

BULETINUL INSTITUTULUI POLITEHNIC DIN IAȘI

Publicat de

Universitatea Tehnică „Gheorghe Asachi” din Iași

Volumul 72 (76), Numărul 1, 2026

Secția

CONSTRUCȚII DE MAȘINI

DOI: 10.2478/bipcm-2026-0007

STATE-OF-THE-ART OF 3D PRINTING IN REMANUFACTURING WITHIN INDUSTRY 4.0

BY

**GABRIEL SIGNEANU^{1,*}, DRAGOȘ-FLORIN CHITARIU^{1,2},
FLORIN-DANIEL EDUȚANU¹, IONUȚ-ALIN BEJENARU¹ and
ANITA SÂNDUCU¹**

¹“Gheorghe Asachi” Technical University of Iași, Faculty of Machine Manufacturing and
Industrial Management, Bd. Prof. D. Mangeron 67, 700050 Iași, Romania

²Academy of Romanian Scientists, Ilfov 3, 050044 Bucharest, Romania

Received: May 19, 2026

Accepted for publication: May 29, 2026

Abstract. This paper provides a state-of-the-art review of 3D Printing for Repair (3DP4R) systems within the framework of Industry 4.0 and the circular economy. Conventional remanufacturing face severe technical bottlenecks due to discontinued spare parts and high inventory costs, leading to prolonged equipment downtime. To address these limitations, this research analyzes the integration of Fused Deposition Modeling (FDM) as a decentralized, on-demand restoration strategy. A structured evaluation of the four-stage 3DP4R operational flow—Analysis, (Re)design, Additive Manufacturing, and Testing—is provided. The study evaluates critical engineering challenges, including the structural discrepancies between isotropic injection-molded components and anisotropic FDM layers, while emphasizing the optimization of internal infill parameters, raster orientation, and post-processing thermal annealing. Conclusively, this paper establishes a conceptual roadmap for digitized product life extension, demonstrating that leveraging digital twins transforms physical warehouses into

*Corresponding author; *e-mail*: gabriel.signeanu@student.tuiasi.ro

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sustainable digital inventories, thereby mitigating the environmental impacts of global industrial logistics.

Keywords: Industry 4.0, Circular Economy, Additive Manufacturing, Repair, Remanufacturing.

1. Introduction

The transition from a linear "take-make-dispose" economic model to a circular economy has become a strategic priority for modern industrial systems.

Within the framework of Industry 4.0, this shift is facilitated by the integration of Cyber-Physical Systems (CPS), the Internet of Things (IoT), and advanced manufacturing technologies (Mboli *et al.*, 2022). Among these, remanufacturing stands out as a key pillar of sustainability, aiming to restore used products to a like-new condition, thereby extending their lifecycle and reducing environmental impact.

Despite its potential, traditional remanufacturing faces significant logistical and technical bottlenecks. Conventional repair methods often rely on the availability of original spare parts, which may be discontinued or subject to long procurement lead times (Shi, 2019).

Furthermore, the high costs associated with maintaining extensive inventories of low-demand components often diminish the economic viability of repairing aging machinery. These challenges frequently lead to prolonged equipment downtime and sub-optimal operational efficiency (Trismawati and Handayani, 2024).

Additive Manufacturing (AM), particularly Fused Deposition Modeling (FDM), emerges as a disruptive solution to these limitations. By enabling the production of complex geometries directly from digital models, AM allows for on-demand manufacturing of spare parts and the direct repair of worn components (Kantaros *et al.*, 2025).

This synergy between Industry 4.0 digitalization and remanufacturing processes gives rise to new frameworks, such as 3D Printing for Repair (3DP4R) (van Oudheusden *et al.*, 2023).

Previous research indicates that while FDM provides geometric flexibility, the functional success of repaired components depends heavily on anisotropic material properties (Ahn *et al.*, 2002) and the optimization of internal infill parameters (Fernandez-Vicente *et al.*, 2016).

While individual aspects of FDM parameters have been extensively documented, a comprehensive consolidation of how these advancements integrate into a unified 3DP4R framework remains limited. Existing literature often analyzes the status of additive manufacturing from a broad engineering perspective (Gao *et al.*, 2015), or focuses strictly on localized material behaviors, such as fiber-reinforced polymers (Brenken *et al.*, 2018) and specific post-processing techniques (Dizon *et al.*, 2021).

