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Exploring the Benefits and Challenges of Additive Manufacturing in Small-Scale Production

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Abstract: Additive manufacturing in construction is beginning to move from an architect‟s modelling tool to delivering full-scale architectural components and elements of buildings such as walls and facades. Building on the advances in AM in these industries, there are several experimental applications of AM in the construction sector. This paper discusses large-scale additive manufacturing processes that have been applied in the construction and architecture arena and focuses on „Concrete Printing‟, an automated extrusion based process. The wet properties of the material are critical to the success of manufacture and a number of new criteria have been developed to classify these process specific parameters. These criteria are introduced and key challenges that face construction scale additive manufacturing are presented.
Keywords: concrete printing, construction automation, digital fabrication, freeform construction, additive manufacturing

I. INTRODUCTION

Additive Manufacturing (AM), commonly known as 3D printing, fabricates components in a layerwise fashion directly from a digital file. AM is a rapidly growing field that is having an impact on multiple industries by simplifying the process to go from a 3D model to a finished product. The growing competitiveness has prompted considerable changes in the product development process for corporations and their designers. In this context, AM advancements have emerged as a solution since they allow enterprises to customise items to match clients' expectations, once AM technical characteristics enable personalised manufacturing [1]. In contrast to conventional subtractive manufacturing, where a product is shaped by removing material to achieve a desired shape, AM creates parts by adding material in layers [2]. Additive manufacturing (AM) is defined by American Society for Testing and Materials as „the process of joining materials to make objects from 3D model data, usually layer upon layer‟ [3]. Over the last 30 years, improvements in materials and process, coupled with clever design has resulted in successful commercial realisation [4]. In addition, the linear cost/production relationship for small batch production in Figure 1 is unique in the manufacturing sector and provides a strong business case for mass customisation, or personalisation of components.

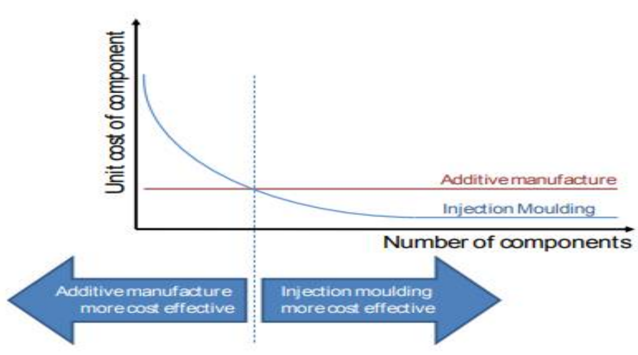


Figure 1: Diagram of cost case for additive manufacturing (reproduced from [8]).

II. ADDITIVE MANUFACTURING PROCESSES

To understand the advantages that AM could bring to construction, it is important to understand the different AM processes. The American Society for Testing and Materials (ASTM) International published a document in collaboration with the International Organization for Standardization (ISO) to define standard terminology for AM [5].

In this document, ISO/ASTM divided AM into seven different processes:

1) Vat Photopolymerization – A process of selectively curing a liquid light-activated polymer with a laser. An example of this process is stereolithography apparatus (SLA), a technique developed by Hull in the 1980's and commercialized first by 3D Systems [6].
2) Material Jetting – A process of selectively depositing drops of material in a layerwise fashion. An example of this process is PolyJet technology from Stratasys [7].
3) Binder Jetting – A process of depositing a powdered material layer upon layer and selectively dropping a liquid binding agent onto each layer to bind the powders together. Binder jetting was primarily developed at MIT in a process called 3D printing (3DP) [8].
4) Material Extrusion – A process of extruding material through a nozzle and depositing it layer-by-layer onto a substrate. The process was invented by Crump and commercialized by Stratasys as Fused Deposition Modelling (FDM) [8], but it now forms the basis for a very wide variety of inexpensive personal 3D printers.
5) Powder Bed Fusion – A process of selectively fusing a powder bed using thermal energy, typically in the form of a laser or electron beam. Selective Laser Sintering (SLS) was developed at the University of Texas at Austin for polymer materials and commercialized by DTM and 3D Systems [9]. Direct Metal Laser Sintering [10] and Selective Laser Melting (SLM) are common versions of powder bed fusion for fabricating metal parts.
6) Sheet Lamination – A process of successively shaping and bonding sheets of material to form an object. An example of sheet lamination process is laminated object manufacturing (LOM) developed by Helisys Inc., in which paper sheets were trimmed to size and glued together [11]. Ultrasonic Additive Manufacturing (UAM), commercialized by Solidica Inc. fabricates metal objects using ultrasonic welding [11].
7) Direct Energy Deposition – A process of fusing materials with focused thermal energy that melts the material as it is being deposited. An example of this process is laser engineered net shaping (LENS), developed at Sandia National Laboratories [11,12], which is particularly useful for repair of damaged metal parts [13].

