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A REVIEW OF SUSTAINABLE DEVELOPMENT OF ADDITIVE MANUFACTURING IN THE CONDITIONS OF DIGITAL AND GREEN TRANSITION

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ABSTRACT

Additive Manufacturing (AM), commonly known as 3D printing, represents a groundbreaking technology driving the advancement of the fourth industrial revolution (Industry 4.0). The production of models, rapid prototypes, components, and final-use parts using 3D printing is significantly more cost-effective compared to traditional manufacturing methods. The primary objective of this paper is to highlight the role of sustainable development in three-dimensional (3D) printing technology for effectively implementing Industry 4.0 amidst the green and digital transition. With the capability to realize virtually any desired object, 3D printing finds applications across various industries including construction, architecture, automotive, aviation, household goods, and medical fields. The analysis of Additive Manufacturing 3D printing technologies involves categorization based on process type, purpose, production equipment, energy consumption, materials, and other factors that influence sustainable development. The implementation of green initiatives and digital transformation is fully integrated into these innovative 3D technologies.

1. INTRODUCTION

Additive Manufacturing (AM), also known as 3D printing according to the definition by the American Society for Testing and Materials (ASTM) Committee F42, encompasses all additive manufacturing technologies (ASTM F2792-12a 2014). This advanced production method, often referred to as Rapid Prototyping, builds the final object layer by layer through the addition of material. Today, 3D printing technology can fabricate a wide range of objects. Initially, a three-dimensional geometric model is created using computer-aided design (CAD) software such as CATIA, SolidWorks, Autodesk Inventor, or similar programs. This digital model is then exported as an STL file or G-code. The STL file is subsequently processed in Slicer software to configure printing parameters like material type, production time, temperature, speed, and

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support structures. This process is crucial for preparing the file for printing on a 3D printer, regardless of the printer type (Alammar et al., 2022; Salmi 2022).

3D printing offers a cost-effective means to produce intricate geometric models and products rapidly and in various iterations based on digital specifications. Additive manufacturing holds potential for enhanced efficiency by integrating with data and the Internet of Things (IoT) in Industry 4.0, thereby facilitating a transition toward sustainable and digital manufacturing practices (Khorasani et al., 2022). Furthermore, 3D printing plays a significant role in sustainable development and life cycle optimization through digitalization (Khorasani et al., 2022).

According to ASTM Committee F42, 3D printing technologies are categorized into seven groups, as outlined in Table 1 (ASTM F2792-12a 2014; Salmi 2022; Sljivic et al., 2017). Present table is giving main classification of the process of AM 3D printing according to the typical material and field of application, listing some of the world's most famous manufacturers of 3D printers.

Table 1. The main classification of the process of AM 3D printing.

Process / Known companies	Typical Materials	Applications
Material Extrusion: Fused Deposition Modeling (FDM); Stratasys, 3D Systems, RepRap, Prusa i3, Ultimaker.	Polymer (ABS, PP, PC, PPS, PLA, ASA), Composite, Wax, WPC-Wood plastic composite.	Prototypes, tools, casting moulds, soft (silicone) functional parts/products.
Material Jetting: Multi-jet modelling (MJM) Object PolyJet, 3D Systems.	Polymer (ABS, PP, Acrylic), Rubber, Wax.	Prototypes, tools, casting moulds, soft, functional parts/products.
Binder Jetting: Powder bed and inkjet head, Plaster-based 3D printing; Zcorp, Voxleljet.	Composite, Gypsum, Ceramic, Sand, Metal, Polymer.	Functional parts/products casting moulds, soft (silicone) tools.
Sheet Lamination: Laminated object manufacturing (LOM), Ultrasonic (UAM); mCor Technologies Iris, Fabrisonic.	Paper, Metal: Steel, Aluminium, Titanium, Cooper.	Prototypes, models, tools, functional parts/products casting moulds, soft.
Vat Photopolymerization: Stereolithography (SLA); Digital Light Processing (DLP), Micro-SLA, (SLA) Stratasys.	Polymer, Epoxy, ABS, PP, Composite, Gypsum, Ceramic, Wax.	Prototypes, models, casting moulds, soft (silicone) tools.
Powder Bed Fusion: Selective Laser Sintering (SLS), Electron beam melting (EBM), Direct metal laser sintering (DMLS); EOSINT.	Metals: Alloy Steel, Steel, Aluminium, Titanium, Ceramic, Polymer, Composite, Rubber.	Prototypes, models, casting moulds, functional parts/products.
Directed Energy Deposition: Focused thermal energy, Laser metal (LMD), (LENS), Trumpf.	Metals: Alloy Steel, Steel, Aluminium, Titanium.	Prototypes, models, functional parts/products.

