (B). (C) Conformal cooling channels (Hölker *et al.*, 2013)



(a) (b) (c)

Figure 7 Examples of conflux technology by SOLIDTEQ

important role to play in allowing a rapid reaction to change at any level in the process spanning design to the user.

Bringing the consumer into the design, production, logistics, maintenance and support loop for Industry 4.0 through the application of IoT adds a next level optimisation potential for production and product service systems integration. This is manifested through the continual feedback supplied by products that indicate real, rather than assumed, usage patterns (Foidl and Felderer, 2015). Production processes also create a rich stream of real-time data along with material suppliers, sub-contractors, logistics and suppliers and maintenance. It is difficult to overstate the importance and advantage of this "full-picture" manufacturing cycle in addressing the efficient 4R of systems, sub-systems, components and materials to a high degree of efficiency.

The key impact of including customer feedback into the design and production cycle is a significant reduction in manufacturing costs and waste. Moreover, this "design intelligence" can be shared and transferred across numerous centralised and distributed facilities to see a reduction in plant duplication and downtime. As a broad generality, the collection of more accurate and pertinent data/information can result in a reduction of the number of fabrication stages with a consequential improvement in the supply chain (Dilberoglu *et al.*, 2017; Gibson *et al.*, 2021c).

Concatenating each of these advances with comprehensive networking gives rise to the "exponential education" of the system as a whole. Again, this has been impossible for I3.0 and remains so for humans, and to date, it is unique to ITC and Industry 4.0. It means when an AI system, machine or production plant is adjusted/updated and/or learns something new, then all the other AIs, machines and production plants on the network are updated accordingly. The advantages for progress and risks to security, reliability and resilience are reasonably axiomatic here, and this entire sphere demands detailed study, experimentation and caution. Clearly, some attenuation in the spread mechanisms and resulting "viral" failure modes are going to be critical.

4. Discussion

4.1 Industry 4.0 assists additive manufacturing in the future

The visualisation of knowledge, in particular through the use of simulations, can help developers understand complex situations to predict the consequences of their decisions. This applies to AM to assist in understanding practice based in inaccessible locations (such as AM in humanitarian logistics) or challenging situations (Gibson *et al.*, 2021f). Visualisation and simulation can be merged to create a synthetic environment that can share real and virtual information to identify conditions and implications before manufacturing starts. This procedure enables AM systems to determine different phenomena such as stiffness, heat flow and temperature before commencing the process (Khairallah *et al.*, 2016) and save time and costs. The production planning and control concept of feeding obtained data from digital sections of AM systems back into the process has the potential to lead to major improvements in machine steps, energy control, reaction time and control loops. This also impacts machine-based, product and energy-related data.

Monitoring capability and the application of the results of that monitoring are key to Industry 4.0 and for AM it enables a continuous engineering process approach in highly automated AM machines (Butt, 2020). Industry 4.0 is the foundation for monitoring AM (process and materials) to generate small cell structures by using control systems. In addition, Industry 4.0 for AM is related to programmable logic controllers that provide consistency to the processes as well as connect the consumer to the manufacturer.

The ability of self-optimisation for closed-loop systems through an Industry 4.0 approach can enable AM processes to optimise the build process in terms of setting appropriate design parameters, establishing and monitoring pre-process and process parameters, etc. This allows machines to be more autonomous with the potential of improving their flexibility and robustness. Self-optimisation improves process tolerances by maintaining the robustness of the production system when using real-time data such as optical powder imaging, meltpool, layer thickness and beam profile monitoring. The ability to use

5G fast data transformation in Industry 4.0 compared to previous revolutions of industry intensifies the control processes of AM machines and increases robustness, reliability, flexibility and subsequently customer satisfaction (Rao and Prasad, 2018). Digital twins are tools that are increasingly being integrated into Industry 4.0 solutions to support this monitoring and optimisation. Digital twins provide a virtual model of a system. For AM, a digital twin can be used to analyse and accelerate the process, either prior to production or, with sufficient feedback systems, in real time. These can be process specific or, by integrating individual components of AM from every downstream of the process setup (Figure 8), they can replicate the production system as a whole. Virtual planning within Industry 4.0 can allow for the more immediate use of information to identify critical defects and problems within AM processes and anticipate and mitigate against problems. This should lead to a higher level of machine availability for the company, faster response times to breakdowns and an improvement in the life cycle of that machine.

From management and strategic perspective, shifting from conventional production to an AM system needs to involve consideration of how to implement AM as part of an Industry 4.0 model. Criteria to be considered would include the impact for the company on its business model, customer interaction and preferences and customer–supplier chains. Industry 4.0 allows AM data to move from the value of the chain to the value of the network creating a more integrated business model of practice.

4.2 Impact of additive manufacturing on Industry 4.0

As a series of digital fabrication technologies that remove the need for retooling for different iterations of the product, AM allows for a shift towards agile manufacturing that aligns with the capabilities framed by Industry 4.0. Batch production and MC maximise the use of Industry 4.0 for high-value products produced either on demand or informed by the real-time market response, over the constraints embedded in conventional mass production. In addition, the ability to apply the results based on data collected through real-time monitoring in an Industry 4.0 process system to an AM process in real time illustrates the potential of the approach to radically redesign production.