This paper addresses the need for a structured review of 3D Printing for Repair (3DP4R) systems within sustainable remanufacturing. It examines current methodologies, identifies key technical challenges and barriers, and outlines future research directions for digitized product life extension.

2. Industry 4.0 and its Role in the Circular Economy

2.1. Definition and Evolution of Industry 4.0

The term "Industry 4.0" (German: Industrie 4.0) was officially introduced at the Hannover Messe in 2011 (Nikishina, 2023) as a strategic high-tech initiative by the German government to modernize the manufacturing sector (Lasi *et al.*, 2014; Hermann *et al.*, 2016). It represents the Fourth Industrial Revolution, a paradigm shift that marks the transition from automated production to intelligent, interconnected manufacturing ecosystems. Historically, this evolution is categorized into four distinct stages:

- The First Industrial Revolution: late 18th century; characterized by mechanization through water and steam power (Pramanik *et al.*, 2019).
- The Second Industrial Revolution: early 20th century; driven by mass production, labor division, and electrical energy (Tien, 2019).
- The Third Industrial Revolution: 1970s; defined by the rise of electronics, PLC-based automation, and Information Technology (IT) (Jayakrishna *et al.*, 2020).
- The Fourth Industrial Revolution (Industry 4.0): present day; centered on the convergence of physical and digital worlds through Cyber-Physical Systems (CPS) (Butzer *et al.*, 2016).

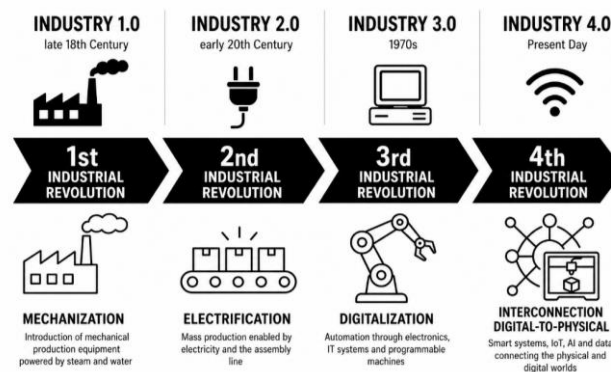


Fig. 1 – The evolution of the four industrial revolutions (Lasi *et al.*, 2014).

As illustrated in Fig. 1, this historical progression highlights the acceleration of industrial capabilities. Industry 4.0 is currently defined as the

convergence of these digital foundations with future-oriented, intelligent technologies (Müller, 2019).

According to Lasi, the transition toward Industry 4.0 is driven by both market demands, including product individualization, shorter innovation cycles, and sustainability requirements, and by the rapid advancement of digital technologies such as networking and Cyber-Physical Systems (Lasi *et al.*, 2014; Jazdi, 2014). Building on this concept, Zhong *et al.* define Industry 4.0 as an intelligent manufacturing ecosystem in which physical and digital systems interact autonomously, enabling real-time monitoring, self-optimization, and decentralized decision-making throughout the product lifecycle (Zhong *et al.*, 2017).

2.2. The Technological Pillars of Industry 4.0

The technological foundation of Industry 4.0 is commonly described through the "Nine Pillars of Industry 4.0", Fig. 2., which enable the transition from conventional manufacturing to smart, interconnected, and decentralized production systems (Vaidya *et al.*, 2018; Nikishina, 2023). These pillars include Big Data and Analytics for real-time decision-making (Rajab *et al.*, 2022), Autonomous Robots capable of flexible and collaborative operations (Chitariu *et al.*, 2024), Simulation and Digital Twins for virtual process optimization (Jayakrishna *et al.*, 2020), Horizontal and Vertical System Integration across the value chain (Vaidya *et al.*, 2018), and the Industrial Internet of Things (IIoT), which enables communication between interconnected devices and systems (Vaidya *et al.*, 2018).

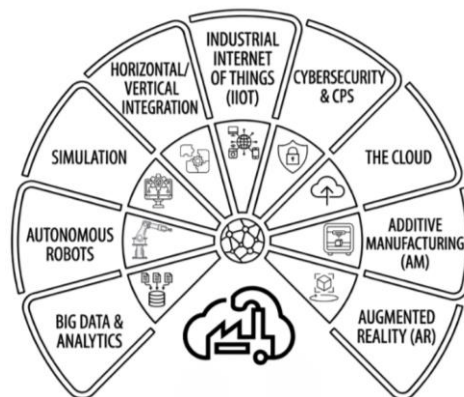


Fig. 2 – The nine technological pillars of Industry 4.0 (Vaidya *et al.*, 2018).

