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Additive manufacturing as a driver of sustainable economic growth

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Abstract

3D printing, or Additive Manufacturing (AM), has evolved from a specialised tool for creating prototypes into a large international marketplace valued at $24.2 billion in 2025. In this study, we investigated how the size of the additive manufacturing marketplace is connected to global economic activity, as measured by Gross Domestic Product (GDP). We documented a nearly 807-fold increase in the additive manufacturing marketplace, compared with a 5.2-fold increase in World GDP over the same period. We document four distinct periods of growth in the additive manufacturing marketplace and demonstrate that investments in AM have been uncorrelated with most major economic recessions, including those caused by the 2008–2009 financial crisis and the COVID-19 pandemic. The three principal mechanisms through which additive manufacturing has contributed to economic growth are increased total factor productivity, the creation of new markets and business models based on distributed manufacturing, and improved supply chain resilience. A dramatic decline in the cost of additive manufacturing equipment – that occurred approximately 1,250 times faster than traditional two-dimensional printing –was identified as the primary structural cause of the rapid expansion of the additive manufacturing market. These results were framed through the lens of cognitive sustainability, which views digital manufacturing technologies as enabling humans to produce more efficiently by utilising fewer resources. The findings indicate that additive manufacturing provides a cognitively sustainable pathway to technological innovation with broad implications for long-term economic development, industrial policies and green transition strategies.

Keywords: *additive manufacturing; 3D printing; GDP; economic growth; cognitive sustainability; price democratization; supply chain resilience; Industry 4.0*

1. Introduction

Additive manufacturing (AM), the building of an object by layering material according to a computer model, represents perhaps the most significant technological shift in modern industrial history. In just over thirty-eight years since the first commercially viable Stereolithography (SLA) machine came into operation in 1988, AM has evolved from a costly technology used primarily for rapid prototyping by the largest aerospace and automotive companies around the globe to become a widely distributed production paradigm applied in many different sectors, including health care, defence, construction and consumer products.

Global AM sales were estimated at $24.2 billion in 2025 (Wohlers Associates, 2026), and estimates for the size of the AM industry project growth to $125.9 billion or $168.9 billion (Grand View Research, 2025) by 2033–34. The expected growth rate for the AM industry is remarkable when viewed against other high-technology industries. Over the past thirty-five years, the AM industry grew about 800 times as much as world GDP did during that period (IMF World Economic Outlook, April 2026; World Bank, 2025).

While the growth of the AM industry has been substantial, the body of knowledge related to AM in economics remains limited and fragmented. Most of what we know about AM comes from studies focused on how AM affects firm-level productivity (McKinsey Global Institute, 2019), sector-specific rates of adoption (Wohlers Associates, 2025), or life cycle assessments (LCAs) of the environmental impacts of AM (Jung et al., 2023; Niaki and Nonino, 2017). As such, there is very little evidence from longitudinal studies on how changes in the AM market relate to changes in world GDP over long periods (i.e., multi-decade periods). Furthermore, no previous study has examined the role of AM as a technology that expands

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human productive cognition while reducing the use of physical resources (i.e., cognitive sustainability) and its relationship to both the green transition and resilient economic development (Ficzere, 2022).