Feature-based CAD-CAM enabled by AM adds value to products, which can help an Industry 4.0 strategy to be competitive (Kruth *et al.*, 1998; Liu *et al.*, 2020). Figure 9, for example, shows the design for the turbine blade including solid shell and internal features which can be changed as required. Producing an internal feature for the blade [Figure 9(C)] needs precision machining which is extremely difficult to obtain by conventional machining processes. A feature of the design shown in Figure 9(C) in a cross-sectional cut through the blade is internal air-cooling channels. The ability to build internal structures into a component is hard to achieve by conventional metal processing but can be achieved by a realistic proposition with AM (Roca *et al.*, 2016; Watkins *et al.*, 2013; Prabhu *et al.*, 2021). However, the as-built turbine blade [Figure 9(A)] demonstrates an important limitation of AM in relation to surface finish, as a rough surface finish introduces possible sites for crack initiation and propagation within the process [Figure 9(A)]. Finishing of the surface for this application when created using an AM process is also necessary, as can be seen in the final part in Figure 9(B).

Usually, the amount of information that can be generated across each fabrication stage directly drives the accuracy of the system. Therefore, integrating digital nodes for a networked system will improve the overall performance of the system. AM systems are increasingly mechanised, for example, the use of autonomous robots to vacuum, sift and take the AM parts out of the chamber is increasing, e.g. in PBF (Khorasani *et al.*, 2020a). Automated systems are also increasingly integral to handling the trajectory of the laser in DED systems, such as strip cladding. As robots are increasingly equipped with adaptive systems, so they are better able to work with minimal human intervention. Arguably, the use of autonomous robots will strengthen AM adoption because they will decrease the human health hazards involved in production. The hazards are related to exposure to fine particles and breathing the flying particles for powder-based AM systems that can cause serious short- or long-term health effects for the operators.

As discussed earlier, MC or personalization (personal to an individual) is a feature of AM that can be central to an Industry 4.0 approach to production. AM, blockchain and

Figure 8 Performance of Digital twin in AM

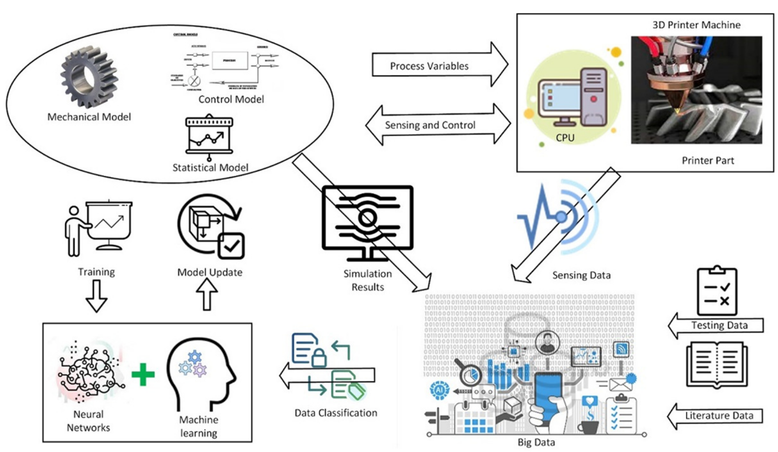
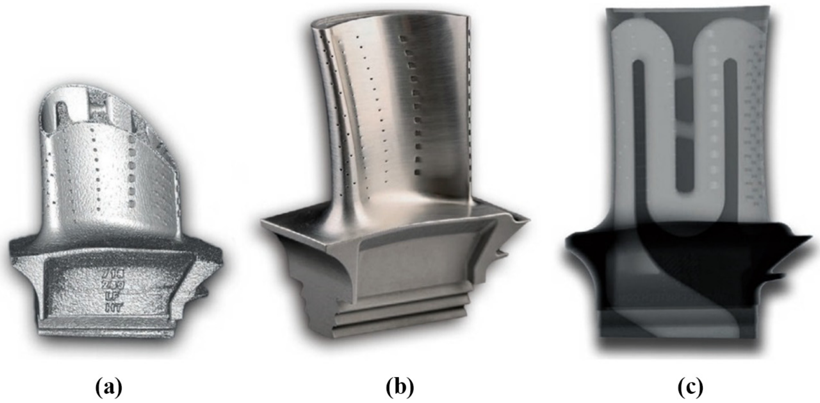


Figure 9 (A) As-built turbine blade, (B) post-processed for surface finishing and (C) neutron radiograph showing the internal channels



Source: Roca *et al.* (2016); Watkins *et al.* (2013)

digital twin provide the possibility of valid transforming individual requirements and preferences into customised services and products at a reasonable cost through connection, digitalisation and sharing in the product life cycle. The synergy of Industry 4.0 and AM generates a framework for personalised products based on digital training and blockchain. Customers can have access to the system through designed user interfaces by stationary and dynamic terminals such as their phones, computers and tablets. In the design phase, customer requirements and preferences should be identified and transformed into the concept of design. The design is visualized with geometric information by CAD. AM provides freedom for designers, to perform product innovation in manufacturing using different features like topology optimisation for the structures and material distribution simultaneously. The synergy between Industry 4.0 and AM provides the possibility to generate the components before the fabrication process which can automatically identify the production issues and save a substantial amount of time and costs (Guo *et al.*, 2020).