Automotive Industry AM has brought improvements to the automotive industry, as demonstrated by innovations such as Bugatti’s Brake calipers [13], General Motors’ seat brackets [14], Local Motors’ Strati chassis ,and Porsche pistons [14]. These recent inventions showcase the industry’s urge for design flexibility, increased customization options, cost reduction, and improved efficiency, indicating the further integration of AM in automotive industries. However, continuous research in product development and material advancements will be necessary to tackle the challenges such as identifying suitable materials with necessary mechanical and thermal performance, addressing low production speeds, and improving the surface finish. Moreover, the use of AM in the automotive industry is still not widespread as a mainstream production route but rather more for niche applications in luxury car segments, spare part manufacturing, or die/mold manufacturing due to unique challenges in scaling AM for the serial production of automotive components.

Potential advancements in methods of implementing AM Advances in AM processes themselves may also facilitate the realization of potential applications in the construction industry. These methods, including fabrication using multiple materials, using in situ resources, utilizing hybrid techniques that combine AM processes with subtractive and formative processes, and expanding opportunities for both off-site and on-site fabrication, are discussed below.

a) Off-site/on-site fabrication AM is most commonly implemented in a controlled environment for high quality parts in both small and large-scale applications. The controlled environment is desirable as materials can react differently and provide different mechanical properties if the environment is suddenly disturbed. For example, in a common small-scale FDM system, enclosures are used for an ABS polymer like the one used in the BAAM system because the extrusion and material fusion processes are sensitive to temperature changes. The same problem occurs when printing with metallic and cementitious materials, which are also sensitive to temperature, humidity, and other environmental factors. The current onsite fabrication AM systems still require that certain environmental conditions be met for best results or that a type of enclosure is provided to keep desirable temperatures. For example, Rudenko [32] mentions that TotalKustom technology is likely to be ideal for warm regions. Research is needed to develop more robust technologies and materials for AM that can facilitate on-site construction. Sensitivity of part properties to environmental factors during fabrication is an important topic of concern, as well as the finishing of printed components. Another issue is the transportation and setup of AM equipment at the building site and its ability to adapt to different applications with different geometries, access levels, and underlying materials[15].

b) Multiple materials Formative processes (e.g., casting of concrete in formwork) typically utilize a single type of concrete for a large portion of a structure. AM could allow multiple materials to be deposited during the construction process using extrusion based processes with multiple nozzles for different materials. Bos et al. [34] proposed a concept of material customization by location, for example, depositing ultra-high performance concrete where structural demands are largest, and low-strength concretes for finishes and areas where structural demands are lower. Using multiple materials is not something new in construction. Concrete and steel are commonly used together due to their complementary mechanical properties and their similar thermal expansion behavior. Concrete exhibits high compressive strength at a relatively low cost, but it exhibits brittle failure and negligible tensile strength. It requires the integration of steel reinforcement to resist tensile stresses and to exhibit more ductile behavior. A combination of AM processes could allow simultaneous material extrusion and direct energy deposition processes to simultaneously deposit material for concrete and steel reinforcement, respectively, resulting in reinforced concrete structures similar to those used in practice today; however, using AM processes allows the concrete and steel reinforcement to take on geometries that are optimized for the structural demands and that may be challenging to produce using conventional techniques. In this approach, two nozzles could be used to fuse metals and extrude concrete separately. New cementitious and metallic materials developed for AM application may exploit the benefits of these common construction materials or may be completely new to the construction industry. Details on how this multi-material deposition process would be executed are definitely worthy of future research to address challenges such as temperature difference between concrete extrusion and metal fusion. The potential of printing multiple materials, is something that could bring advantages in the construction industry, but research is needed to develop new construction materials that are optimized for use in AM while still providing desirable structural performance. These new materials can be developed for improved fresh-state and final-state properties depending on the desired AM process and application, such as viscosity (for extrusion processes), early strength gain after deposition, thermal expansion and resistivity, layer-to-layer mechanical bonding, ductility, reduced embodied energy, and more. At the same time, these new materials must be economical for AM to become a feasible alternative in construction [16].