The remaining pillars comprise Cyber-Physical Systems and Cybersecurity for secure integration of physical and digital environments, Cloud Computing for large-scale data exchange and connectivity (Jayakrishna

et al., 2020), Additive Manufacturing for customized and decentralized production (Pramanik *et al.*, 2019), and Augmented Reality, which supports maintenance, repair, and operational decision-making through real-time information delivery (Vaidya *et al.*, 2018). Together, these technologies form the core infrastructure of modern smart manufacturing systems.

3. Additive Manufacturing

Fundamental Principles: The Additive Logic in Remanufacturing

According to the joint international standard ISO/ASTM 52900, Additive Manufacturing (AM) is formally defined as the “process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies” (Gibson *et al.*, 2020).

Unlike conventional processes such as milling or turning, which involve the removal of material, AM enables the direct fabrication of components from digital models, offering unprecedented geometric freedom and improved material efficiency.

Additive Manufacturing is characterized by the production of physical objects from three-dimensional digital data through the layer-by-layer consolidation of material.

This process begins with the mathematical discretization of a solid 3D CAD model into a series of thin, horizontal two-dimensional cross-sections. This 'digital slicing' provides the precise toolpaths required for the physical reconstruction of the component, transforming a digital surrogate into a tangible asset through the sequential deposition of material.

This "bottom-up" approach is the technological enabler that transforms a damaged component into a remanufactured asset.

To facilitate the study of additive manufacturing methods, various classification criteria have been developed. The most widely recognized approach is established by the ASTM standards, which identify seven fundamental technology categories: Powder Bed Fusion, Directed Energy Deposition, Material Extrusion, Vat Photopolymerization, Binder Jetting, Material Jetting, and Sheet Lamination (Dipu, 2025; Yeshiwas *et al.*, 2025).

In the specific context of remanufacturing, this principle allows for a high degree of resource efficiency. While a new part requires 100% of its volume to be fabricated, remanufacturing uses the existing component (the "core") as a substrate, adding only the material lost to wear or damage. This process restores the product to a "like-new" condition, effectively closing the industrial loop as defined in Circular Economy frameworks. By building "layer-upon-layer" directly onto a pre-existing part, AM transcends its role as a

prototyping tool, becoming a core production method for high-value asset recovery.

4. Methodological Framework: Integrating 3DP4R into the Remanufacturing Ecosystem

4.1. The Strategic Importance of Remanufacturing in the Circular Economy

The global industrial sector is facing a critical resource challenge; since 1965, the consumption of raw materials has increased by 65% (Butzer *et al.*, 2016), leading to accelerated depletion and environmental degradation (Kerin and Pham, 2019; Suryo Wasono *et al.*, 2019).

To address this, **remanufacturing** has emerged as a core element of the Circular Economy, offering a strategic path to enhance resource efficiency and mitigate environmental impact (Hatcher *et al.*, 2011).

While definitions may vary across industrial sectors, the **BS 8887-220:2010** standard serves as the universal benchmark. It defines remanufacturing as the "*return of a product to at least its original performance with a warranty that is equivalent to or better than that of the newly manufactured product*" (British Standards Institution, 2010). To fully grasp the technical superiority of this strategy, it must be distinguished from other life-cycle interventions:

- **Repair:** A localized process focused on returning a broken or failed component to a functional state. The intervention is usually limited to fixing a specific fault, often without a guarantee that the rest of the component will meet its original lifespan or performance specifications (British Standards Institution, 2010).
- **Refurbishment (Reconditioning):** A more thorough process than repair, involving the aesthetic and functional restoration of a product to a "satisfactory" working condition. While it improves the part, it does not necessarily aim to match the original manufacturer's specifications.
- **Remanufacturing:** Representing the highest tier of value retention, this process involves total disassembly and restoration. Unlike the previous methods, it ensures that the "durable core" is returned to a "like-new" state, fulfilling the rigorous criteria of the aforementioned BS 8887 standard (Gan *et al.*, 2014).