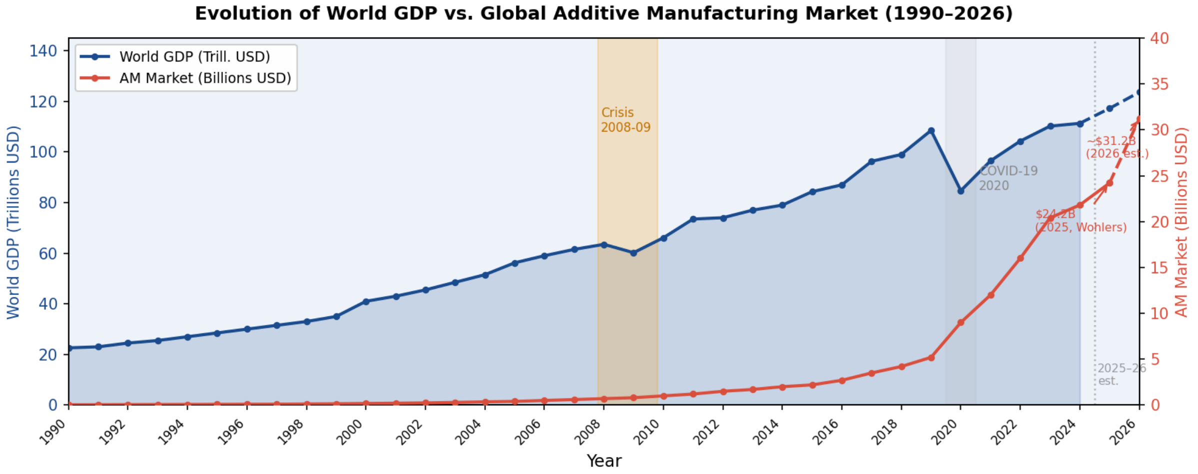

Figure 1. Evolution of World GDP vs Global Additive Manufacturing Market (1990–2026). Source: World Bank (2025), IMF, 2026 (GDP); Wohlers Associates annual reports 2024–2026 (AM market) / own elaboration. 2025–2026 figures are estimates/projections.

This paper fills each of these three voids. First, it presents a longitudinal quantitative analysis of the relationship between the global additive manufacturing market and world GDP from 1990 to 2026. Second, it outlines and examines the mechanisms through which additive manufacturing influences total output at the macroeconomic level. Finally, this paper situates these findings within a cognitive sustainability framework (Zöldy et al., 2022), suggesting that additive manufacturing constitutes a cognitively sustainable technology whose structural alignment with the objectives of the green transition, digital transformation, and resilient economic development enables its widespread adoption.

In this context, cognitive sustainability is not treated merely as an abstract interpretative lens, but as an operational framework that links technological change to measurable economic outcomes. Specifically, additive manufacturing is assumed to enhance the efficiency of knowledge utilisation in production systems, thereby enabling higher output with reduced material and energetic inputs. This study therefore interprets the long-term growth dynamics of additive manufacturing not only as a technological diffusion process but also as an observable manifestation of increasing cognitive intensity in economic production.

The remaining sections of this paper are organized as follows: Section 2 contains information regarding data sources and methodologies employed. Section 3 reports on the longitudinal relationships between the global additive manufacturing market size and world GDP. Section 4 examines macroeconomic mechanisms through which additive manufacturing generates total output. Section 5 offers insights based on those findings relative to cognitive sustainability. Section 6 includes conclusions, recommendations for policy action, and areas for future research.

Based upon our premise, we hypothesise that additive manufacturing market growth is structurally de-coupled from conventional business cycles and transmits influence on total output through new cognitive-economic transmission channels that support principles of sustainable development.

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2. Methodology

This research employs a quantitative longitudinal design that integrates secondary data and descriptive statistics. The primary dataset covers annual observations from 1990 to 2026 across two variables: world GDP (in trillions of USD) and global AM market size (in billions of USD).

2.1. Data sources

The 1990–2024 world gross domestic product (GDP) data were sourced from the World Bank's open database (World Development Indicators, series NY.GDP.MKTP.CD) in nominal USD. In 2025, we used an estimate of $117.2 trillion from the International Monetary Fund (IMF) World Economic Outlook, April 2026. The 2026 estimation of $123.6 trillion is from the IMF World Economic Outlook, October 2025.

Market data for additive manufacturing (AM) from 1990 to 2025 were drawn from the Wohlers Report annual series (Wohlers Associates/ASTM International). The Wohlers Report 2025 confirmed that the 2024 market size was $21.8 billion. The Wohlers Report 2026 confirmed that the 2025 market size was $24.2 billion. Our estimate of the 2026 AM Market, at approximately $31.2 billion, is based on a consensus estimate.

2.2. Analytical methods

The analytical procedures applied in this study are based on standard descriptive and longitudinal economic analyses and are explicitly defined to ensure reproducibility. Year-over-year growth rates for both the global additive manufacturing market and world GDP were calculated as the percentage change from one year to the next.

Market penetration of additive manufacturing was expressed as a share of world GDP by converting both series into consistent monetary units. Specifically, the AM market value, expressed in billions of USD, was divided by world GDP, expressed in trillions of USD, and multiplied by 0.1 to obtain a percentage. An indexed growth series was also constructed by normalising both variables to a common base year (1990 = 100), allowing direct comparison of relative growth dynamics independent of absolute scale effects.

