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Research Article

Review of the Progress of Additive Manufacturing (2010–2025): Manufacturing Systems, Process Modeling, and Industrial Relevance

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Abstract: Additive manufacturing (AM) has progressed from a prototyping-oriented technology to an emerging class of digitally enabled manufacturing systems with growing industrial relevance. However, despite substantial advances in process capabilities, its transition into robust, large-scale production remains uneven and highly constrained. This systematic review critically examines peer-reviewed AM literature published between 2010 and 2025, with a specific focus on process modeling, manufacturing system integration, and industrial deployment. The analysis reveals a clear evolution from early empirical process tuning toward physics-based, data-driven, and hybrid modeling approaches aimed at improving process stability, defect control, and repeatability. While these developments have significantly enhanced scientific understanding, their industrial impact has been limited by high computational cost, lack of model generalizability, fragmented monitoring frameworks, and persistent reliance on post-build inspection for certification. The review further demonstrates that industrial scalability has been driven more by system-level innovations—such as multi-laser platforms, in-situ sensing, and hybrid manufacturing lines—than by isolated process improvements. Nevertheless, these complex systems often introduce new vulnerabilities related to thermal management, control integration, and economic viability. Overall, the findings indicate that the primary barriers to widespread AM adoption are no longer rooted in process feasibility, but in system-level reliability, certification readiness, and integration within established manufacturing ecosystems. This review concludes that future progress in AM will depend on a shift from process-centric optimization toward system-engineered solutions that align modeling, monitoring, control, and manufacturing economics within an industrial context.

Keywords: Additive manufacturing; Process modeling; Manufacturing systems; Industrial integration; System-level reliability

1. Introduction

Additive manufacturing (AM) has transitioned from a niche prototyping technology to a strategically important manufacturing process for producing complex, high-value components. This transition has been driven not only by advances in layer-wise fabrication technologies but also by the increasing integration of AM into industrial manufacturing systems characterized by digitalization, automation, and data-driven control [1–3]. Unlike conventional manufacturing routes, AM enables unprecedented geometric freedom and functional integration; however, its widespread industrial adoption remains constrained by challenges related to process stability, scalability, and certification.

Over the past decade, research efforts have increasingly shifted from demonstrating geometric feasibility toward addressing manufacturing-relevant concerns such as repeatability, residual stress control, defect mitigation, and system-level integration [4,5]. In particular, the emergence of physics-based process models, in-situ monitoring technologies, and intelligent control architectures has significantly enhanced understanding of AM processes. Nevertheless, many of these advances remain confined to laboratory-scale demonstrations, with limited translation into robust industrial practice.

Existing review articles have predominantly focused on individual AM processes, material systems, or application domains. While valuable, such reviews often lack a system-level perspective that connects process modeling, manufacturing system design, and industrial deployment. For manufacturing engineers and decision-makers, this

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fragmented view complicates the evaluation of AM as a viable production technology.

Therefore, this study presents a systematic literature review of additive manufacturing research published between 2010 and 2025, with explicit emphasis on **manufacturing systems, process modeling, and industrial relevance**, in alignment with the scope of the *Journal of Manufacturing Processes*. By synthesizing developments across these dimensions, this review aims to (i) clarify how AM technologies have evolved toward industrial manufacturing systems, (ii) identify persistent technical and organizational barriers, and (iii) highlight research directions necessary for large-scale industrial adoption

2. Systematic Review Methodology

2.1 Review Protocol

The review methodology follows PRISMA principles adapted for manufacturing and process engineering research [6]. A predefined protocol ensured transparency, repeatability, and methodological rigor.

2.2 Research Questions

The review was guided by the following research questions:

1. How have additive manufacturing processes and process models evolved between 2010 and 2025?
2. What system-level developments have enabled industrial-scale AM adoption?
3. What challenges remain for AM as a manufacturing process?

2.3 Data Sources and Search Strategy

Literature searches were conducted using Web of Science, Scopus, Science Direct, SpringerLink, and IEEE Xplore. Keyword combinations included:“additive manufacturing” OR “metal additive manufacturing” AND “process modeling” OR “manufacturing systems” OR “industrial application”.

2.4 Inclusion and Exclusion Criteria

Only peer-reviewed journal articles published in English between 2010 and 2025 were included. Studies focusing solely on conceptual design without process or system analysis were excluded.