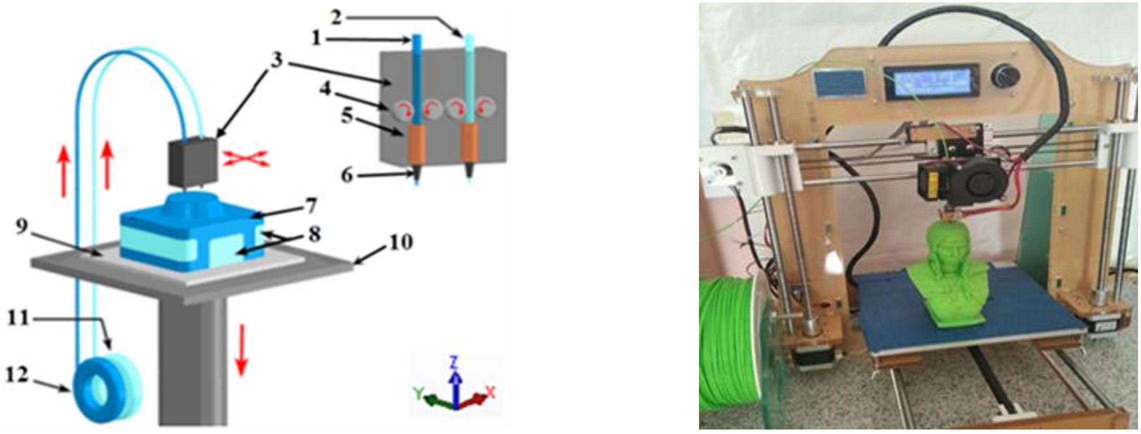
2. ADDITIVE MANUFACTURING 3D PRINTING UTILIZATION ACCROS MULTIPLE SECTORS

This paper provides an in-depth exploration of the current state of Additive Manufacturing (AM) 3D printing technologies and their efficient application across diverse industrial sectors, including aerospace, automotive, architecture, medicine, academia, and emerging areas, within the framework of sustainable development and environmental impact.

AM 3D printing technologies excel in the rapid production of prototypes, models, tools, components, and final-use parts, both in individual and serial manufacturing contexts (Sljivic et al., 2017; Salmi 2022). The research emphasizes the interconnectedness between 3D printing, Industry 4.0, technology sustainability, and environmental impact, focusing on energy efficiency, resource optimization, and waste reduction.

The analysis includes specific examples illustrating sustainable AM 3D printing practices across various sectors. Notably, material extrusion is one of the most widely adopted processes across industries. In this method, such as in Fused Deposition Modelling (FDM), a filament of a specific diameter is extruded through a nozzle that follows the object's cross-section to build up its geometry layer by layer. The nozzle incorporates resistance heaters to heat and liquefy the material, enabling it to flow and form successive layers.

Materials used in this process range from ABS plastic, polyamides, and polycarbonates to metals, composites, and molten wax. Figure 1(a) illustrates the layer-by-layer formation using the FDM method, while Figure 1(b) depicts a household 3D printer producing a model of a doll's head. Fusion deposition modelling (FDM) scheme can be described as follows: 1-Material, construction filament, 2-Material, support filament, 3-Extrusion head, 4-Drive wheels, 5-Flow manifolds, 6-Extrusion nozzles, 7-Model, fabrication facility, 8-Support, 9-Foam base, 10-Fabrication platform, 11-Support material coil, 12-Model material coil. These visuals exemplify the practical implementation and versatility of AM technologies in everyday settings.