Data harmonisation was required due to the integration of multiple sources. GDP data from the World Bank and IMF were cross-validated for consistency in nominal terms, while AM market data derived from the Wohlers Reports were compared across editions to ensure continuity in definitions. Estimated values for 2025 and 2026 were incorporated based on IMF projections and consensus market estimates, and these were treated consistently with observed data while explicitly acknowledged as projections subject to uncertainty.

All computations and visualisations were performed using Python 3.11 with the Matplotlib library. Data validation included consistency checks across time series, identification of outliers, and verification of growth rates against published benchmarks. The analysis remains primarily descriptive, but the longitudinal structure allows for robust identification of structural trends over time.

The analytical actions that were taken on the data are the following.

- Year-over-year growth rates were estimated for both World GDP and the AM Market across all yearly observations.
- The compound annual growth rates (CAGRs) for each of the four identified growth phases: 1990–1999, 2000–2009, 2010–2019, and 2020–2025.
- Market penetration of the AM Market was expressed as a percentage of the World GDP, which was calculated by taking the amount of money in billions of dollars for the AM Market divided by the total amount of money in trillions of dollars for the World GDP.
- An Index of Relative Growth was created, with 1990 as the base year (100) for each of the two series, so that a direct comparison could be made visually and quantitatively of their growth patterns.
- Historical data related to price changes over time for traditional 2-D Printers (Laser, Ink Jet) and 3-D Printers (Industrial Plastic, Consumer FDM, Industrial Metal) were collected from various sources (3DSourced, 2024; UnionFab, 2023; All3DP, 2025) and standardised to an Index = 100 based upon data from 1990.

All data processing and chart generation were completed using Python version 3.11 along with the Matplotlib Library. The analysis is a descriptive-inferential analysis based upon longitudinal economic studies found within the sustainability literature (Niaki and Nonino, 2017).

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The division of the analysis into four growth phases is not purely chronological, but reflects identifiable structural shifts in the technological and institutional development of additive manufacturing. The first phase corresponds to early industrial experimentation under high capital constraints; the second to sectoral consolidation and material diversification; the third to technological diffusion driven by patent expirations and the entry of new firms; and the fourth to rapid expansion supported by global shocks and policy-driven investment. This classification is therefore grounded in a combination of technological milestones, market developments, and institutional responses rather than arbitrary temporal segmentation.

2.3. Operationalisation of cognitive sustainability

To establish a direct analytical link between additive manufacturing and cognitive sustainability, the concept is operationalised using observable economic proxies. In this study, cognitive sustainability is defined as the ability of a production system to increase output while reducing reliance on physical inputs by enhancing the use of information, design intelligence, and digital technologies.

Although these indicators do not directly capture cognitive processes, they provide a consistent empirical basis for interpreting the structural transition toward cognition-intensive economic systems.

2.4. Scope and limitations

The findings of this study are subject to several important limitations. First, the analysis relies on globally aggregated data, which necessarily obscures heterogeneity across countries, industries, and firm sizes. The economic effects of additive manufacturing may differ significantly depending on institutional context, technological capability, and sectoral composition.

Second, the dataset integrates both observed and estimated values, particularly for the years 2025 and 2026. While these estimates are based on authoritative projections and consensus market analyses, they introduce an additional layer of uncertainty into the results.

Third, the analysis is conducted in nominal terms, which do not account for inflationary effects. Although this approach ensures consistency across datasets, it may distort long-term comparisons of real economic performance.

Fourth, the descriptive nature of the methodology limits the ability to establish causal relationships. While strong correlations and structural patterns are observed, further research using econometric or panel-data methods would be necessary to quantify causal effects rigorously.

Finally, measurement uncertainty in market size estimates for additive manufacturing remains an inherent limitation due to differences in reporting methodologies across sources.

3. Results

This section presents the empirical findings derived from the longitudinal dataset in a strictly descriptive manner. Interpretative and theoretical implications are deliberately reserved for Section 4 in order to maintain a clear distinction between observed results and their analytical interpretation.