4.2. Operational Flow: Analysis of the Remanufacturing Process

The transformation of a reparable product into a remanufactured product follows a structured sequence of operations that can be adapted according to the condition of the component and the technical requirements of the recovery process. The workflow consists of six main stages: disassembly,

cleaning, inspection and diagnosis, restoration, reassembly, and testing, fig. 3 (Gamage *et al.*, 2013). Disassembly involves the systematic separation of product components, a process increasingly supported by Industry 4.0 technologies such as IoT, Virtual Reality, and Augmented Reality to improve efficiency and reduce the risk of damage (Hatcher *et al.*, 2011; Chang *et al.*, 2017). Cleaning removes contaminants that could affect subsequent operations, while inspection and diagnosis assess wear, dimensional accuracy, and structural integrity to identify repair requirements (Butzer *et al.*, 2016).

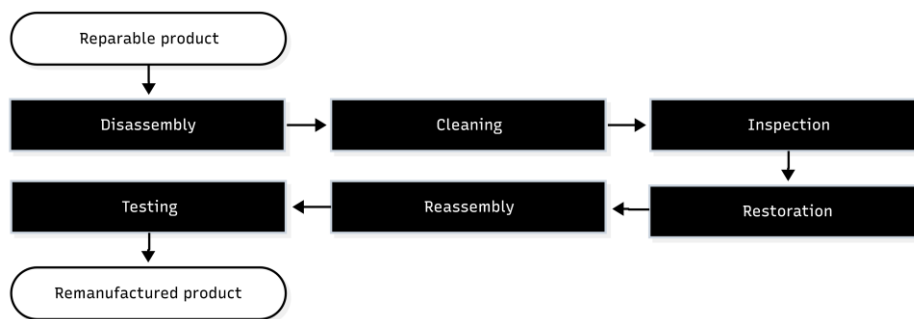


Fig. 3 – The sequential stages of the industrial remanufacturing process.

The restoration stage represents the core value-adding activity, where damaged components are recovered and returned to their functional specifications. Once restored, the components are reassembled according to established tolerances and assembly requirements (Butzer *et al.*, 2016).

The process concludes with testing and validation, ensuring that the remanufactured product satisfies the performance criteria associated with "like-new" quality and complies with the requirements of BS 8887-220:2010 (British Standards Institution, 2010).

4.3. The 3DP4R Sub-process: A Digital Paradigm in Industry 4.0 Remanufacturing

The **3D Printing for Repair (3DP4R)** framework transforms remanufacturing from a manual craft into a data-driven digital process. Within the **Industry 4.0** ecosystem, this process represents an integrated lifecycle that bridges the gap between physical failure and digital restoration through a structured, iterative methodology (Bolaños Arriola *et al.*, 2022).

4.3.1. Preliminary Phase: Defect Diagnosis:

Before any additive intervention, a systematic diagnosis is mandatory. This stage involves identifying failure symptoms, determining root causes, and

isolating the components for reproduction. This ensures the 3D-printed replacement addresses the original structural weaknesses (van Oudheusden *et al.*, 2023).

4.3.2. The Four Stages of the 3DP4R Operational Flow Once diagnosed, the process follows a cycle where each stage is critical for achieving a "like-new" status, consistent with **BS 8887** remanufacturing standards:

- **Stage 1: Analysis**

The analysis stage gathers the information required for component recovery by evaluating assembly interfaces, functional requirements, and the feasibility of Additive Manufacturing. Depending on the component condition, Fig. 4, four scenarios are considered: Scenario A (existing digital model), Scenario B (intact component), Scenario C (damaged component requiring reconstruction), and Scenario D (missing component requiring contextual reverse engineering) (Bolaños Arriola *et al.*, 2022).

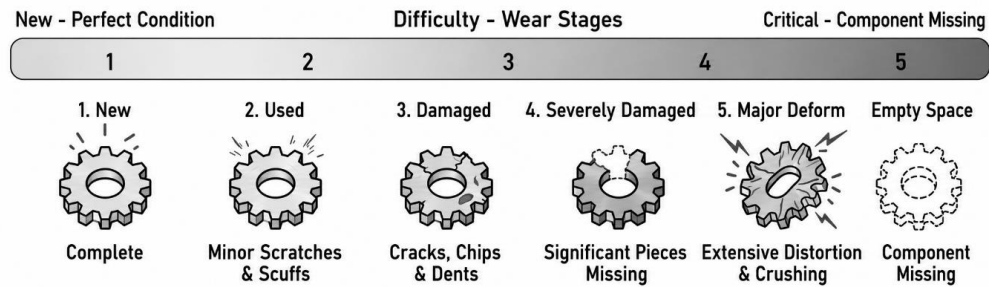


Fig. 4 – Level of difficulty for part completeness - Bolaños Arriola *et al.* (2022).