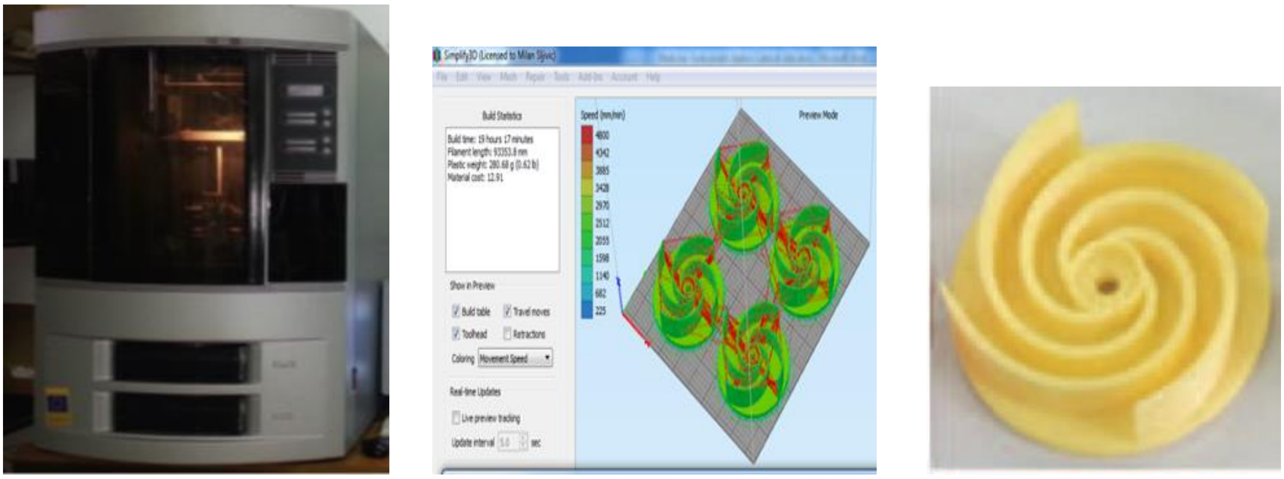


(a) (b)

Figure 1. (a) Fusion deposition modelling scheme (FDM); (b) Home 3D printer

2.1 Applications of Material Extrusion – Fusion Deposition Modelling (FDM) technology

A functional propeller designed for a water pump was investigated and printed using a professional FDM 3D printer, the Dimension Elite-Stratasys (USA), at the Laboratory of the Faculty of Mechanical Engineering in Banja Luka, as depicted in Figure 2(a). The propeller was printed using ABS polymer, and successful post-processing was achieved through manual methods. All printing parameters were defined using Simplify3D software for slicing, as shown in Figure 2(b). The functional propeller was printed in life-size, producing three copies per pass, as illustrated in Figure 2(c) (Sljivic et al., 2017). The direct advantages of this approach include full flexibility in designing complex geometric shapes, direct creation of components from digital models, reduced production time, minimized waste materials, and a transition towards environmentally friendly practices.



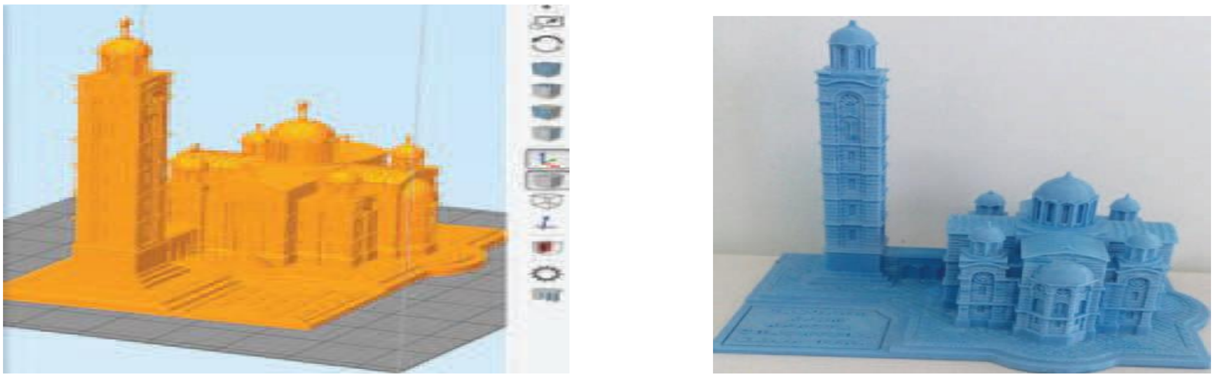
Build time: 19 hours 17 minutes
Filament length: 93353.8 mm
Plastic weight: 280.68 g (0.62 lb)
Material cost: 12.91