Big data within AM processing can be obtained by embedding multiple sensors around the build chamber and can be used in a closed-loop system for process monitoring and control (Chin, 2017; Davoodi *et al.*, 2020). In addition, cloud manufacturing offers an effective way to connect and use various manufacturing processes by the appropriate linking of AM with different manufacturing systems, including subtractive digital technologies, such as CNC machining. An extension of the integration of data systems in this context is where product information is transferred from and to the sellers in real time through the cloud. This has the potential to speed up the planning and therefore the production rate, reducing lead time and arguably stimulating Industry 4.0 acceptance as shown in Figure 10 (Zhou *et al.*, 2018; Li *et al.*, 2010). Essentially, customer real-time feedback is a straightforward procedure for AM systems because the design of the product and the production, delivery and even repair or return of that product for that customer can be held online. This feature enhances Industry 4.0's ability to support a customer-centric market.

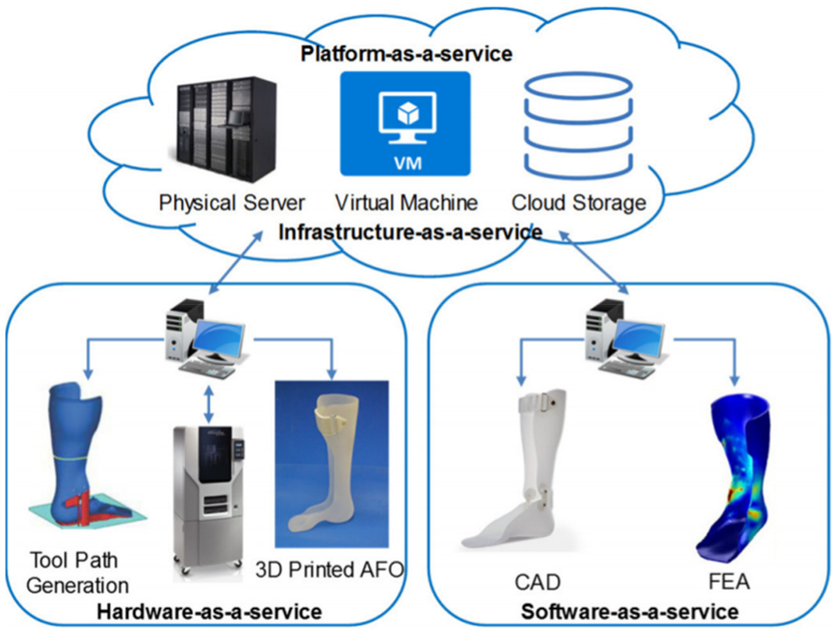
4.3 Internet of Things environmental challenges

Predictions of just how many "Things" will populate the IoT over the next decade vary wildly between 20 and 250 billion devices, but estimates suggest that "Things" online, versus our mobiles and other online devices, already reached parity in around 2020. Regardless of the precision of these estimates, from a sustainability point of view, it is argued that the planet cannot support even a low estimate of 20 billion 5G connected "Things" consuming around 1 W (Gohil *et al.*, 2013). As of the time of writing some 5G towers are consuming up to 10 kW and being turned off at night (in China) to conserve power. In another dimension, the supply of rare earth and other materials is energy consumption for the production of the necessary chips and batteries. These factors, therefore, herald the necessity of a change of direction in network philosophy and the design of things/tags/chips and communication modes (Patil *et al.*, 2012).

In addition to the energy supply for IoT, recent developments in electronics in this context have focused on organic materials comprising organic molecules or compounds that demonstrate relevant characteristics, such as conductivity. These have shown potential viability for displays and signal processing but still require further research and development. The communication energy cost remains the more immediate challenge, but perhaps the easiest to remedy by changing the mode of operation. Today's networks use complex analogue and digital modes with distance and bandwidth the prime target. This is not the case for the IoT and it is, therefore, possible to reduce the distance drastically to reduce the energy required from 100 W of mW to μW or even nW by using short-range links to mesh nets or localised aggregators. This process is governed by the inverse square power law with each factor of 10 reductions in distance realising a 100-fold reduction in energy (Haas, 2018). This efficiency gain can be further magnified by a move to "pure" digital operation as opposed to the hybrid analogue/digital modes of 3G, 4G and 5G.

The areas of efficient energy storage, non-volatile memory retention, sparse processing and cyber security are currently being addressed as they will soon become critical as the IoT

Figure 10 Cloud storage and AM



Source: Shih *et al.* (2017)

rapidly grows beyond the forecasts, including with AM embedded active tags, on components and sub-systems.

The big advantage of customised production is the ability to maximise the value for the customer through bespoke product life cycle management, enabled by data transformation (DT) data. However, it would create significant operational challenges. Providing access to a digital training database for customers to inform producers in a product service systems approach (product as part of a system, rather than a stand-alone) would mean the producer would need to be able to approve every unique revision for safety, quality and cost-efficiency. This will substantially increase the manufacturing lead time and costs, causing potential unsustainable complexity in the supply chain. A safety question for the data privacy and ownership accordingly also arises when the DT data of the product life cycle is shared – and co-created – by the customer in collaboration with the producer. Recently emerged blockchain technology offers a potentially promising method for the genuine transmission of the DT data between producers and customers. However, blockchain alone is not enough, as it does not yet act as an effective mechanism for ownership sharing and controlling. Future developments within customised production will need to consider the intellectual property implications, and effective strategies for ownership sharing and controlling are vital if they are to realize the full potential of a paradigm of customised production (Guo *et al.*, 2020; Mandolla *et al.*, 2019). This means that collective responsibility for sustainability will require individuals to reconnect with the manufacturer of the products they consume. Solving effective strategies for personalisation, shared ownership and control can be a solution, however challenging the digital management of this will be, as well as developments in the education of manufacturers, designers and engineers working in the field[99].