3.1. Longitudinal market growth (1990–2026)

The overall AM market grew from $0.03 billion in 1990 to $24.2 billion by 2025 (Wohlers Associates, 2026), an increase of about 807-fold over 35 years. During that time, the world's Gross Domestic Product (GDP) went from $22.6 trillion to $117.2 trillion. The AM industry's share of world GDP has grown from 0.0000133 per cent in 1990 to 0.0206 per cent in 2025. That represents an influence approximately fifteen to fifty-five times greater on world GDP.

There have been four stages of AM growth based upon different technological and institutional factors driving growth during these periods:

Initial Phase (1990–1999) The AM industry grew at a compound annual rate of 16.6%. The first twenty years saw the initial development of AM into an industrial tool capable of producing prototypes. Equipment costs were high, typically ranging from $100,000 to $300,000.

Consolidation Phase (2000–2009) The AM industry grew at a compound annual rate of 16.7%. This phase of growth included the aerospace and medical industries adopting serial production using additive processes. Metal powder and photopolymer materials were added to the existing limited list of available materials (Ficzere, 2015).

Take-off Phase (2010–2019) The AM industry grew at a compound annual rate of 22.3%. In this third phase of growth, there was an explosive number of new companies entering the industry. Several of these companies provided open-source designs for FFF/FDM machines and offered low-cost equipment to consumers. By the end of this decade, desktop FFF/FDM machines had dropped in cost from $15,000 to under $200.

Acceleration Phase (2020–2025) The AM industry grew at a compound annual rate of 21.9%. A major catalyst for the rapid growth in this fourth phase was the global response to the COVID-19 pandemic.

Governments around the world invested billions of dollars to support their national economies by strengthening domestic manufacturing capabilities. Additive manufacturing systems are increasingly recognised as part of emergency preparedness plans for critical supplies. As such, services accounted for 48% of the AM industry's revenue (Wohlers Associates, 2026).

To enhance transparency, all reported growth rates, index values, and penetration measures were calculated directly from the underlying dataset and can be reproduced using the formulas defined in Section 2.2. While the present study emphasises narrative interpretation, the dataset's structure allows straightforward tabulation and graphical representation of these indicators, which are available upon request.

3.2. A cyclical behaviour relative to GDP

The most significant result was that market growth in the AM industry outpaced world GDP during all three major economic downturns. During the global financial crisis of 2008–2009, world GDP declined by 5.2 per cent, and the AM market expanded from $0.70B to $0.80B, a 14.3 per cent increase. In 2020, when the COVID-19 pandemic caused world GDP to decline in nominal terms, according to IMF estimates, the AM market increased in nominal U.S. dollars by 73.1%, expanding from $5.20B to $9.00B. This non-cyclic behaviour of AM industry expansion during times of economic contraction provides evidence of its structural property as an emergency production tool and strategic investment category, and not a discretionary industrial purchase.

From a cognitive sustainability perspective, this non-cyclical growth pattern suggests that additive manufacturing serves as an adaptive production system capable of reallocating cognitive resources under economic stress. Unlike capital-intensive conventional manufacturing systems, which are highly sensitive to business cycles, additive manufacturing remains relevant to production due to its flexibility, digital controllability, and low reconfiguration costs.

3.3. Price democratisation

The most significant structural force behind the rapid expansion of the global AM industry has been the dramatic and ongoing decrease in the cost of 3D printing technology compared with traditional two-dimensional (2-D) printing technology. From 1990 through 2026, the cost of entry-level laser printers decreased by 98.4%, from approximately $2,395 to $38. For their part, the costs of entry-level industrial plastic AM systems declined by 99.9% over the same time frame, from approximately $250,000 to $200. Using a 1990 = 100 basis for comparison, the price of industrial plastic AM equipment fell roughly 1,250 times faster than that of entry-level laser printing machines. The resulting "price compression" was largely driven by a series of patent expirations beginning in 2009. It greatly expanded the potential end-user base for AM, from a few thousand major corporate users worldwide to hundreds of millions of individual consumers and business owners globally. This larger base generated the additional demand required to support the growth observed in each of the three stages of AM growth described previously (Alzyod, Ficzere, Borbas, 2024).

