EAI Endorsed Transactions
on Digital Transformation of Industrial Processes Review Article EAI.EU

Research on the Monitoring of Selected Parameters of Technological Devices in the Conditions of a Digital Enterprise

Rebeka Tauberová[1*], Lucia Knapčíková[2]

[1]Faculty of Manufacturing Technologies with a Seat in Presov, Department of Industrial Engineering and Informatics, Technical University of Košice, Bayerova 1, 08001 Prešov, Slovakia

Abstract

Digitization is a key concept of the Fourth Generation Industrial Revolution. In industrial enterprises, digitization allows for the study of various influences on production processes without the need to intervene in real production. Thanks to technologies such as augmented reality, virtual reality, 3D printing, digital twins, and artificial intelligence, it is possible to conduct research activities monitoring selected parameters without interfering with the production process. Financial resources invested in transforming a traditional company into a digital enterprise ultimately save production costs. Simulation programs enable quick and easy planning of production changes, resulting in more efficient processes and savings in raw materials. The concept of digitization has gained greater importance, especially in connection with events like COVID-19, which affected daily life worldwide. Many companies realized the significant advantage of digitizing production. The pressure of events and economic impacts accelerated the implementation of digitization and intelligent automation. The use of artificial intelligence tools in production enables remote control of manufacturing.

Keywords: Additive manufacturing, Polyvinyl Butyral, Granulate, Recycling, Circular economy

Received on 16 of July 2025, accepted on 28 July 2025, published on 29 July 2025

doi: 10.4108/dtip.9737

1. Introduction

In the context of rapid technological advancement and increasing global challenges, the manufacturing sector is undergoing a profound transformation. The imperative to optimize energy consumption and resource use is more pressing than ever, driven by both environmental concerns and economic pressures. Manufacturing inherently requires significant energy input to convert raw materials into finished products, making efficiency and sustainability critical objectives for modern industry.

Additive manufacturing, often positioned as the antithesis of traditional subtractive methods like turning or milling, exemplifies this shift toward sustainability and innovation. Its core advantages—cost-effectiveness, accessibility, and environmental friendliness—are reshaping how products are designed and produced. Unlike traditional manufacturing, which often generates substantial material waste, additive manufacturing minimizes waste by building objects layer by layer, using only the material necessary for the final product. This not only conserves resources but also reduces the environmental footprint of production processes.
The integration of recycled materials as filaments further enhances the sustainability of additive manufacturing. By reusing materials that would otherwise become waste, manufacturers can close the loop in the material lifecycle, aligning their operations with the principles of the circular economy. The use of various sensors and digital monitoring tools enables precise control and optimization of the printing process, ensuring high-quality outcomes while minimizing energy and material consumption. Moreover, additive manufacturing unlocks unprecedented

*Corresponding author. Email: rebeka.tauberova@tuke.sk

design freedom, allowing for the creation of complex geometries and customized solutions that are difficult or impossible to achieve with conventional methods. This flexibility is particularly valuable in industries such as aerospace, automotive, healthcare, and consumer goods, where rapid prototyping and tailored products are in high demand. The convergence of additive manufacturing with digital technologies—such as virtual reality, augmented reality, and the Industrial Internet of Things (IIoT)—is further revolutionizing the sector. Real-time data collection, process automation, and advanced analytics empower manufacturers to monitor and optimize every stage of production. These capabilities not only improve operational efficiency but also support predictive maintenance, reduce downtime, and enhance product quality. At the same time, the shift toward sustainable manufacturing is being accelerated by regulatory frameworks and growing consumer awareness. Companies are increasingly expected to demonstrate environmental responsibility, reduce carbon emissions, and adopt circular practices. Additive manufacturing is well-suited to meet these expectations, offering a pathway to greener, more resilient, and adaptable industrial systems.

In addition, the adoption of additive manufacturing supports the decentralization of production. By enabling localized manufacturing and reducing the need for extensive transportation and warehousing, it contributes to shorter supply chains, lower logistics costs, and reduced greenhouse gas emissions. This localization enhances supply chain resilience, allowing businesses to respond quickly to market fluctuations and disruptions.