5. Conclusions

Industry 4.0 provides the flexibility in production processes to fabricate customised products for almost every sector and purpose. AM plays a major part in this capability by allowing manufacturers to reprogram rather than retool production lines. It also facilitates continual optimisation of design through production and supply by tapping the wealth of (near) real-time data provided by the IoT including the behaviours of customers and product and material usage records. These are critical in shaping the complete manufacturing progression from "mass production to MC" and from "centralized to decentralized" manufacturing. AM also implies major changes in design and fabrication practices – allowing the creation of complex multi-functional parts of dimensional accuracy that were impossible in I3.0.

In our view, the power and influence of the IoT should not be underestimated in this equation of change. It is not merely an inventory tool, but an active (near) real-time "member" of the design, simulation, CAD-CAM, production, logistics, supply, support, customer, maintenance and 4R cycle/team. It can provide accurate and timely information throughout every operation and cycle for the lifetime of a product. The influence of the IoT and M2M can be ubiquitous and a major source of exponential learning for machines and a new route to understanding and education for human designers and users. Using AM through Industry 4.0 allows manufacturers to respond to the trend of enhancing customisation because customers attribute a higher added value to customised products and services than conventional processes. Data generated from interaction with the users and the development of production as a whole life cycle is strategic information and should be converted to intelligent systems for decision-making. The advantages AM provide mark is as a powerful tool to assist

Industry 4.0 through the freedom in geometry, material design, quality and logistics it provides. AM enables feature-based design and manufacturing and bespoke manufacturing which add value for the market in an agile production system

It is important to recognise that we are transitioning from a deterministic and designed industrial world of fairly predictable cause and effect to an evolving, fluid world of emergent properties and surprises, and ultimately we need to be aware of the consequences of our actions and their impact on our world and the environment. Lessons will need to be learned. The single most important feature of Industry 4.0 and AM is its potential to contribute towards the realisation of more sustainable industries and patterns of production and consumption. Our industrial past has been about the survival of the workable, but Industry 4.0 and the future are about the survival of the most adaptable.

6. Future work

Implementing horizontal integration between AM and Industry 4.0 will need more investigation to reveal how to effectively integrate design features, product specifications, machine data and manufacturing in integrated production and product service systems. Further research is required to find out which degree and for which types of products, customisation could be expected to be profitable and how real-time monitoring can maximise production efficiencies. The opportunities offered by AM and Industry 4.0 and the design and production challenges are restricted by our established industrial mindset. To exploit the characteristics of both to the benefit of society, the economy and the environment, we need to be prepared to use the imagination of individuals in responding more effectively to working with digital convergence.

References

A Bain survey. (2018a), "Meeting mass customization demands with 3D printing", available at: www.forbes.com/sites/baininsights/2013/11/05/having-it-their-way-the-big-opportunity-in-personalized-products/#4a5f712516b9 [Online].

Abdelrahim, H.F. and Abdelaly, A. (2020), "Process sensing of collaborative manufacturing system for large complex lost-foam supported by Industry 4.0".

Adanur, S. and Jayswal, A. (2021), "Additive manufacturing of interlaced fibrous structures", *Rapid Prototyping Journal*, Vol. 27.

Aslan, E. (2020), "How supply chain management will change in the Industry 4.0 era?", *Handbook of Research on Sustainable Supply Chain Management for the Global Economy*, IGI Global, Turky.

Azar, A.S., Reiersen, M., Hovig, E.W., M'Hamdi, M., Diplas, S. and Pedersen, M.M. (2021), "A novel approach for enhancing the fatigue lifetime of the components processed by additive manufacturing technologies", *Rapid Prototyping Journal*, Vol. 27.

Blinder, A.S. (2006), "Offshoring: the next industrial revolution?", *Foreign Affairs*, Vol. 85 No. 2, pp. 113-128.

Boschetto, A., Bottini, L., Cardini, V., Eugeni, M., Gaudenzi, P. and Veniali, F. (2021), "Aircraft part substitution via additive manufacturing: design, simulation, fabrication and testing", *Rapid Prototyping Journal*, Vol. 27 No. 5, pp. 995-1009.

Bourell, D.L. (2016), "Perspectives on additive manufacturing", *Annual Review of Materials Research*, Vol. 46 No. 1, pp. 1-18.

Butt, J. (2020), "Exploring the interrelationship between additive manufacturing and Industry 4.0", *Designs*, Vol. 4 No. 2, p. 13.

Cerda-Avila, S.N., Medellín-Castillo, H.I. and Lim, T. (2021), "Analytical models to estimate the structural behaviour of fused deposition modelling components", *Rapid Prototyping Journal*, Vol. 27 No. 4, pp. 658-670.

Chen, S. and Zhou, M. (2021), "Evolving container to unikernel for edge computing and applications in process industry", *Processes*, Vol. 9 No. 2, p. 351.