III. CURRENT CHALLENGES AND FUTURE PROSPECTS FOR AM

AM is emerging as a groundbreaking technology with immense potential to revolutionize various industries. It allows for the creation of three-dimensional objects by adding material layer by layer, offering unprecedented design freedom and manufacturing flexibility. While AM has already made significant strides, it also faces a range of challenges that need to be addressed. This section discusses current challenges and future directions for AM inventions, highlighting the transformative impact they can have on industries and the potential obstacles that need to be overcome. As an example, an AM machine makes the core of a sphere and after that, a machining process reduces the burrs and increases the geometrical accuracy of the sphere. Figure 2 represents a schematic flowchart of a hybrid AM-machining process, which can be used in micro/nano-scale applications. In this process, the input material is fed into the system and a fully computer controlled system and based on the feedback, it will go to the finished parts or it will go back to different stages of the manufacturing process [17].

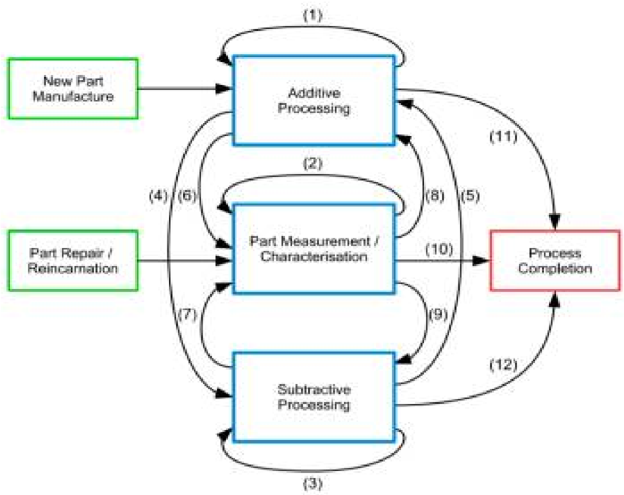


Figure 2. A closed loop of hybrid manufacturing for micro/nano-scale additive manufacturing [85].

A. Micro–Nano-Scale Fabrication

This refers to the additive manufacturing and manipulation of materials and structures at the microscopic and nanoscopic levels [17], typically ranging from a few micrometers down to nanometers. This field combines the principles of engineering, physics, chemistry, and biology to create structures and devices with precise control over their size, shape, and composition [18]. By leveraging specialized techniques such as lithography, etching, deposition, and self-assembly, micro–nano-scale fabrication enables the development of miniaturized systems with unique properties and functionalities.