Overall, additive manufacturing represents a paradigm shift in how products are conceived, developed, and delivered. Its integration with digital technologies and sustainable practices not only drives efficiency and innovation but also positions manufacturing enterprises to thrive in an increasingly dynamic and environmentally conscious global market. As the industry continues to evolve, the role of additive manufacturing will be central to achieving long-term sustainability, competitiveness, and growth. [8]

The novelty of this work lies in the integration of recycled polyvinyl butyral (PVB) as a sustainable feedstock with advanced additive manufacturing, utilizing programmable logic controllers (PLCs) for real-time process monitoring and optimization. This combined approach demonstrates how circular economy principles can be translated into practical digital manufacturing workflows, promoting efficiency, waste reduction, and enhanced traceability within industrial enterprises.

The scope of this paper encompasses the development and evaluation of a framework that connects material recycling, additive manufacturing, and industrial automation. Through detailed process analyses and a practical case study, the manuscript illustrates how digital enterprise concepts can be realized by merging these technologies, ultimately contributing to sustainability and operational improvement in modern manufacturing environments.

2. Current state of the issue

Additive manufacturing is a process of creating physical objects from digital models by layering and depositing material. It is an advanced manufacturing technology that creates 3D objects based on CAD drawings. Additive manufacturing is widely used in engineering, especially for custom products, medical applications, and conceptual models for the automotive industry. There are several types of additive manufacturing systems, including:

- FDM (Fused Deposition Modeling)
- DMD (Direct Metal Deposition)
- SLS (Selective Laser Sintering)
- IJM (Inkjet Modeling)
- SLA (Stereolithography)

FDM is the most widespread due to its simple operation and relatively low cost.

Today, the market offers countless materials for creating various objects. Each filament, representing the input material, has different specifications affecting the additive manufacturing process. The most commonly used filaments are: [5]

- **PLA (Polylactic Acid):** Ecological, but more difficult to handle after printing.
- **ABS (Acrylonitrile Butadiene Styrene):** Not ecological, but recyclable and easier to handle than PLA.
- **PVB (Polyvinyl Butyral):** A special resin used in automotive windshields. Legislation requires the recycling of cars and windshields, making recycled PVB easily obtainable.

The image shows a batch of cleaned and processed PVB granules collected in a plastic-lined container. These granules are produced from waste PVB, commonly sourced from decommissioned laminated automotive glass. Before use, the material is sorted and purified to remove contaminants, then shredded into small, uniform pellets ideal for extrusion into 3D printing filament. The uniform particle size enhances melt flow and consistency during filament production. Utilizing recycled PVB as a feedstock supports the circular economy by diverting polymer waste from landfills and enabling the development of sustainable additive manufacturing materials.

Figure 1 Recycled polyvinyl butyral (PVB) granulate prepared for additive manufacturing**.**

Polyvinyl butyral (PVB) is an advanced thermoplastic polymer with unique properties that make it increasingly relevant for additive manufacturing and sustainable production processes. Originally developed for use in safety glass, especially in the automotive and architectural industries, PVB has evolved into a versatile material with applications extending far beyond its initial purpose. PVB is known for its excellent adhesion, flexibility, toughness, and clarity. Its molecular structure is characterized by a high content of hydroxyl groups, which significantly influence its adhesion to various substrates and its compatibility with other polymers and additives. This makes PVB especially valuable in composite formulations and as a binder in multilayered materials. The hydroxyl content allows PVB to bond strongly with glass and other surfaces, which is why it is widely used in laminated safety glass. PVB exhibits good resistance to many chemicals and moderate thermal stability, making it suitable for various industrial applications. It offers a balance of flexibility and strength, enabling its use in products that require impact resistance and durability.

One of the most significant advantages of PVB in the context of modern manufacturing is its recyclability. End-of-life vehicles and building renovations generate large quantities of laminated glass, from which PVB can be recovered and processed into granulate form. This recycled PVB granulate serves as a valuable raw material for new applications, supporting circular economy principles. Legislation in many regions mandates the recycling of automotive glass, ensuring a consistent supply of post-consumer PVB. By reusing PVB, manufacturers can reduce the demand for virgin polymers, lower waste generation, and minimize the environmental footprint of their operations.

The use of recycled PVB in additive manufacturing is a promising development. Through extrusion processes, PVB granulate can be converted into filament suitable for 3D printing. This approach not only diverts waste from landfills but also provides a high-quality, customizable material for producing new components. Extruders melt and process PVB granulate, creating filaments that can be used in various 3D printing technologies. PVB filaments can be blended with other polymers or reinforced with fibers (such as carbon or glass fibers) to tailor mechanical and thermal properties for specific applications. The ability to continuously recycle and reuse PVB aligns with the goals of the circular economy, promoting resource efficiency and reducing reliance on non-renewable materials.