☑ Build table ☑ Travel moves
☑ Toolhead ☐ Retractions
Coloring: Movement Speed
☐ Live preview tracking
Update interval 5.0 sec

(a) (b) (c)

Figure 2. (a) 3D Printer Dimension Elite-Stratatis (USA); (b) Defining all operating parameters in Simplify 3D software. (c) Printed propeller

Development of a complex Model of the Church of Christ the Savior, Banja Luka, successfully done by FDM technology, Figure 3(a) and Figure 3(b). The Model of the Church scanned was with reverse engineering technology, and then created in the SolidWorks software Figure 3(a). Figure 3(b) show the finished printed model of the Church. The applied technique for making the model of the church used can be successful for 3D printing of models of archaeological monuments, even entire settlements, independent buildings, bridges, museum exhibits, and many other valuable finds and objects.



(a) (b)

Figure 3. (a) Model of the Church of Christ the Savior, Banja Luka; (b) Printed model of the church on a 3D printer Dimension Elite-Stratatis

There are now professional FDM 3D printers on the market suitable for series and mass production. This manuscript presents one such from concern UltiMaker S7, shown in Figure 4(a) with two characteristic end-use printed elements, Figure 4(b) (All3DP.pro., 2023). Using the UltiMaker S7 professional 3D printer, a very wide range of models, end end-use and components can be printed from stainless steel and plastic (All3DP.pro., 2023). This 3D printing process has the potential to support greater efficiency, cost-effectiveness, and reduced environmental impact on industrial systems and product life cycles compared to traditional production.

(a) (b)

Figure 4. **(**a) Professional 3D printer UltiMaker S7; **(**b) End-use parts made with the professional 3D printer UltiMaker S7

Advanced 3D printers developed that use the same working principle as FDM called Fused Filament Fabrication (FFF) can successfully print metal and ceramics (Sljivic et al., 2022). Figure 5(a) shows one (FFF) 3D printer from 3DEO (USA) capable of producing high-quality metal components of small to medium sizes up to 250 mm (Sljivic et al., 2022). Two characteristic case studies of metal 3D printing produced by this company are shown in Figure 5(b) and Figure 5(c) (Sljivic et al., 2022).

(a) (b) (c)

Figure 5. (a) Metal FFF 3D printer; (b) One end-use metal component; (c) One optimized pair of toothed bars

2.2 Applications of Large-format Additive Manufacturing 3D printing technology

Developed successful have been Large-format 3D printers for printing for industry, mass production, printing car prototypes, moulds, stencils, museum exhibits as well as end-use parts; (Schwaar, 2024). In Figure 6(a) The mModix Big-180X large-format 3D printer for commercial use with a build volume of 1,800 x 600 x 600 mm presented is (Schwaar., 2024). Creating applications on this Large-format 3D printer is faster and cheaper than conventional technologies, and the production of waste is almost negligible. Recycled materials can used also successfully be for printing.


(a) (b) (c)

Figure 6. (a) The mModix Big-180X. (b) and (c) The Exabot large-format 3D printers from Re:3D

Figures 6(b) and 6(c) illustrate The Exabot large-format 3D printer from Re:3D (USA) for a wide range of commercial needs. These printers have a dual extruder with base and soluble support material and can process PLA, ABS, PC, and thermoplastics with a melting point below 350°C (Schwaar, 2024). Large-format 3D printers can print the most complex geometric forms of models, prototypes, and parts for large-scale and end use accurately and sustainably.

The main requirements of the standard on the conditions for digital and green transition for the sustainable development of 3D printing in large formats fully implemented are.