2.5 Study Selection (PRISMA)

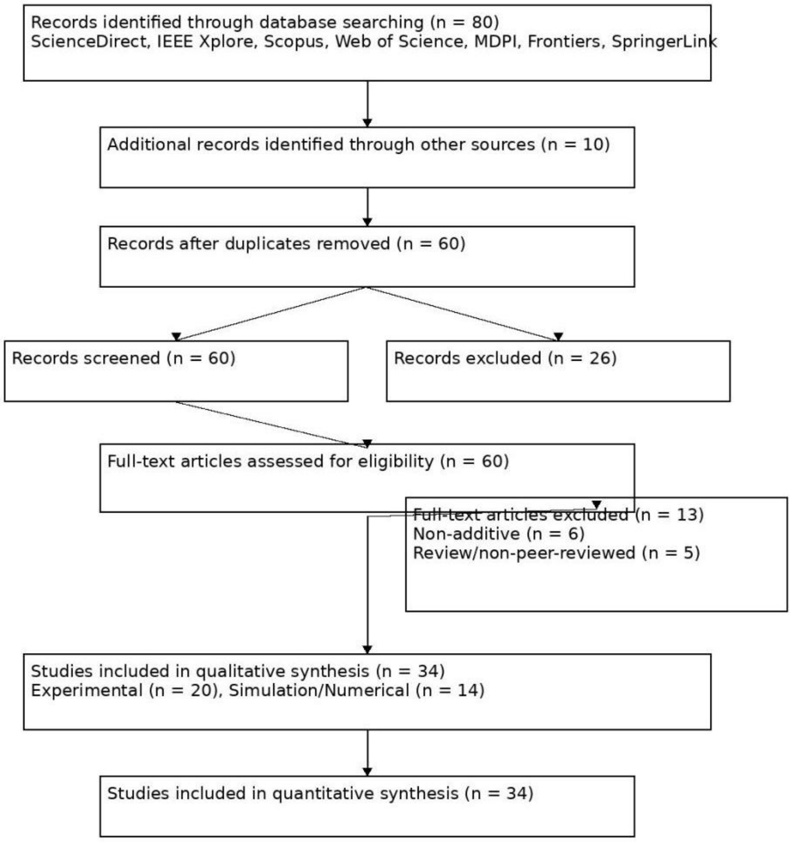

Figure 1. PRISMA flow diagram for systematic literature selection.

3. Evolution of Additive Manufacturing Processes and Modeling

3.1 Process Development and Stability

Early investigations into additive manufacturing (2010–2014) were predominantly driven by empirical parameter optimization aimed at achieving acceptable geometric fidelity and repeatability [7–9]. While these studies successfully established baseline processing windows, they largely treated AM processes as deterministic systems, overlooking inherent stochastic variations such as powder spreading inconsistencies, thermal fluctuations, and laser–material interactions. As a result, early process stability improvements were often machine-specific and exhibited limited transferability across platforms or materials.

Moreover, the reliance on trial-and-error optimization constrained scalability, as parameter sets calibrated for laboratory conditions frequently failed under industrial operating environments characterized by longer build times and higher thermal accumulation. This limitation motivated a shift toward physics-based modeling approaches capable of capturing process–structure relationships beyond empirical correlations.

3.2 Physics-Based and Numerical Process Modeling

Between 2015 and 2019, thermo-mechanical finite element models and computational fluid dynamics simulations became central to understanding defect formation mechanisms in metal AM processes [10–12]. These models significantly improved predictive capabilities for residual stress development, distortion, and melt pool dynamics. However, their industrial applicability remained constrained by high computational cost and the need for extensive material property datasets, many of which are temperature- and phase-dependent and not readily available for AM-specific alloys.

Furthermore, while physics-based models enhanced mechanistic understanding, they often operated in an offline mode, limiting their direct use in real-time process control. This disconnect between modeling fidelity and manufacturing responsiveness remains a critical bottleneck in deploying model-driven AM systems at production scale.