Chin, B. (2017), "The perfect combo: 3D printing & big data [online]", [Accessed]. January 2021.

Cvitić, I. (2020), "Development and implementation possibilities of 5G in Industry 4.0", *Advances in Design, Simulation and Manufacturing III: Proceedings of the 3rd International Conference on Design, Simulation, Manufacturing: The Innovation Exchange, DSMIE-2020*, Manufacturing and Materials Engineering, Springer Nature, *Kharkiv*, June 9-12, 2020, Vol. 1, p. 166.

Dastbaz, M. and Cochrane, P. (2019), *Industry 4.0 and Engineering for a Sustainable Future*, Springer, UK.

Davoodi, E., Fayazfar, H., Liravi, F., Jabari, E. and Toyserkani, E. (2020), "Drop-on-demand high-speed 3D printing of flexible milled carbon fiber/silicone composite sensors for wearable biomonitoring devices", *Additive Manufacturing*, Vol. 32, p. 101016.

Dilberoglu, U.M., Gharehpapagh, B., Yaman, U. and Dolen, M. (2017), "The role of additive manufacturing in the era of Industry 4.0", *Procedia Manufacturing*, Vol. 11, pp. 545-554.

Elhoone, H., Zhang, T., Anwar, M. and Desai, S. (2020), "Cyber-based design for additive manufacturing using artificial neural networks for Industry 4.0", *International Journal of Production Research*, Vol. 58 No. 9, pp. 2841-2861.

Engelman, R. (2015), "The second industrial revolution, 1870-1914", Retrieved July, 21, 2017.

Fang, X., Ren, C., Zhang, L., Wang, C., Huang, K. and Lu, B. (2021), "A model of bead size based on the dynamic response of CMT-based wire and arc additive manufacturing process parameters", *Rapid Prototyping Journal*, Vol. 27 No. 4, pp. 741-753.

Foidl, H. and Felderer, M. (2015), "Research challenges of Industry 4.0 for quality management", *International Conference on Enterprise Resource Planning Systems*, Springer, pp. 121-137.

Gardan, J. (2016), "Additive manufacturing technologies: state of the art and trends", *International Journal of Production Research*, Vol. 54 No. 10, pp. 3118-3132.

Gibson, I., Rosen, D.W., Stucker, B. and Khorasani, M. (2021a), *Additive Manufacturing Technologies*, Springer, US.

Gibson, I., Rosen, D.W., Stucker, B. and Khorasani, M. (2021b), "Development of additive manufacturing technology", *Additive Manufacturing Technologies*, Springer, US.

Gibson, I., Rosen, D.W., Stucker, B. and Khorasani, M. (2021c), "Direct digital manufacturing", *Additive Manufacturing Technologies*, Springer, US.

Gibson, I., Rosen, D.W., Stucker, B. and Khorasani, M. (2021d), "The impact of low-cost AM systems", *Additive Manufacturing Technologies*, Springer, US.

Gibson, I., Rosen, D.W., Stucker, B. and Khorasani, M. (2021e), "Introduction and basic principles", *Additive Manufacturing Technologies*, Springer, US.

Gibson, I., Rosen, D.W., Stucker, B. and Khorasani, M. (2021f), "Software for additive manufacturing", *Additive Manufacturing Technologies*, Springer, US.

Gohil, A., Modi, H. and Patel, S.K. (2013), "5G technology of mobile communication: a survey", *2013 International Conference on Intelligent Systems and Signal Processing (ISSP)*, IEEE, pp. 288-292.

Guanghui, S., Chengqi, G., Dongliang, Q., Dongtao, W., Lei, T. and Tong, G. (2020), "An aerospace bracket designed by thermo-elastic topology optimization and manufactured by additive manufacturing", *Chinese Journal of Aeronautics*, Vol. 33, pp. 1252-1259.

Guo, D., Ling, S., Li, H., Ao, D., Zhang, T., Rong, Y. and Huang, G.Q. (2020), "A framework for personalized production based on digital twin, blockchain and additive manufacturing in the context of Industry 4.0", *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, IEEE, pp. 1181-1186.

Haas, H. (2018), "LiFi is a paradigm-shifting 5G technology", *Reviews in Physics*, Vol. 3, pp. 26-31.

Hölker, R., Jäger, A., Khalifa, N.B. and Tekkaya, A.E. (2013), "Controlling heat balance in hot aluminum extrusion by additive manufactured extrusion dies with conformal cooling channels", *International Journal of Precision Engineering and Manufacturing*, Vol. 14 No. 8, pp. 1487-1493.

Hooshmand, M.J., Mansour, S. and Dehghanian, A. (2021), "Optimization of build orientation in FFF using response surface methodology and posterior-based method", *Rapid Prototyping Journal*, Vol. 27 No. 5, pp. 967-994.

Hussin, R.B., Sharif, S.B., Abd Rahim, S.Z.B., Suhaimi, M.A. B., Khushairi, M.T.B.M., EL-Hadj, A.A. and Shuaib, N.A. B. (2021), "The potential of metal epoxy composite (MEC) as hybrid mold inserts in rapid tooling application: a review", *Rapid Prototyping Journal*, Vol. 27 No. 6, pp. 1069-1100.