B. Additively Manufactured Electronics

Additively Manufactured Electronics (AME) is an emerging field that combines the principles of 3DP and electronics manufacturing to create functional electronic devices and circuits directly through additive processes [18]. By integrating conductive and dielectric inks or materials into the 3DP process, AME enables the simultaneous fabrication of complex, three-dimensional structures and the deposition of electronic components [19], interconnects [20], and circuits [244]. This innovative approach offers several advantages, including the ability to create customized, lightweight, and geometrically complex electronics with reduced material waste and shorter production cycles [21]. Additively Manufactured Electronics (AME) represents a transformative approach in electronics fabrication, integrating additive manufacturing techniques to produce electronic components and devices layer by layer. This method enables the creation of complex geometries and three-dimensional circuits that are challenging to achieve with traditional manufacturing processes. Key benefits of AME include enhanced design flexibility, the ability to print on non-flat surfaces, and the integration of electronic functions directly into structural components, leading to more compact and efficient designs However, challenges such as material compatibility, process optimization, and ensuring the reliability of printed electronics remain areas of active research and development. As the technology advances, AME is poised to revolutionize sectors including consumer electronics, aerospace, and medical devices by enabling rapid prototyping, customization, and the production of high-performance electronic devices.

IV. METHODOLOGY

Published literature was assessed focussing on key concentration of additive manufacturing research and development in Africa. Journal articles, conferences and monographs indexed in Scopus database were extracted for the study. Keywords such as“Additive Manufacturing” and “3D Printing” from January 2015 to September 2021 was used. The keywords were examined in the title, abstracts and then integrated to prevent double counting. Individual publications were examined focusing on the affiliations of the authors and collaborating institutions, research focus, type of paper, respective fields that the research was conducted, year of publication and country. Documents with no affiliations in Africa were excluded. Though the review focused on research in Africa, global outlook on the application and current stage of AM research was summarized for contextual understanding [22].

Additive manufacturing (AM), commonly known as 3D printing, offers significant advantages for small-scale production, including rapid prototyping, enhanced design flexibility, and reduced material waste. These benefits enable manufacturers to produce complex, customized products efficiently without the need for extensive tooling. Additionally, the initial investment in AM technology and the need for specialized expertise may pose barriers for small-scale producers. Despite these challenges, the versatility and agility of AM make it a compelling option for low-volume, specialized production runs, particularly when traditional manufacturing methods are less feasible or cost-effective [23].

V. WHY BUILD AN ADDITIVE MANUFACTURING SCALING STRATEGY

A. Step 1: Build a Dedicated Additive Manufacturing Team

Every successful business initiative starts with a strong team. Organizations should consolidate AM efforts across the entire organization, building one dedicated, core additive manufacturing team with the relevant stakeholders. This team can serve as an organization-wide resource for sharing all incoming developments and knowledge related to additive manufacturing. At this stage, engineering and product development teams can grow familiar with the professional 3D printers, 3D printing software, and basic design and printing workflows. Unlike earlier 3D printers, modern professional 3D printers are much more user friendly, with a much less steep learning curve.

B. Step 2: Getting Started

With one or more professional 3D printers, the team can gradually shift production of parts from traditional manufacturing processes to additive manufacturing. Here, engineering departments should be involved in determining which parts are ideal for additive manufacturing fabrication. Despite the advantages of 3D printing, the organization may still be limited to only one or two professional 3D printers; to make the best use of resources, specific criteria should be outlined to determine which parts make the most sense to produce through 3D printing.

C. Step 3: Experiment and Build

Organizations at this step are ready to more comprehensively experiment with additive manufacturing. This is the phase where organizations will build up in-house design and production management expertise, which will be transferred to engineers and operators. New workflows specific to additive manufacturing may be built out, with production for parts that have been rapidly prototyped and validated.