Beyond additive manufacturing, PVB's unique combination of properties enables its use in several advanced fields. As an interlayer in laminated glass, PVB enhances safety, sound insulation, and UV resistance in buildings. PVB films are used in photovoltaic panels, contributing to durability and performance. Its compatibility with fibers and other polymers makes PVB a valuable matrix material in lightweight composites for automotive, aerospace, and sports equipment. Ongoing research is focused on further improving the recyclability, processability, and performance of PVB-based materials. Innovations in separation technologies, additive formulations, and processing methods are expected to expand the role of PVB in sustainable manufacturing and high-performance applications. As industries continue to prioritize environmental responsibility and circularity, PVB stands out as a model material for the next generation of manufacturing practices. [9], [10]

With an extruder, it is possible to produce filament from recycled PVB, which can then be used as input material for additive manufacturing. The figure illustrates the operating principle of a polymer extruder, a device commonly used in additive manufacturing for producing filament from raw or recycled plastic materials.

- Component A: This section represents the hopper or feed chamber, where plastic granulate or pellets are loaded into the extruder. The granulate serves as the raw material for filament production.

- Component B: This is the barrel containing a rotating screw (or auger). As the screw turns, it transports the granulate forward, gradually heating and melting the material through friction and external heaters. The close-up shows the mixing and melting process, where the material is homogenized and pushed forward under pressure.

- Component C: This is the extrusion die or nozzle, where the molten polymer is forced out in a continuous strand. The extruded material cools and solidifies into filament, which can then be used for 3D printing.

This process enables the conversion of plastic waste or recycled materials into high-quality filament, supporting sustainable manufacturing practices and the principles of the circular economy. The extruder's ability to process various types of polymers, including recycled polyvinyl butyral (PVB), makes it a valuable tool for both material innovation and waste reduction in modern production environments. [1]

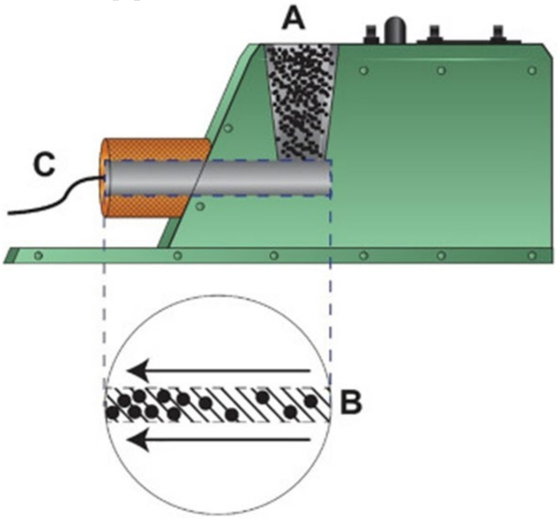

Figure 2 Schematic of the extruder operating principle for recycled PVB filament production.

The advantage of external extruders is the ability to produce filament from various materials, including recycled products or rejects. Most extruders also have a grinder for crushing 3D prints or waste. The output is a high-quality plastic fiber—filament—essential for additive manufacturing. Using recycled materials increases production sustainability and supports the circular economy.
The circular economy aims to move away from the classic linear model based on high consumption of non-renewable resources.

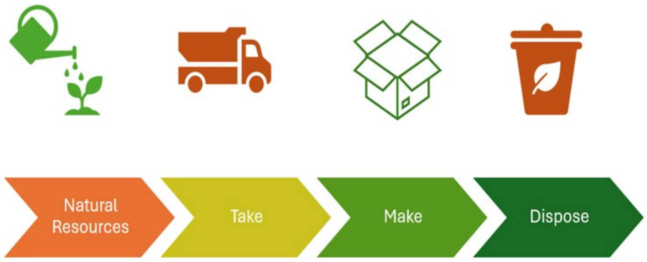

Figure 3 Linear model of economy: the "Take-Make-Dispose" approach. [12]

The linear economic model, often summarized as "Take-Make-Dispose," represents the traditional approach to industrial production and consumption. This model is characterized by a one-way flow of materials and resources, starting with the extraction of natural resources, followed by manufacturing, consumption, and ultimately disposal as waste.
In the first stage, natural resources are extracted from the environment to serve as raw materials for production. These resources are then transported and processed in manufacturing facilities, where they are transformed into finished products. After production, goods are distributed to consumers for use. Once these products reach the end of their useful life, they are discarded, typically ending up in landfills or incinerators, with little to no effort made to recover or recycle materials.