Jeon, B., Yoon, J.-S., Um, J. and Suh, S.-H. (2020), "The architecture development of Industry 4.0 compliant smart machine tool system (SMTS)", *Journal of Intelligent Manufacturing*, Vol. 31, No. 8, pp. 1-23.

Kanagachidambaresan, G., Anand, R., Balasubramanian, E. and Mahima, V. (2020), *Internet of Things for Industry 4.0*, Springer, India.

Kanji, G.K. (1990), "Total quality management: the second industrial revolution", *Total Quality Management*, Vol. 1 No. 1, pp. 3-12.

Khairallah, S.A., Anderson, A.T., Rubenchik, A. and King, W.E. (2016), "Laser powder-bed fusion additive manufacturing: physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones", *Acta Materialia*, Vol. 108, pp. 36-45.

Khorasani, A., Gibson, I., Awan, U.S. and Ghaderi, A. (2019a), "The effect of SLM process parameters on density, hardness, tensile strength and surface quality of Ti-6Al-4V", *Additive Manufacturing*, Vol. 25, pp. 176-186.

Khorasani, A.M., Gibson, I., Ghaderi, A. and Mohammed, M.I. (2019b), "Investigation on the effect of heat treatment and process parameters on the tensile behaviour of SLM Ti-6Al-4V parts", *The International Journal of Advanced Manufacturing Technology*, Vol. 101 Nos 9/12, pp. 3183-3197.

Khorasani, A.M., Gibson, I., Ghasemi, A. and Ghaderi, A. (2019c), "A comprehensive study on variability of relative density in selective laser melting of Ti-6Al-4V", *Virtual and Physical Prototyping*, Vol. 14 No. 4, pp. 349-359.

Khorasani, A., Gibson, I., Veetil, J.K. and Ghasemi, A.H. (2020a), "A review of technological improvements in laser-based powder bed fusion of metal printers", *The International Journal of Advanced Manufacturing Technology*, Vol. 108 Nos 1/2, pp. 191-209.

Khorasani, A.M., Gibson, I., Ghasemi, A. and Ghaderi, A. (2020b), "Modelling of laser powder bed fusion process and analysing the effective parameters on surface characteristics of Ti-6Al-4V", *International Journal of Mechanical Sciences*, Vol. 168, p. 105299.

Khorasani, M., Ghasemi, A., Awan, U.S., Hadavi, E., Leary, M., Brandt, M., Littlefair, G., O'Neil, W. and Gibson, I. (2020c), "A study on surface morphology and tension in laser powder bed fusion of Ti-6Al-4V", *The International Journal of Advanced Manufacturing Technology*, Vol. 111 Nos 9/10, pp. 2891-2909.

Khorasani, M., Gibson, I., Ghasemi, A., Brandt, M. and Leary, M. (2020d), "On the role of wet abrasive centrifugal barrel finishing on surface enhancement and material removal rate of LPBF stainless steel 316L", *Journal of Manufacturing Processes*, Vol. 59, pp. 523-534.

Khorasani, M., Ghasemi, A., Rolfe, B. and Gibson, I. (2021a), "Additive manufacturing a powerful tool for the aerospace industry", *Rapid Prototyping Journal*, Vol. 28.

Khorasani, M., Ghasemi, A.H., Awan, U.S., Singamneni, S., Littlefair, G., Farabi, E., Leary, M., Gibson, I., Veetil, J.K. and Rolfe, B. (2021b), "On the role of process parameters on meltpool temperature and tensile properties of stainless steel 316L produced by powder bed fusion", *Journal of Materials Research and Technology*, Vol. 12, pp. 2438-2452.

Kief, H.B., Roschiwal, H.A. and Schwarz, K. (2017), "CNC-Handbuch", *Automatisierungstechnik Grundlagen, Komponenten, Systeme, Haan-Gruiten Schmid, D.(Hrsg.): Steuern und Regeln für Maschinenbau und Mechatronik, Haan-Gruiten Habermann, Weiß: Step*.

Knuth, J. (1999), "Material increase manufacturing by rapid prototyping technique", *Annals of the CIPP*, Vol. 40, pp. 603-604.

Kruth, J.-P., Leu, M.-C. and Nakagawa, T. (1998), "Progress in additive manufacturing and rapid prototyping", *Cirp Annals*, Vol. 47 No. 2, pp. 525-540.

Lasi, H., Fettke, P., Kemper, H.-G., Feld, T. and Hoffmann, M. (2014), "Industry 4.0", *Business & Information Systems Engineering*, Vol. 6 No. 4, pp. 239-242.

Leary, M. (2019), *Design for Additive Manufacturing*, Elsevier, Australia.

Lee, J., Bagheri, B. and Kao, H.-A. (2015), "A cyber-physical systems architecture for Industry 4.0-based manufacturing systems", *Manufacturing Letters*, Vol. 3, pp. 18-23.

Li, B.-H., Zhang, L., Wang, S.-L., Tao, F., Cao, J., Jiang, X., Song, X. and Chai, X. (2010), "Cloud manufacturing: a new service-oriented networked manufacturing model", *Computer Integrated Manufacturing Systems*, Vol. 16, pp. 1-7.