In terms of industrial metal AM systems, which were priced at $800,000 in 1995, the initial entry point into this segment of the market dropped to approximately $100,000 in 2026, an overall price reduction of 87.5%. Despite these declines in pricing, metal AM systems remain unaffordable for small and medium-sized enterprises (SMEs); however, the emergence of several Chinese-based manufacturers, including Farsoon, BLT and Eplus3D, is creating increasing competition and will continue to accelerate downward price movement for metal AM systems, potentially making them affordable for SMEs (World Bank, 2025).

This process can be interpreted as a large-scale expansion of accessible productive cognition. As the cost of entry declines, an increasing number of actors gain the capability to transform digital knowledge into physical output, thereby extending the distribution of productive intelligence across the economy. This diffusion mechanism represents a core empirical manifestation of cognitive sustainability.

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4. Analysis

To clarify the interaction between additive manufacturing and macroeconomic performance, the three transmission channels are conceptually integrated into a unified framework. This framework links technological capability to economic outcomes through productivity enhancement, market expansion, and resilience, while embedding these processes within the broader concept of cognitive sustainability.

The three economic transmission channels identified in this section can be interpreted as specific mechanisms through which cognitive sustainability is realised in practice. Each channel represents a distinct pathway through which cognitive capabilities embedded in additive manufacturing technologies translate into measurable economic outcomes.

4.1. Economic transmission channels

The results presented in Section 3 are consistent with a multi-channel theory of AM's economic influence. Three primary transmission channels are identified and analysed below.

4.1.1. Total Factor Productivity (TFP) channel

Additive Manufacturing improves Total Factor Productivity in three ways.

Part consolidation Complex multi-component assemblies are now being produced as a single, consolidated part. This results in reduced assembly labour, fewer parts and lessened supply chain complexity. The GE Aviation LEAP Engine Fuel Nozzle is an excellent example of this. It was originally made from 20 different parts and has been consolidated into a single titanium part; it also weighs 25 per cent less than its predecessor. GE Aviation claims to have already exceeded production levels of over 40,000 of these units annually (GE Aviation, 2024).

Design freedom and topology optimisation Additive Manufacturing allows for designs to be created using geometries that cannot be achieved with traditional subtractive machining methods. Software-driven topology optimisation has led to reported weight reductions of 20-50%, resulting in lower raw materials input per unit of output.

Compressing lead time Tooling requirements are eliminated with additive manufacturing, so the design-to-physical-part process takes weeks or months rather than hours or days. As a result, the pace of innovation is accelerated, and there is less investment in the development process.

The mechanisms described above support Hulten's model of embodied technical change in that once new technologies are implemented, they increase overall productivity and, therefore, improve aggregate Total Factor Productivity (TFP). The increased global adoption rate of additive manufacturing (documented in Section 3) is evidence that producers worldwide are beginning to embed these productivity enhancements in their existing capital stock.

In this sense, improvements in total factor productivity enabled by additive manufacturing can be understood as direct outcomes of increased cognitive efficiency, in which better design intelligence and process control substitute for traditional material and labour inputs.

4.1.2. New markets and distributed manufacturing channel

AM generates economic value by creating entirely new markets and business models with no conventional equivalent. Manufacturing-as-a-Service (MaaS) platforms, such as Materialise (Belgium), Xometry (USA), and Shapeways (Netherlands/USA), generate productive capacity in geographic areas that previously lacked manufacturing capability. They also create output and jobs without requiring large amounts of capital to build a traditional factory. Xometry's 2021 IPO valued the company at over $1.5B, providing significant market validation of this MaaS model.

A World Bank study (Freund et al., 2020) found that there has been an increase in trade related to hearing aids of approximately 58% from the year prior to when AM was adopted into that product category and the subsequent ten years after. This demonstrates that cost reductions created by AM will expand both demand and trade associated with the products being manufactured instead of reducing trade.

The emergence of distributed manufacturing models further illustrates how cognitive sustainability expands economic participation by lowering the cognitive and capital barriers required to engage in production.