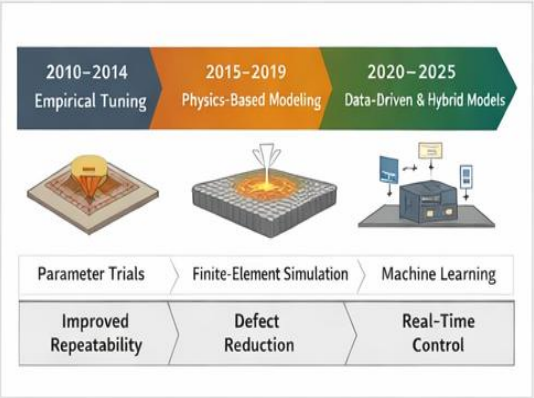

Fig 2. Multi-Scale Process Modeling In AM

3.3 Data-Driven and Hybrid Modeling Approaches

Recent research (2020–2025) has increasingly adopted data-driven and hybrid physics–machine learning models to overcome the limitations of purely numerical simulations [13–15]. These approaches demonstrate strong potential for real-time defect prediction and adaptive process control. However, their reliability is strongly dependent on training data quality, sensor calibration, and process consistency.

A key unresolved challenge is the generalizability of trained models across machines, materials, and geometries. Many reported machine learning frameworks achieve high predictive accuracy within controlled experimental datasets but exhibit degraded performance when transferred to industrial production environments. Consequently, hybrid modeling strategies that embed physical constraints within data-driven frameworks are emerging as a promising but still immature solution requiring further validation.

Table 1. Evolution of AM processes and modeling approaches.

Period	Dominant Focus	Manufacturing Impact
2010–2014	Empirical process tuning	Improved repeatability
2015–2019	Physics-based modeling	Defect reduction
2020–2025	Data-driven & hybrid models	Real-time control

4. Manufacturing Systems and Industrial Integration

4.1 Industrial AM Platforms

The transition from prototyping to industrial manufacturing has been enabled by the development of high-power, multi-laser powder bed fusion systems and large-scale directed energy deposition platforms [16–18]. These systems significantly expand build volume and deposition rates; however, increased system complexity introduces new challenges in process synchronization, thermal management, and inter-laser interference.

Notably, industrial scalability has often been achieved at the expense of process robustness, necessitating advanced monitoring and control strategies to maintain part quality across extended production cycles. This trade-off underscores the need to view AM not as a standalone process but as an integrated manufacturing system.

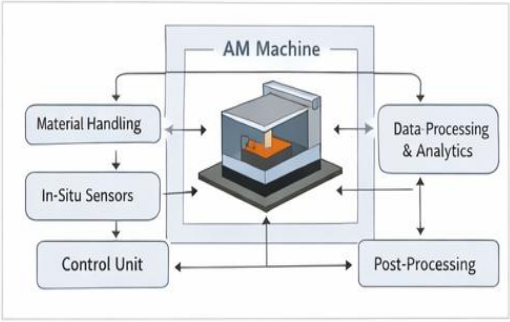

Figure 2. Industrial AM System Architecture

4.2 Monitoring, Control, and Quality Assurance

In-situ monitoring technologies, including optical imaging, pyrometry, and acoustic sensing, have become essential components of industrial AM systems [19–21]. While these tools enable defect detection, their effectiveness in closed-loop control remains limited by sensor latency, data processing speed, and the absence of standardized quality metrics.

Importantly, most industrial implementations currently rely on post-build inspection for certification-critical components, indicating that real-time quality assurance has not yet achieved sufficient maturity for widespread regulatory acceptance. Bridging this gap represents a key research priority for AM process certification and industrial trust.

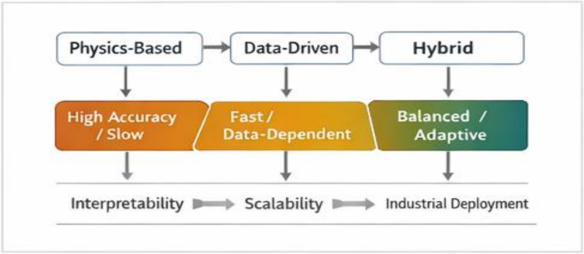

Fig. 3.Monitoring and Control in AM

4.3 Integration into Production Systems

Recent studies emphasize the integration of AM within hybrid manufacturing systems that combine additive, subtractive, and post-processing operations [22,23]. While such integration enhances dimensional accuracy and surface integrity, it also increases capital cost and system complexity. Consequently, industrial adoption remains concentrated in high-value, low-volume sectors where design flexibility offsets economic barriers.