Li, S., Waheed, U., Bahshwan, M., Wang, L.Z., Kalossaka, L. M., Choi, J., Kundrak, F., Lattas, A., Ploumpis, S. and Zafeiriou, S. (2021), "A scalable mass customisation design process for 3D-printed respirator mask to combat COVID-19", *Rapid Prototyping Journal*, Vol. 27 No. 7, pp. 1302-1317.

Liu, X., Wang, W., Guo, H., Barenji, A.V., Li, Z. and Huang, G.Q. (2020), "Industrial blockchain based framework for product lifecycle management in Industry 4.0", *Robotics and Computer-Integrated Manufacturing*, Vol. 63, p. 101897.

Lyons, B. (2014), "Additive manufacturing in aerospace: examples and research outlook", *The Bridge*, Vol. 44, pp. 13-19.

Mandolla, C., Petruzzelli, A.M., Percoco, G. and Urbinati, A. (2019), "Building a digital twin for additive manufacturing through the exploitation of blockchain: a case analysis of the aircraft industry", *Computers in Industry*, Vol. 109, pp. 134-152.

Meng, L., Zhang, W., Quan, D., Shi, G., Tang, L., Hou, Y., Breitkopf, P., Zhu, J. and Gao, T. (2020), "From topology optimization design to additive manufacturing: today's success and tomorrow's roadmap", *Archives of Computational Methods in Engineering*, Vol. 27 No. 3, pp. 805-830.

Mezghani, A., Nassar, A.R., Dickman, C.J., Valdes, E. and Alvarado, R. (2021), "Laser powder bed fusion additive manufacturing of copper wicking structures: fabrication and capillary characterization", *Rapid Prototyping Journal*, Vol. 27 No. 6, pp. 1181-1188.

Mittal, S., Khan, M.A., Romero, D. and Wuest, T. (2018), "A critical review of smart manufacturing & Industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs)", *Journal of Manufacturing Systems*, Vol. 49, pp. 194-214.

Mostafa, K.G., Momesso, G.A., Li, X., Nobes, D.S. and Qureshi, A.J. (2021), "Dual graded lattice structures: generation framework and mechanical properties characterization", *Polymers*, Vol. 13 No. 9, p. 1528.

Nagesha, B., Dhinakaran, V., Shree, M.V., Kumar, K.M., Chalawadi, D. and Sathish, T. (2020), "Review on characterization and impacts of the lattice structure in additive manufacturing", *Materials Today: Proceedings*, Vol. 21, pp. 916-919.

Obreja, C., Stan, G., Andrioaia, D. and Funaru, M. (2013), "Design of an automatic tool changer system for milling machining centers", *Applied Mechanics and Materials*, Trans Tech Publ, pp. 69-73.

Parpala, R.C., Popescu, D. and Pupaza, C. (2021), "Infill parameters influence over the natural frequencies of ABS specimens obtained by extrusion-based 3D printing", *Rapid Prototyping Journal*, Vol. 27 No. 6, pp. 1273-1285.

Patil, S., Patil, V. and Bhat, P. (2012), "A review on 5G technology", *International Journal of Engineering and Innovative Technology (IJEIT)*, Vol. 1, pp. 26-30.

Peraković, D., Periša, M., Zorić, P. and Cvitić, I. (2020), "Development and implementation possibilities of 5G in Industry 4.0", *Design, Simulation, Manufacturing: The Innovation Exchange*, Springer, 166-175.

Prabhu, R., Masia, J.S., Berthel, J.T., Meisel, N.A. and Simpson, T.W. (2021), "Maximizing design potential: investigating the effects of utilizing opportunistic and restrictive design for additive manufacturing in rapid response solutions", *Rapid Prototyping Journal*, Vol. 27 No. 6, pp. 1161-1171.

Puerta, A.P.V., Lopez-Castro, J., López, A.O. and Vidal, S.R. F. (2021), "On improving the surface finish of 3D printing polylactic acid parts by corundum blasting", *Rapid Prototyping Journal*, Vol. 27 No. 7, pp. 1398-1407.

Qin, Q., Huang, J., Yao, J. and Gao, W. (2021), "Design and optimization of projection stereolithography additive manufacturing system with multi-pass scanning", *Rapid Prototyping Journal*, Vol. 27 No. 3, pp. 636-642.

Rao, S.K. and Prasad, R. (2018), "Impact of 5G technologies on Industry 4.0", *Wireless Personal Communications*, Vol. 100 No. 1, pp. 145-159.

Reeves, P., Tuck, C. and Hague, R. (2011), "Additive manufacturing for mass customization", *Mass Customization*, Springer.

Renteria, A., Garcia, L.F., Diaz, J.A., Delfin, L.C., Regis, J.E., Reza, E.I., Espalin, D., Tseng, T.-L.B. and Lin, Y. (2021), "Fabrication of bulk alumina structures with humidity sensing capabilities using direct ink write technique", *Rapid Prototyping Journal*, Vol. 27 No. 4, pp. 822-833.

Rifkin, J. (2011), *The Third Industrial Revolution: how Lateral Power is Transforming Energy, the Economy, and the World*, Macmillan.

Roca, J.B., Vaishnav, P., Fuchs, E.R. and Morgan, M.G. (2016), "Policy needed for additive manufacturing", *Nature Materials*, Vol. 15 No. 8, pp. 815-818.

Rojko, A. (2017), "Industry 4.0 concept: background and overview", *International Journal of Interactive Mobile Technologies (IJIM)*, Vol. 11 No. 5, pp. 77-90.