2.3 Applications of Additive Manufacturing 3D printing in construction

The first German ready-to-move 3D printed house was printed at the end of July 2021, printed by PERI at the COBOD BOD2 printer in Beckum, North Rhine-Westphalia, as part of the Innovative Buildings program, shown in Figure 7(a) (Construction Index. 2021). The American company SQ4D from New York, which focused on engineering and building high-quality sustainable houses, printed the first 3D-printed house in the USA for sale, shown in Figure 7(b). The company believes that this 3D technology will soon be able to eliminate more expensive and inferior quality, making 3D configuration payable. The use of concrete reduces costs by at least 30%, as well as makes the structure more fire-resistant than traditional methods (Fermin, 2021). The first 3D printed house in Serbia "ProtoDom" premiered in the Science and Technology Park Cacak, made by two people and one 3D printing machine in just 21h and 15 min, as shown in Figure 7(c). The manufacturer of the 3D printing house, the company Natura Eco made the house from concrete and performed the necessary tests, which confirmed the safety of being resistant to winds, earthquakes, and other disasters (FoNet., 2021).

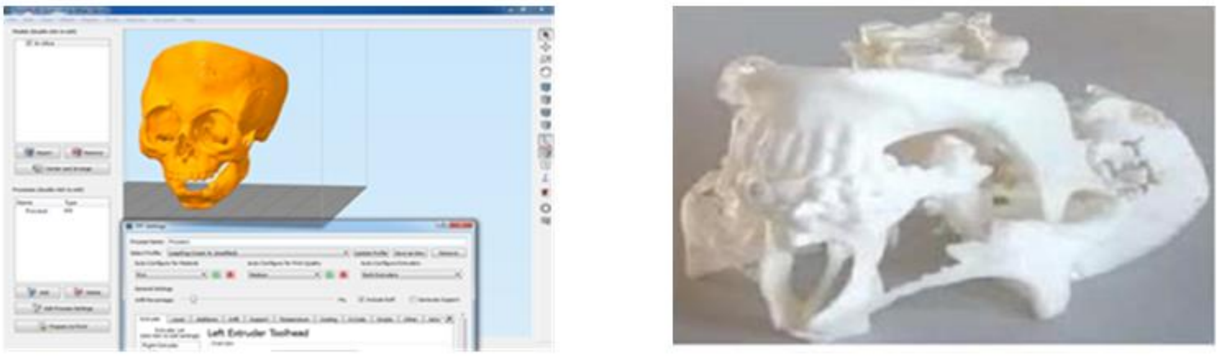
(a) (b) (c)

Figure 7. (a) The first German 3D printing house. (b) The first 3D-printed house for sale in the USA. (c) The first printing house in Serbia.

From the analysis of additive production of 3D printing in construction, it can be concluded that this process has great potential to accelerate construction, contribute to the strength of structural elements, and significantly reduce waste material, which contributes to better environmental ecology and reduces the number of construction workers and workers. To achieve this, it is necessary to adjust and make a suitable printer concerning the type and size of the object to be printed. Then the appropriate mixture of materials for 3D printing is very important. Tests have shown that cement-based mortar mixed with appropriate components, which harden quickly, achieved the best results.

