3D Printing in Critical Infrastructure System

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Additive manufacturing methods are among the technologies that have extremely versatile and a broad potential for use in many fields. However, it should be considered that in relation to critical infrastructure, they can also be considered from the traditional point of view of production systems allowing for the manufacture of machine and equipment components. At the same time, they can be an element of the system, performing functions in crisis situations to sustain the operation of strategic technical equipment, such as the production of spare parts by 3D printing in the absence of access to original parts.

critical infrastructure | energy system | 3D printing | mechanical engineering | additive manufacturing | manufacturing for de | manufacturing for defense systems | manufacturing of components for energy systems

1. Introduction to 3D Printing Applications in the Area of Critical Infrastructure

An additional advantage of 3D printing is the dispersion of infrastructure in many places, including manufacturing companies, universities and research institutes, local government units and schools, as well as a significant number of printers in the hands of private users. Taking this into account, three patterns in the use of additive technologies can be distinguished in relation to the production and operation of critical infrastructure. The first pattern refers to the use of 3D printers in the process of production machinery and equipment in the energy industry, for example. The second pattern allows 3D printing equipment to be used as a planned overhaul system with mobile repair centres being used, for example, as technical repair vehicles in the energy services or the armed forces. The third pattern refers to a distributed 3D printer system that can be integrated and ready for action when emergencies occur [1]. This approach requires the creation of a database of equipment that is in private ownership, in the government sector and with commercial organisations. This type of approach could be an element included in the National Programme for Critical Infrastructure Protection. To this end, an analysis of the potential areas of use for 3D printing should be undertaken, particularly in the field of energy security [2].

Additive technologies are subject to a continuous standardisation process in accordance with ISO standards. These standards often set out guidelines for product design, data processing, specific applications or industries, and also refer to the materials used, the processes and quality controls [3][4][5][6][7][8][9][10][11][12]. The standards do not refer to the classification of critical infrastructure applications, but distinguish the basic additive processes, which include:

- VP—Vat Photopolymerisation: a process involving layered photopolymerisation to a defined volume using a concentrated beam of ultraviolet light [13];
- MJ—Material Jetting: an additive manufacturing technology involving the layered printing of liquid material onto a model based on layered cross-sections. The change of state from liquid to solid usually occurs by solidification or photopolymerisation [14];
- BJ—Binder Jetting: the bonding of powdered material with a liquid binder. A process in which a powdered material is bonded together by depositing a liquid binder (adhesive) from a print head onto the cross-section of a layered model [15][16];
- PBF—Powder Bed Fusion: the selective bonding of powdered material. A process in which heat energy selectively melts layers within a powder bed [17][18][19];
- MEX—Material Extrusion: the extrusion of layers of material. A process in which a thermoplastic material is extruded into a fibre (thread) that is layered according to a digitally specified path [20][21][22];
- DED—Directed Energy Deposition: the targeted melting of supplied material. A process in which concentrated energy melts a material in layers during deposition (concentrated heat energy emitted as a laser beam, electron beam or plasma arc) [23][24][25][26][27];
- SL—Sheet Lamination: cross-section lamination. A process in which successive sections of a model are cut out from sheets of material glued to each other in succession [28][29][30][31].

The presented list of incremental processes refers to the ISO standard, but it should be remembered that each of these processes is used by companies producing 3D printers to implement their own technologies.

2. Summary of Additive Technology Methods

The adoption of additive technologies in the area of critical infrastructures implies the possibility of manufacturing infrastructure components from suitable materials using devices of varying complexity and environmental constraints. Many additive technologies require a complex infrastructure to maintain a proper working environment. Other additive methods require the use of specialised materials that must be stored and processed under specific conditions. However, there are also 3D printing systems that are less sensitive to external factors. This is usually related to the quality and accuracy of the dimensions and shapes of the products, and consequently determines their potential for application. Taking the above into account, a summarised description of the additive methods was prepared, which will form the basis for the analysis of applications in the area of critical infrastructure. The criteria that determine the adoption of 3D printing for the production of critical infrastructure components were identified and include: the accuracy of dimensions and shape, the properties of the starting materials and those produced in the additive process, the requirements of the technology with regard to the environmental factors, the possibility of producing spare parts in mobile repair systems [12], and the production of high quality machine parts. Furthermore, the potential of additive technologies should be considered in relation to the needs of companies and institutions responsible for maintaining the critical infrastructure. Applications range from small parts in polymeric materials to complex power plant components, such as turbine blades and gears.