Rossit, D.A., Tohmé, F. and Frutos, M. (2019), "Industry 4.0: smart scheduling", *International Journal of Production Research*, Vol. 57 No. 12, pp. 3802-3813.

Routray, S.K., Javali, A., Ghosh, A.D. and Sarangi, S. (2020), "An outlook of narrowband IoT for Industry 4.0", *2020 Second International Conference on Inventive Research in Computing Applications (ICIRCA)*, *IEEE*, pp. 923-926.

Sames, W.J., List, F., Pannala, S., Dehoff, R.R. and Babu, S.S. (2016), "The metallurgy and processing science of metal additive manufacturing", *International Materials Reviews*, Vol. 61 No. 5, pp. 315-360.

Schmitt, M. and Kim, I.Y. (2021), "Topology optimization for infill in Mex", *Rapid Prototyping Journal*, Vol. 27 No. 8, pp. 1580-1590.

Schütze, A., Helwig, N. and Schneider, T. (2018), "Sensors 4.0–smart sensors and measurement technology enable Industry 4.0", *Journal of Sensors and Sensor Systems*, Vol. 7 No. 1, pp. 359-371.

Shapiro, A.A., Borgonia, J., Chen, Q., Dillon, R., Mcenerney, B., Polit-Casillas, R. and Soloway, L. (2016), "Additive manufacturing for aerospace flight applications", *Journal of Spacecraft and Rockets*, Vol. 53 No. 5, pp. 952-959.

Shih, A., Park, D.W., Yang, Y.-Y.D., Chisena, R. and Wu, D. (2017), "Cloud-based design and additive manufacturing of custom orthoses", *Procedia Cirp*, Vol. 63, pp. 156-160.

Simion, E. and Géraud-Stewart, R. (2020), *Innovative Security Solutions for Information Technology and Communications*, Springer, Romania.

Singh, S.N., Venkatesh, V.S.S. and Deoghare, A.B. (2021), "A review on the role of 3D printing in the fight against COVID-19: safety and challenges", *Rapid Prototyping Journal*, Vol. 27 No. 2, pp. 407-420.

SmarTech. (2018b), "SmarTech report: 3D printing in dental market to reach".

Suresh, A., Udendhran, R. and Yamini, G. (2020), "Internet of Things and additive manufacturing: toward intelligent production systems in Industry 4.0", *Internet of Things for Industry 4.0*, Springer.

Thompson, M.K., Moroni, G., Vaneker, T., Fadel, G., Campbell, R.I., Gibson, I., Bernard, A., Schulz, J., Graf, P., Ahuja, B. and Martina, F. (2016), "Design for additive manufacturing: trends, opportunities, considerations, and constraints", *CIRP Annals*, Vol. 65 No. 2, pp. 737-760.

Tiwary, V.K., Arunkumar, P. and Malik, V.R. (2021), "An overview on joining/welding as post-processing technique to circumvent the build volume limitation of an FDM-3D printer", *Rapid Prototyping Journal*, Vol. 27 No. 4, pp. 808-821.

Tomlin, M. and Meyer, J. (2011), "Topology optimization of an additive layer manufactured (ALM) aerospace part", *Proceeding of the 7th Altair CAE technology conference*, pp. 1-9.

Veetil, J.K., Khorasani, M., Ghasemi, A., Rolfe, B., Vrooijink, I., VAN Beurden, K., Moes, S. and Gibson, I. (2021), "Build position-based dimensional deviations of laser powder-bed fusion of stainless steel 316L", *Precision Engineering*, Vol. 67, pp. 58-68.

Wang, X., Xu, S., Zhou, S., Xu, W., Leary, M., Choong, P., Qian, M., Brandt, M. and Xie, Y.M. (2016), "Topological design and additive manufacturing of porous metals for bone scaffolds and orthopaedic implants: a review", *Biomaterials*, Vol. 83, pp. 127-141.

Wankhede, V.A. and Vinodh, S. (2021), "Application of total interpretive structural modeling for analyzing factors of additive manufacturing and Industry 4.0 integration", *Rapid Prototyping Journal*, Vol. 27 No. 8, pp. 1591-1608.

Watkins, T., Bilheux, H., An, K., Payzant, A., Dehoff, R., Duty, C., Peter, W., Blue, C. and Brice, C. (2013), "Neutron characterization", *Advanced Materials & Processes*, Vol. 23, pp. 23-27.

Wohlers, T. (2019), "Wohlers Report 2018, 3D printing and additive manufacturing, state of the industry", Wohlers Associates.

Wohlers, T. (2020), "Wohlers Report 2018, 3D printing and additive manufacturing, global state of the industry", Wohlers Associates.

Zhou, L., Zhang, L., Zhao, C., Laili, Y. and Xu, L. (2018), "Diverse task scheduling for individualized requirements in cloud manufacturing", *Enterprise Information Systems*, Vol. 12 No. 3, pp. 300-318.

Further reading

Deradjat, D. and Minshall, T. (2015), "Implementation of additive manufacturing technologies for mass customization", *International association for management of technology IAMOT 2015 conference proceedings*, pp. 2079-2094.

Corresponding author

Amir Hossein Ghasemi can be contacted at: amir_hosein_ghasemi2012@yahoo.com