2.4 Additive Manufacturing 3D printing and 3D bioprinting for medical applications

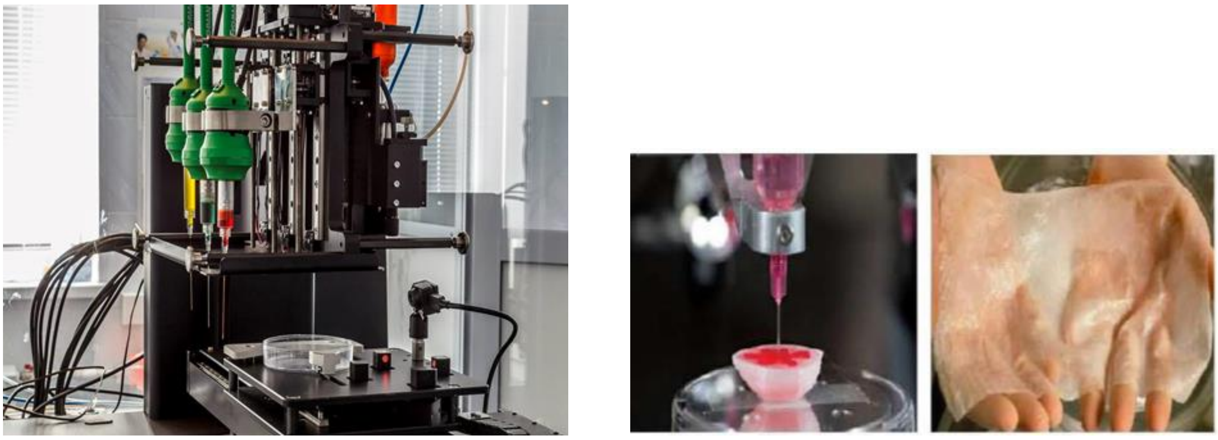
Additive technologies of 3D printing and 3D bioprinting in medicine are used for a very large number of applications, namely: creating models for planning a complex surgical intervention; craniofacial implants in the hip, knee, and spinal implants and others; bioprinting of human tissues and organs; prosthetic dentistry; production of various medical tools and other 3D printed and bioprinted procedures (Murphy & Atala, 2014; Mironov et al., 2011). For the successful application of the techniques of 3D printing and 3D bioprinting for medical applications, the most important influencing factor is the choice of the appropriate material. The application of 3D printing and 3D bioprinting is based on 4 basic steps of a 3D printing system: (i) Imaging 3D image of the object by computed tomography (CT) or magnetic resonance imaging (MRI), with digital (DICOM) medical file format, (ii) Image processing, including segmentation and surface modelling steps, (iii) Production with a 3D printer or 3D bioprint, and (iv) Post-processing techniques (Murphy&Atala, 2014; Mironov et al., 2011; Sljivic at al., 2017). Figure 8(a) and Figure 8(b) show an example of 3D printing of the skeleton of the head of an anonymous patient according to the above procedure for the preparation of surgery performed at University Clinical Center Banja Luka in cooperation with the Mechanical Faculty of Banja Luka (Sljivic et al., 2017).



(a) (b)

Figure 8. (a) Head jaws presented in SolidWorks. (b) Printed head jaws for medical intervention

Figure 9(a) shows one Inkjet 3D bioprinter from the Laboratory "3D Bioprinting Solution" Printer – Moscow (Mironov et al., 2011). Figure 9(b) Bioprinting for testing drugs and vaccines and Figure 9(c) Bioprinting for human skin (Murphy & Atala, 2014; Mironov et al., 2011). 3D bioprinting technology is a sophisticated technology of the future because products obtained by bioprinting technology can mimic both the biological and functional properties of the natural structures and tissues of our bodies. This leads to a wide range of different types of applications.



(a) (b) (c)

Figure 9. (a) Inkjet 3D bioprinting. (b) Bioprinting for testing drugs and vaccines (c) Bioprinting of human skin

World-renowned researchers are working hard to apply the bioprinting technique using stem cells that can be obtained from a patient's adipose tissue. Stem cells are then transformed into a laboratory cell conglomerate that fills a bioprinter cartridge to process the formed biological production of the corresponding tissue or organ (Murphy&Atala, 2014; Mironov et al.2011). We can conclude that the possibilities of 3D printing and 3D bioprinting applications in medicine are unlimited and represent a revolutionary future in modern medicine and dentistry.

3. CONCLUSION

The paper not only underscores the significant potential and benefits of advanced additive manufacturing 3D printing within the context of Industry 4.0 but also emphasizes its transformative impact on various sectors. In addition to design flexibility, shortened production times, and environmental advantages, 3D printing offers unparalleled innovation and customization capabilities that are reshaping traditional manufacturing paradigms.

One of the key advantages of 3D printing is its ability to create complex geometries and customized products with precision and efficiency. This capability unlocks new possibilities across industries, such as aerospace, automotive, healthcare, consumer goods, and more. For example, in aerospace, 3D printing allows for the production of lightweight yet durable components that improve fuel efficiency and performance. In healthcare, it enables the fabrication of patient-specific implants and prosthetics tailored to individual needs.

Beyond innovation, additive manufacturing significantly contributes to sustainable practices by reducing material waste and optimizing production processes. By only using the necessary amount of material required for each part, 3D printing minimizes waste compared to traditional subtractive manufacturing methods. This waste reduction not only conserves resources but also lowers manufacturing costs and supports environmental sustainability.

The adoption of 3D printing represents more than just a technological advancement; it signifies a strategic shift towards more agile, efficient, and environmentally conscious production methods. As industries continue to embrace additive manufacturing, the boundaries of what can be achieved in terms of product design, production flexibility, and sustainability will continue to expand, driving further advancements and innovations in the era of Industry 4.0.

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