Vat Photopolymerisation (VP) is one of the first 3D printing technologies available on the market for professional applications. The final product is made by layered photopolymerisation in a defined volume using a concentrated ultraviolet light beam. This technology is amongst the most accurate and, at the same time, the most precise. The photopolymerisation process requires stable environmental conditions and the equipment cannot operate near sources of either low or high frequency vibration. Therefore, the operation of devices requires stable environmental conditions with regard to both the ambient temperature and humidity. Furthermore, VP devices must also not be operated in dusty environments or be exposed to UV radiation. Photopolymerisation can be achieved either by scanning the resin surface with a UV laser beam or by projecting cross-sections of the model in layers using a projector. Resins with photoinitiators that allow for the photopolymerisation process to take place are used to produce prototypes. Different types of resins with properties imitating specific thermoplastic materials can be used. This makes the manufacture of plastic components or spare parts for critical infrastructure possible. The working chambers of machines make it possible to print items ranging from small objects with dimensions of just a few millimetres to objects with lengths of more than 1000 mm. Due to its sensitivity to the environmental conditions, the volumetric photopolymerisation process is not suitable for mobile repair stations [13].

Material Jetting (MJ) is an additive process in which a liquid material is printed onto a layered cross-section of a model; the change of state from liquid to solid usually occurs through solidification or photopolymerisation. This technology is versatile and allows the manufacture of specific and yet precise products from polymeric materials. At the same time, it can be used to produce technological tools for subsequent stages of the production process, which makes it highly adaptable. For example, it is possible to make injection moulds for the short series production of injection moulded products from polymeric materials. Due to its sensitivity to environmental conditions, the volumetric photopolymerisation process can be difficult to implement in mobile repair stations. One example of the application of MJ technology in a crisis situation is the manufacture of protective visor components using PolyJet technology during the supply shortage caused by the COVID-19 pandemic [14]. In the first period of the pandemic, all safeguards and protective measures were needed, especially for medical and uniformed services. In subsequent phases of the pandemic, some security measures were abandoned, but the glass helmets are still used by doctors during medical procedures, including dental procedures.

Binder Jetting (BJ) involves bonding a powdered material with a liquid binder process by printing it from a special head onto a cross-section of a layered model. The technology allows for the production of mainly visual models with the possibility of imprinting coloured textures. Due to the relatively low strength of the models, it is rarely used for the production of functional prototypes. An additional advantage of the BJ process is the ability to directly produce casting moulds for metal alloys, making this method very functional for the rapid production of tools used in the foundry industry. Taking this into account, it is possible to use it for the manufacture of cast critical infrastructure components, for their direct production as well as for repair work. This makes it possible, for example, to produce castings of spare parts for critical infrastructure for which the originals cannot be sourced. Of course, this type of casting should be treated as a semi-finished product for further finishing [15][16].

Powder Bed Fusion (PBF) is a process in which thermal energy selectively fuses layers within a powder bed volume. A distinction must be made here between PBF processes for polymeric materials and metal alloys. In the case of polymeric materials, this technology is mostly used to manufacture products from polyamide-based materials. These processes are mostly dedicated to stationary manufacturing, but it is also possible to find equipment that can meet the criteria for mobile repair systems. As far as the processing of metal alloy powders is concerned, the PBF process is extremely versatile and allows for the manufacture of high-quality components used in the construction of critical infrastructure equipment. These include highly stressed components, such as the blades of power turbines or the gears of gearboxes used in the energy industry. For example, Siemens manufactures burners for power generation equipment and rotor components for industrial turbines, using the Direct Metal Laser Sintering (DMLS) process. In most cases, the devices are stationary and require an extensive infrastructure, but it is possible to find 3D printers on the market that can meet the criteria for mobile renovation systems due to their small size, low energy and gas utility requirements, and a design that allows for the device to be transported. An example of such a device is the XM200C system[17][18][19].

Material Extrusion (MEX)—a process involving the extrusion of a thermoplastic material into a fibre (thread) arranged in layers according to a digitally determined path. This technology is widely used both in the industry and by private users. It offers the possibility of manufacturing high-strength products from polymeric materials with continuous operating temperatures of up to 260 °C (310 °C—short-term loads), which allows for the technology to be used to manufacture components for critical infrastructure. It enables the processing of many materials, both insulators and polymer matrix conductors. The adaptability of the process makes it possible to manufacture products under industrial conditions and to equip mobile repair systems. An example of such a solution is the mobile spare parts production system developed at the Rzeszow University of Technology, designed for work in field conditions for energy repair services as well as for the armed forces[20][21][22].