D. Step 4: Assess and Scale

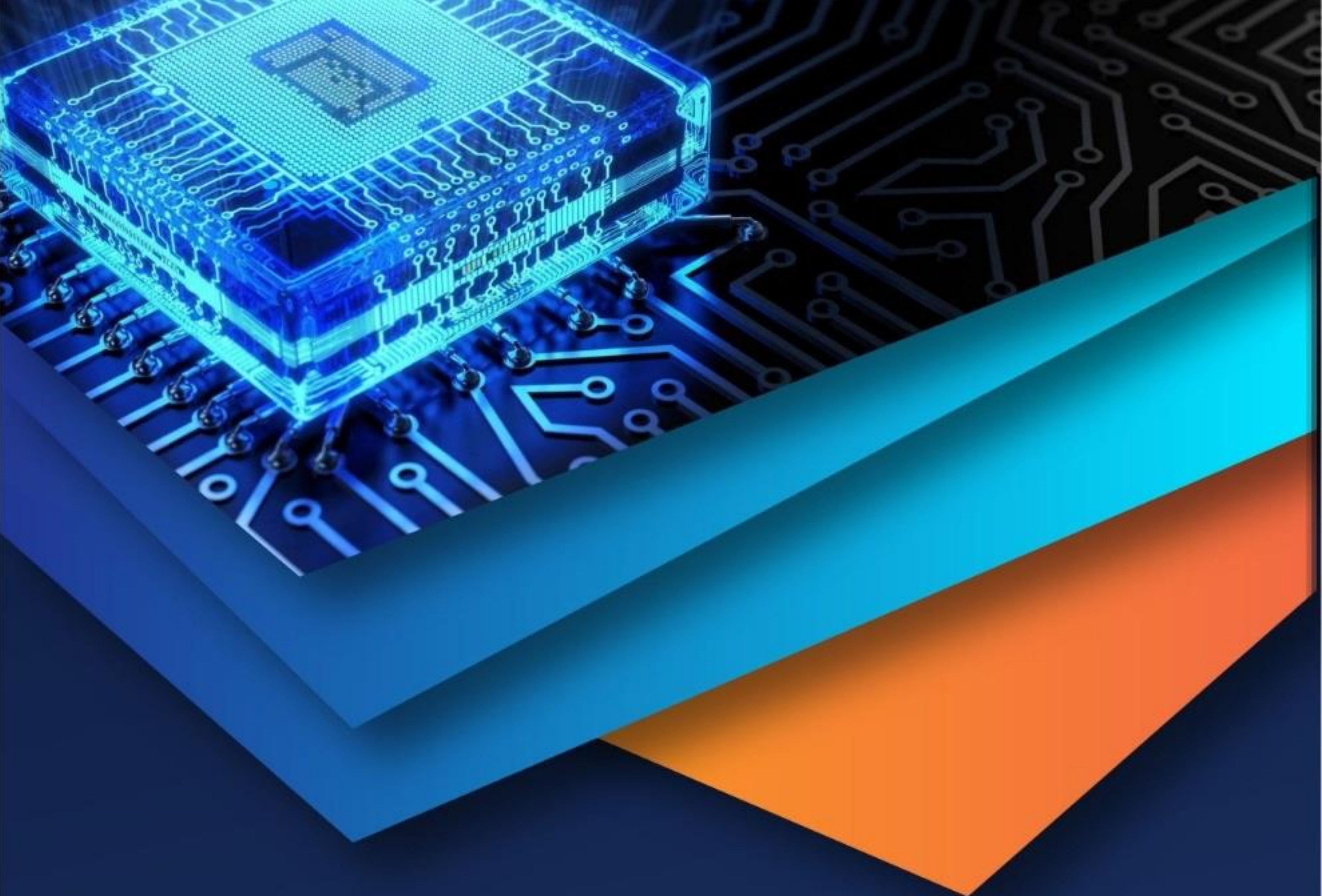
Here, organizations have already validated the use of additive manufacturing for the initial, small-scale production of parts. The next focus should be scaling up the use of additive manufacturing into a wider breadth of applications, while also formalizing processes with professionalized management of the AM ecosystem. As value and return on investments are assessed, promising results from the initial investigations into implementing additive manufacturing may prompt organizations to consider bringing in further additional 3D printers to support new capabilities and business models [23].

VI. CONCLUSION

AM is having an impact on many industries and growing as an alternative or complimentary approach relative to other manufacturing methods such as formative and subtractive processes. Aerospace, automotive, and other industries have explored the benefits of using AM in their day-to-day activities, finding new applications for different AM processes. The construction industry has become interested and has started exploring proof-of-concept AM applications that could be applied in the sector, looking to mitigate current challenges such as worker safety in harsh environments, decreases in skilled workforce availability, and waste of materials. More broadly, AM is seen as a way of addressing construction productivity challenges.