This approach is resource-intensive and leads to significant waste generation and environmental impact. The continuous extraction of finite resources accelerates their depletion, while the disposal of products contributes to pollution and ecosystem degradation. The linear model's lack of material recovery and reuse highlights its unsustainable nature, especially in the context of growing environmental concerns and resource scarcity. As industries and societies increasingly recognize these limitations, there is a growing movement toward more sustainable economic models, such as the circular economy, which emphasize resource efficiency, recycling, and minimizing waste. The linear model serves as a reference point for understanding why a transition to circular practices is necessary for long-term environmental and economic sustainability.
Its principle is a closed cycle of raw materials, preventing waste and landfilling. Material circulation ensures repeated use of materials in production. Modern technologies, such as extruders for producing filaments, enable material independence, which is the essence of the circular economy. Extruders also allow the production of new composite materials for engineering, medicine, or other fields. Polymer nanocomposites, especially those reinforced with carbon fibers, are of particular interest. These composites offer lower weight, high tensile strength, stiffness, and temperature resistance. Adding carbon fibers to PLA filaments reduces material shrinkage and increases durability and resistance to aggressive conditions. However, carbon fiber production is energy-intensive, costly, and environmentally challenging due to emissions.
The circular economic model represents a transformative approach to production and consumption, shifting away from the traditional linear "Take-Make-Dispose" process. Instead, it is based on the continuous circulation of materials and resources within the economy, aiming to minimize waste and maximize resource efficiency.
In this model, raw materials are extracted and used to manufacture products, but unlike the linear approach, the life cycle of products does not end with disposal. After their initial use, products and materials are systematically collected, reused, refurbished, or recycled, re-entering the production process as valuable inputs. This closed-loop system is designed to extend the lifespan of resources, reduce environmental impact, and decrease the dependence on finite natural resources.

Key elements of the circular economy include:

- Resource Efficiency: Materials are used for as long as possible, extracting maximum value before recovery and regeneration.
- Reuse and Refurbishment: Products and components are reused or refurbished to extend their useful life.
- Recycling: Waste materials are processed and transformed into new raw materials, closing the material loop.
- Sustainable Design: Products are designed for durability, repairability, and recyclability, supporting ongoing circulation.

The circular model reduces waste generation and environmental pollution, supports innovation in product design and business models, and fosters economic resilience by decoupling growth from resource consumption. As societies and industries increasingly adopt circular principles, this model is seen as essential for achieving long-term sustainability and addressing global challenges such as resource scarcity and climate change. [4]

Figure 4 Circular model of the economy illustrating the cyclical flow of resources from extraction, manufacturing, consumption, recovery, and back to production, highlighting the contrast with the traditional linear model [12]

2.1. Connecting Additive Manufacturing with Industrial Enterprises

The integration of additive manufacturing (AM) technologies, such as 3D printing, into industrial enterprises has become increasingly prevalent, offering significant benefits in terms of flexibility, efficiency, and data-driven production management. A key advancement in connecting AM with industrial settings is the use of Programmable Logic Controllers (PLCs). PLCs are specialized industrial computers designed to automate and monitor production processes. By linking 3D printers with PLCs, manufacturers can:

- Automate production workflows: PLCs enable real-time control of multiple machines, allowing for automated start, stop, and adjustment of 3D printing processes based on predefined parameters.
- Monitor critical parameters: Sensors attached to 3D printers can continuously measure variables such as print head temperature, chamber temperature, humidity, vibration, print quality, and energy consumption. This data is collected and processed by the PLC, enabling immediate responses to deviations or faults.
- Data archiving and analysis: All collected data can be stored for long-term analysis, supporting predictive maintenance, quality control, and process optimization. Historical data access simplifies troubleshooting and process improvement.

The connection between additive manufacturing and industrial enterprise systems yields several advantages:

- Enhanced process transparency: Real-time monitoring provides operators and engineers with a clear overview of ongoing production, facilitating quick decision-making.
- Remote control and diagnostics: Through networked PLCs, production lines can be supervised and adjusted remotely, reducing the need for on-site personnel and enabling rapid response to issues.
- Improved traceability: Each print job and its associated parameters can be tracked, ensuring traceability of parts for quality assurance and regulatory compliance.
- Energy and resource optimization: By analyzing sensor data, manufacturers can identify opportunities to reduce energy consumption and material waste, supporting sustainability goals.