Directed Energy Deposition (DED)—a process in which focused energy melts a material in layers as it is deposited (the focused heat energy is emitted as a laser beam, electron beam or plasma arc). Wire Arc Additive Manufacturing (WAAM) can also be added to the group of DED technologies. This process builds on the experience of welding and surfacing technologies and is suitable for the manufacture of high-strength metal alloy products. The dimensional accuracy of the manufactured components is considerably lower than that of the PBF processes, so it is necessary to plan machining allowances at a specified level when designing products, especially if the component is intended to work with other parts in a machine assembly. An important advantage of this technology is the possibility of producing parts from scratch, as well as to repair them by the additive reconstruction of damaged parts. This makes it possible to use the technology to provide a manufacturing and repair system for critical infrastructure components. This type of equipment should mostly be used in climate-controlled rooms. Powdered materials should also be stored under special conditions to avoid altering their properties. In some cases, it is possible to adapt equipment for mobile repair systems as an element of critical infrastructure [23][24][25][26][27].

Sheet Lamination (SL)—cross-section lamination, a process in which successive sections of a model are cut out of sheets of material glued to each other successively. It is currently a niche technology used in industrial design and used to produce casting models for ceramic moulds. Due to the properties of the materials used and the complexity of the process, its application to the manufacture of critical infrastructure components is limited [28][29][30][31].

The presented analysis of additive technologies in relation to applications for the manufacture of critical infrastructure products and their use as a component has allowed the results to be tabulated.

An additional advantage of 3D printing is the dispersion of infrastructure in many places, including manufacturing companies, universities and research institutes, local government units and schools, as well as a significant number of printers in the hands of private users. Taking this into account, three patterns in the use of additive technologies can be distinguished, in relation to the production and operation of critical infrastructure. The first pattern refers to the use of 3D printers in the process of manufacturing machinery and equipment in the energy industry, for example. The second pattern allows 3D printing equipment to be used as a planned maintenance system consisting of mobile maintenance centres commonly used as maintenance trucks in the energy services or armed forces. The third pattern refers to a distributed system of 3D printers that can be integrated and ready for action when emergencies arise. This approach additionally requires the creation of a database of devices that are in private ownership as well as in government and local government institutions. This type of approach could be an element included in the National Programme for Critical Infrastructure Protection. To this end, an analysis of potential areas of use for 3D printing should be undertaken, particularly in the field of energy security.

3. Energy Demand of Processes

It is also possible to analyse the energy requirements of additive processes, which, in comparison to classical manufacturing processes, belong to processes with relatively low energy consumption. However, this is not a simple task that can be a separate issue, as it is influenced by various factors that include the type of additive process, the type of material being processed, the size of the 3D printer, and whether thermal parameters need to be maintained during the process. In general, it can be stated that the processing of metal alloys requires more process energy than the processing of polymeric materials. Additionally, the implementation of the additive process in thermally stabilised working chambers will require more energy than for the processes carried out in open working spaces. A summary of the process energy demand for additive processes is presented in **Table 1**.

Table 1. Energy demand of processes.

AM Process	VP	MJ	BJ	PBF	MEX	DED	SL
Desktop or laboratory 3D printer (polymers)	2	3	3	6	2	NA	4
Industrial 3D printer (polymers)	5	5	6	9	6	NA	6

AM Process	VP	MJ	BJ	PBF	MEX	DED	SL
Desktop or laboratory 3D printer (metal alloys)	NA	NA	NA	7	3 Composite metal polymer	7	5
Industrial 3D printer (metal alloys)	NA	NA	NA	10	7 Composite metal polymer	10	7

w energy demand and 10 a very high energy demand, with respect to the additive technologies themselves. The values in the table were introduced based on the technical data of the incremental machines, without taking into account the details of the manufacturing process of specific products.

Analysing the generalised data from **Table 1**, it can be seen that metal alloy processing requires more energy than polymer processing. Industrial equipment also consumes more energy than home or laboratory printers. The total energy demand during the manufacture of a product by means of an additive process requires a broader analysis not only of the process itself, but also of the shape and dimensions of the object and the technological parameters of the process itself. It is a complex issue closely related to the component to be manufactured and the number of components to be produced in a single additive process.

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