Additive Manufacturing → CNC Machining → Surface Finishing → Automated Inspection

Figure 4. Hybrid Manufacturing Production Line

5. Comparative Summary of Major Additive Manufacturing Technologies

Table 2.Comparative summary of major additive manufacturing technologies with respect to process capability, materials, and industrial relevance (2010–2025).

AM Technology	Process Principle	Compatible Materials	Accuracy / Surface	Build Rate	Advantages	Limitations	Industrial Applications	Key Refs
Material Extrusion (FDM)	Thermoplastic extrusion	ABS, PLA, PEEK, composites	Low–Medium	Medium	Low cost, scalable	Anisotropy	Tooling, fixtures	[1,8,30]
Vat Photopolymerization	UV curing of resin	Photopolymers	Very High	Medium–High	Fine detail	Durability	Medical, dental	[1,8,25]
Powder Bed Fusion	Laser/e-beam melting	Ti, Al, steels	High	Low	High strength	Cost, stress	Aerospace, implants	[4,5,9]
Directed Energy Deposition	Energy-fed deposition	Metal wires/powders	Medium	High	Repair capability	Resolution	Repair, tooling	[17,18,22]
Binder Jetting	Binder on powder	Metals, ceramics	Medium	Very High	Fast production	Post-sintering	Automotive	[29,32]

6. Discussion

The reviewed literature indicates that additive manufacturing maturity is increasingly defined by system-level reliability rather than isolated process innovations. Despite substantial advances in process modeling and monitoring, AM systems still struggle to consistently meet industrial requirements for repeatability, certification, and cost competitiveness.

A notable disconnect persists between academic model development and industrial deployment, with many advanced models remaining underutilized due to computational or integration constraints. Addressing this gap requires closer alignment between process modeling, sensor development, and manufacturing system design.

7. Future Research Directions

Future research should prioritize:

- Scalable hybrid models capable of real-time deployment across platforms
- Standardized monitoring metrics linked to certification frameworks
- System-level optimization, rather than isolated process tuning
- Economic and sustainability assessments grounded in industrial data [31–34]

Without addressing these challenges, AM risks remaining a niche manufacturing solution rather than a broadly adopted industrial process.

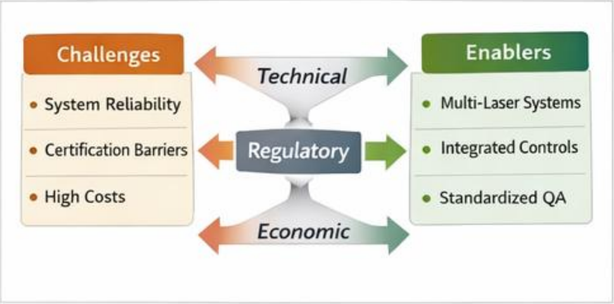

Figure 9. Future Development of Additive Manufacturing

8. Conclusion

This systematic review demonstrates that additive manufacturing has progressed beyond its prototyping origins toward an emerging class of digitally enabled manufacturing systems. Advances in process modeling, in-situ monitoring, and system integration have significantly improved process understanding and part quality, particularly in metal-based AM processes. However, industrial maturity remains uneven across technologies and application domains.

The analysis reveals that the primary limitations of AM are no longer rooted in basic process feasibility but in **system-level reliability, scalability, and integration with industrial production environments**. Despite the availability of sophisticated numerical and data-driven models, their adoption in industrial settings is often constrained by computational demands, data availability, and certification requirements. Consequently, many AM installations continue to rely on conservative processing strategies and extensive post-build inspection.

From a manufacturing systems perspective, AM should be viewed not as a replacement for conventional processes but as a complementary technology whose value is maximized when integrated within hybrid and automated production lines. Achieving this integration requires closer alignment between process modeling, real-time monitoring, control strategies, and manufacturing economics.

In conclusion, the future competitiveness of additive manufacturing will depend on its evolution from process-centric innovation to **system-engineered manufacturing solutions**. Addressing this challenge demands interdisciplinary research that bridges materials science, manufacturing engineering, control systems, and industrial engineering. The insights provided in this review offer a structured foundation for guiding both academic research and industrial implementation of additive manufacturing technologies.

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