The emergence of smart factories is transforming the manufacturing landscape. By combining additive manufacturing, PLCs, and Industrial Internet of Things (IIoT) devices, enterprises are creating interconnected systems where machines communicate autonomously to optimize production. This level of automation and data exchange enables real-time adjustments, improved resource allocation, and increased flexibility in responding to changing market demands.

Despite these advancements, several challenges must be addressed to fully realize the benefits of such integration. Interoperability remains a complex issue, as seamless communication between different brands and models of 3D printers, sensors, and PLCs is not always straightforward. Cybersecurity is also a critical concern; as manufacturing systems become more connected, protecting sensitive data and preventing unauthorized access are essential to maintaining operational integrity. Furthermore, workforce training is necessary to ensure that employees can operate and maintain advanced digital systems, requiring ongoing education and skill development.

Looking ahead, the digital transformation in manufacturing is expected to deepen the synergy between additive manufacturing and enterprise systems. Future developments will likely include greater automation and self-optimization of production lines, integration with enterprise resource planning (ERP) systems for comprehensive digital manufacturing and expanded use of artificial intelligence for real-time process control and optimization. By embracing these technological advancements, industrial enterprises can achieve higher productivity, flexibility, and sustainability, positioning themselves competitively in the rapidly evolving global market. [11]

2.2 Integration Challenges of PLCs and Additive Manufacturing Systems

Integrating PLCs with AM equipment faces several key challenges: [15], [16]

- **Interoperability:** Multiple vendors use different protocols (e.g., OPC UA, MQTT, proprietary APIs), complicating unified control and data exchange. Efforts to implement middleware or industrial IoT platforms can address this but add layers of complexity .
- **Cost Considerations:** Initial investment in automation hardware and software, along with operator training, represents a significant expense. However, long-term benefits include reduced downtime and higher product quality.
- **Cybersecurity:** Connecting AM systems to enterprise networks increases risks of unauthorized access, data tampering, and IP theft. Strategies such as network segmentation, firewalls, and regular firmware updates are crucial .
- **Scalability:** Custom integration solutions may be non-scalable. Use of open standards and modular hardware is recommended.

2.3 Case Study: PLC Integration in Additive Manufacturing for Digital Enterprises

A medium-sized industrial enterprise specializing in polymer-based additive manufacturing (AM) sought to increase production efficiency, traceability, and sustainability. The company used Fused Deposition Modeling (FDM) technology with recycled polyvinyl butyral (PVB) filament, aligning its operations with circular economy principles. However, the lack of centralized process monitoring and data-driven control limited productivity and consistency in quality.

To address these issues, the enterprise integrated Programmable Logic Controllers (PLCs) into its additive manufacturing systems. Each 3D printer was connected to a PLC, which interfaced with multiple sensors monitoring critical parameters such as print head temperature, humidity, vibration, and energy consumption. The PLCs were networked with the company's Industrial Internet of Things (IIoT) infrastructure, enabling real-time data exchange and remote control of production lines. Automated workflows were established, with the PLCs controlling machine start/stop sequences, material feed rates, and error recovery. Historical process data was stored and linked with product batches for complete traceability, while sensor data analysis enabled predictive maintenance, allowing maintenance teams to intervene before breakdowns occurred. In addition, PLC algorithms optimized energy use by reducing idle time and minimizing material waste, particularly when processing recycled PVB filament.

As a result, the enterprise achieved a 25% reduction in production downtime due to real-time diagnostics and predictive maintenance. Material waste decreased by 15% through precise control of extrusion parameters and the reuse of off-spec filament. Product quality and batch traceability improved, enhancing customer confidence and meeting regulatory standards. The enterprise also reduced its environmental footprint by combining additive manufacturing with circular economy practices, such as filament extrusion from recycled materials.

The primary challenges encountered during implementation were interoperability between different printer models and ensuring cybersecurity in the connected PLC-IIoT environment. Workforce upskilling was also necessary to enable operators to manage the new automated processes effectively.

This case demonstrates that PLC integration with additive manufacturing significantly improves efficiency, flexibility, and sustainability. By leveraging real-time data and digital enterprise tools, manufacturers can move toward Industry 5.0-ready operations. [13], [14]

Conclusion

Additive manufacturing is not only about creating 3D objects but also about the careful selection and preparation of materials that serve as the foundation for innovative production processes. The market offers a diverse range of commonly used and easily accessible materials, but what truly distinguishes modern additive manufacturing is the ability to develop new composite materials and to reprocess waste, giving discarded materials a second life through advanced technologies. This approach directly supports the principles of the circular economy, where the circulation and reuse of raw materials are essential for a more sustainable and resilient way of life.