REFERENCES

[1] T. Bonwetsch, F. Gramazio, and M. Kohler. "Digitally Fabricating Non-Standardised Brick Walls." Paper presented at the ManuBuild conference proceedings, Rotterdam, 2007.
[2] Shotcrete, http://www.shotcrete.co.uk.
[3] Buildoffsite, http://buildoffsite.org.
[4] Formtexx, http://www.formtexx.com.
[5] ASTM. "Astm F2792-10 Standard Terminology for Additive Manufacturing Technologies." American Society for Testing and Materials (ASTM), http://www.astm.org/DATABASE.CART/HISTORICAL/F2792-10.htm.
[6] Materialise. "Automotive Testimony: Perfect Bumper Match.", http://www1.materialise.com/materialise/view/en/359256- Plastic+Omnium+bumper.html.
[7] Stratasys. "Urbee, 3d Printed Car Exterier.", http://www.stratasys.com/Resources/Case-Studies/Automotive-FDM-TechnologyCase-Studies/Urbee.aspx.
[8] R. Hague, I. Campbell, and P. Dickens. "Implications on Design of Rapid Manufacturing." Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, Vol 217, no. 1 (2003), 25-30.
[9] PP3DP. "Personal Portable 3d Printer.", http://pp3dp.com.
[10] bitsfrombytes. "Affordable 3d Printing.", http://www.bitsfrombytes.com.
[11] Stratasys Patent Expires, 3D Printing Industry Insiders Comment on Impact-3D Printing Industry. Available online: https:// 3dprintingindustry.com/news/stratasys-patent-expires-3d-printing-industry-insiders-comment-on-impact-185454/ (accessed on 11 June 2023).
[12] Copyright Law United States OF THE and Related Laws Contained in Title 17 of the United States Code. Available online: https://www.copyright.gov/title17/title17.pdf (accessed on 19 May 2023).
[13] Tibbits, S. Things Fall Together; Princeton University Press: Princeton, NJ, USA, 2021; ISBN 9780691189710.
[14] Definitions for Maintaining a Trademark Registration|USPTO. Available online: https://www.uspto.gov/trademarks/maintain/ forms-file/definitions-maintaining-trademark#Section%208%20and%209 (accessed on 19 May 2023).
[15] EOS, A United Kingdom Trademark of EOS Worldwide, LLC. Application Number: UK00918108117: Trademark Elite Trademarks. Available online: https://www.trademarkelite.com/uk/trademark/trademark-detail/UK00918108117/EOS (accessed on 11 June 2023).
[16] Frequently Asked Questions on Trade Secrets. Available online: https://www.wipo.int/tradesecrets/en/tradesecrets_faqs.html (accessed on 19 May 2023).
[17] Rimmer, M. Metal 3D printing: Patent law, trade secrets, and additive manufacturing. Front. Res. Metrics Anal. 2022, 7, 958761. [CrossRef] [PubMed]
[18] Design Patent Application Guide|USPTO. Available online: https://www.uspto.gov/patents/basics/apply/design-patent (accessed on 19 May 2023).
[19] Dean, L.; Loy, J. Generative Product Design Futures. Des. J. 2020, 23, 331–349. [CrossRef]
[20] Loy, J.; Novak, J.; Diegel, O. 3D Printing for Product Designers: Innovative Strategies Using Additive Manufacturing; Taylor & Francis: Oxford, UK, 2023; pp. 1–283. [CrossRef]
[21] Beltagui, A.; Gold, S.; Kunz, N.; Reiner, G. Special Issue: Rethinking operations and supply chain management in light of the 3D printing revolution. Int. J. Prod. Econ. 2023, 255, 108677. [CrossRef]
[22] Zhang, Y.; Westerweel, B.; Basten, R.; Song, J.-S. Distributed 3D Printing of Spare Parts via IP Licensing. Manuf. Serv. Oper. Manag. 2022, 24, 2685–2702. [CrossRef]



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