- **Stage 2: (Re)design and Digital Geometry Acquisition**

The (re)design phase adapts the component for additive manufacturing, addressing the differences between isotropic injection-moulded parts and anisotropic FDM structures (Ahn *et al.*, 2002). Optimization may include reinforcing critical regions, increasing wall thickness, and adapting geometry to process-specific constraints (Brenken *et al.*, 2018; Bolaños Arriola *et al.*, 2022), while considering the selected AM technology (Yang and Kota, 2025).

Digital models can be generated through direct measurements, optical 3D scanning, or photographic references (Gao *et al.*, 2015).

- **Stage 3: Additive Manufacturing and Process Optimization**

This stage converts the digital model into a physical component through controlled additive manufacturing processes (Bolaños Arriola *et al.*, 2022).

Material selection, print orientation, shell thickness, infill density, and layer height directly influence mechanical performance and dimensional accuracy (Ahn *et al.*, 2002; Nikishina, 2023; Fernandez-Vicente *et al.*, 2016).

Process monitoring, together with post-processing operations such as mechanical finishing and annealing, contributes to improved durability and performance (Dizon *et al.*, 2021; Gopal *et al.*, 2023).

- **Stage 4: Testing and Functional Validation**

The final stage verifies that the remanufactured component satisfies geometric, mechanical, and functional requirements. Dimensional inspections, structural assessments, and operational testing are performed to evaluate performance, durability and safety. When requirements are not met, the results are used to support further redesign and optimization within the 3DP4R workflow.

5. Conclusions

This comprehensive review has navigated the transition from traditional linear industrial models to a circular ecosystem empowered by Industry 4.0 technologies. By examining the convergence of Additive Manufacturing and remanufacturing, several critical insights emerge regarding the future of industrial sustainability and technical recovery.

The research confirms that Industry 4.0 is not merely an evolution of automation, but a fundamental enabler of the Circular Economy. The integration of Cyber-Physical Systems and the "Nine Pillars"—particularly Additive Manufacturing and Digital Twins—provides the technical infrastructure necessary to move beyond the "take-make-dispose" paradigm.

Remanufacturing, once a manual and resource-heavy process, has been transformed into a high-precision, data-driven discipline that meets the rigorous performance standards of the BS 8887-220:2010 benchmark.

In conclusion, the state-of-the-art in remanufacturing within Industry 4.0 points toward a future of decentralized, on-demand repair. The ability to digitize failed components and reproduce them locally reduces the carbon footprint of global logistics and prevents the premature disposal of complex machinery.

While challenges in material performance and digitization speed remain, the frameworks discussed in this article, specifically 3DP4R, offer a scalable and scientifically grounded pathway for industrial asset recovery.

This study underscores that in a world of finite resources, the most valuable "raw material" is the data that allows us to repair rather than replace.

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STADIUL ACTUAL AL CUNOAȘTERII PRIVIND IMPRIMAREA 3D ÎN REMANUFACTURARE ÎN CONTEXTUL INDUSTRIEI 4.0

(Rezumat)

Această lucrare prezintă o analiză a stadiului actual al cercetării privind sistemele de imprimare 3D pentru reparații (3DP4R) în contextul Industriei 4.0 și al economiei circulare. Remanufacturarea convențională se confruntă cu blocaje tehnice majore din cauza pieselor de schimb scoase din producție și a costurilor ridicate de stocare, fapt ce determină perioade prelungite de nefuncționare a echipamentelor. Pentru a depăși aceste limitări, cercetarea de față analizează integrarea FDM ca strategie de restaurare descentralizată, realizată la cerere. Este prezentată o evaluare structurată a fluxului operațional 3DP4R, împărțit în patru etape: analiză, (re)proiectare, fabricație aditivă și testare. Studiul evaluează provocările ingineresti critice, inclusiv diferențele structurale dintre componentele izotrope matrițate prin injecție și straturile anizotrope obținute prin FDM, subliniind importanța optimizării parametrilor de umplere internă, a orientării traseului de depunere și a tratamentului termic de recoacere.

În concluzie, lucrarea stabilește o strategie conceptuală pentru extinderea duratei de viață a produselor prin metode digitalizate, demonstrând că utilizarea modelelor virtuale interconectate transformă depozitele fizice în baze de date pentru producție la cerere, reducând astfel impactul logistic global asupra mediului.