The integration of additive manufacturing with digital technologies and industrial automation, such as programmable logic controllers (PLCs), further enhances the efficiency, traceability, and flexibility of manufacturing systems. By leveraging real-time data collection, predictive maintenance, and digital twins, enterprises can optimize production, minimize downtime, and respond rapidly to changing market demands. These advancements not only improve operational performance but also contribute to significant reductions in energy consumption and material waste. Moreover, the adoption of circular economy principles in manufacturing promotes environmental stewardship by reducing resource depletion, lowering greenhouse gas emissions, and minimizing landfill waste. It encourages innovation in product design, business models, and supply chains, fostering economic resilience and competitiveness in the global market. As industries continue to evolve, the synergy between additive manufacturing, digitalization, and circular economy practices will play a pivotal role in achieving long-term sustainability goals.

In summary, embracing these technologies and principles enables industrial enterprises to move beyond traditional linear models, paving the way for a future where productivity, environmental responsibility, and sustainable growth are harmoniously aligned.

The digitalization of production processes through PLC-supported data acquisition not only increases process transparency and traceability but also enables predictive maintenance and remote diagnostics, minimizing downtime and supporting more sustainable operations.

Acknowledgements

This article is a partial result of the project VEGA 1/0210/25 and KEGA 014TUKE-4/2025 granted by the Ministry of Education, Research, Development and Youth of the Slovak Republic.

References

[1] Byrley, P., Ariel Geer Wallace M., Boyes K. W., Rogers, K. Particle and volatile organic compound emissions from a 3D printer filament extruder. Vol 736, 20 September 2020, 139604.

[2] Stansbury, J. W., Idacavage, M. J. 3D printing with polymers: Challenges among expanding options and opportunities. Vol 32, January 2016.

[3] Giles, H. F., Wagner, J. R. Extrusion: The Definitive Processing Guide and Handbook. 2013.

[4] Circular Economy Institute. 2022. Circular Economy.

[5] Mohamed, O. A., Masood, S. H., Bhowmik, J. L. Optimization of fused deposition modeling process parameters: a review of current research and future prospects. 25 February 2015.

[6] Nunna, S., Ravindran A. R., Mroszckok, J., Creighton, C., Varley, R. J. A review of the structural factors which control compression in carbon fibres and their composites. Vol 303, 1 January 2023.

[7] Pakdel, E., Kashi, S., Varley, R. Wang X. Recent progress in recycling carbon fire reinforced composites and dry carbon fibre wastes. Vol 166, March 2021.

[8] European Commission. Digital Compass 2030: A Digital Decade, European Way. 2021.

[9] Zhang, X., Hao, H., Shi, Y., Ciu, J. The mechanical properties of Polyvinyl Butiral (PVB) at high strain rates. Vol 93, 15 September 2015.

[10] Olabisi, O., Adewale, K. Handbook of Thermoplastics. 2016.

[11] Alphonsus, E. R., Abdullah, M. O. A review on the application of programmable logic controllers (PLCs). Vol 60, July 2016.

[12] Tauberová, R., Knapčíková, L., Czarnecka-Komorowska, D., Matysiak, W., Hajkowski, J., Winczek, J., & Strametz, D. (2024, October). Application of Recycled Materials into Sustainable Manufacturing in the Context of Industry 5.0. In EAI International Conference on Management of Manufacturing Systems (pp. 19-29). Cham: Springer Nature Switzerland.

[13] Tartici, I., Kilic, Z. M., Bartolo, P.: A systematic literature review: Industry 4.0 based monitoring and control systems in additive manufacturing. *Machines* 11(7), 712 (2023).

[14] Stavropoulos, P.: Digital Twins of Manufacturing Processes Under Industry 5.0. In: *Advances in Artificial Intelligence in Manufacturing II: Proceedings of the 2nd European Symposium on Artificial Intelligence in Manufacturing*, Athens, Greece, October 16, 2024, p. 3. Springer Nature (2025).

[15] Martinov, G., Kovaleko, A.: Additive process equipment control system for integration into a flexible manufacturing system. In: *2019 XXI International Conference Complex Systems: Control and Modeling Problems (CSCMP)*, pp. 519–523. IEEE (2019).

[16] Parvanda, R., Kala, P.: Trends, opportunities, and challenges in the integration of the additive manufacturing with Industry 4.0. *Prog. Addit. Manuf.* 8(3), 587–614 (2023).