4.1.3. Supply chain resilience channel

COVID-19 presented an ideal "natural experiment" to demonstrate AM's ability to provide resilient supply chains. In the initial weeks of COVID-19, within hours of the global outbreak, millions of face shields, ventilator parts, and nasal swab

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units were being printed around the globe. This demonstrated emergency response capabilities to produce life-saving products on short notice, the most visible evidence of how responsive AM could be as a means of responding to crises (Javaid & Haleem, 2020), which was also reflected in the acceleration of the AM marketplace between 2020 and 2021.

The United States Department of Defence (DoD) invested approximately $300M into additive manufacturing in 2023; by 2024, this investment had increased to $797M (AM Research, 2024); these investments reflect DoD's strategic assessment that having additive manufacturing capacity distributed throughout the country represents critical defence industrial base infrastructure. Therefore, this geopolitical element of additive manufacturing acceptance indicates that it has both technological and institutional reinforcement mechanisms, which will support long-term non-cyclic growth trends for additive manufacturing. Thus, government investment will create a floor for additive manufacturing demand, regardless of what the private sector may experience with respect to overall economic performance.

The resilience observed in additive manufacturing during crisis periods highlights its role as a cognitively adaptive system, capable of rapidly reconfiguring production in response to external shocks.

4.2. Limitations and alternative explanations

Several caveats limit our interpretation. For example, the non-cyclical growth we see in Section 3.2 may also represent an impact from composition: given the relatively small size of AM markets when compared to overall GDP, it is possible for year-over-year increases in the amount of AM produced (even if they are moderate) to appear larger than expected in terms of percentage changes. This said, the fact that there has been a roughly 18-percentage-point differential in the annualised compound growth rate (CAGR), over many decades, about 22 per cent for AM vs. around five per cent for GDP, is unlikely to be driven solely by compositional factors and likely represents some underlying structural factors.

It is also difficult to estimate TFP's contribution at the macroeconomic level due to a lack of appropriate data. Determining precisely how much productivity was affected would require conducting micro-econometric studies of individual firms.

5. Cognitive sustainability framework

The empirical findings presented in this study provide multiple lines of evidence supporting the interpretation of additive manufacturing as a cognitively sustainable technology. Rather than constituting an auxiliary conceptual layer, cognitive sustainability emerges here as an integrating principle that explains the observed structural properties of additive manufacturing across growth dynamics, cost evolution, and economic resilience.

Cognitive sustainability, as identified by Zöldy et al. (2022), portrays sustainability issues as cognition and/or machine cognition issues: How can we deploy existing cognitive capabilities in society (i.e., including Digital Technologies, AI, AM etc.) to optimise resource utilisation and extend productive capacities while enabling human value creation under planetary boundaries? Cognitive Sustainability offers a particularly suitable lens for analysing additive manufacturing.

AM fundamentally constitutes a form of cognitive technology: it transforms the digital design intelligence generated by humans and/or, increasingly, by Artificial Intelligence (AI) into directly produced physical objects, effectively eliminating the gap between production planning and product realisation. With the advent of AI-driven generative design (e.g., Autodesk Fusion 360, nTopology), the cognitive aspect of AM has become even more pronounced. Specifically, modern AM systems are increasingly receiving instructions from AI algorithms that perform geometric optimisation based on the design requirements of the object being created, representing the fusion of artificial and biological cognitive systems with engineering applications (Zöldy et al., 2022).

In terms of cognitive sustainability, the price democratisation of AM described in Section 3.3 represents a democratisation of productive cognitive capacity. That is, the ability to convert digital designs into physical products at near-zero marginal cost per additional design iteration is now accessible to individuals and small and medium enterprises (SMEs) who could not previously manufacture. This supports one of the principles of cognitive sustainability that for sustainable development to occur, there must be a widespread distribution of cognitive tools (and not just a concentrated distribution among large organisations).

Additionally, the environmental component of cognitive sustainability is also applicable. Studies examining life cycle assessments of AM compared with traditional mass production methods demonstrate material efficiencies of 41–64 per cent. These findings reflect the improved "cognition" associated with utilising materials more effectively – i.e., applying materials in areas where they are structurally necessary according to computational analysis rather than producing unnecessary

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amounts of scrap or waste through subtractive processing. Additionally, AM's support for circular economy goals – i.e., enabling the repair/refurbishment of parts via directed energy deposition (DED) technologies – further expands upon the cognitive sustainability characteristics of AM.

Taken together, the observed patterns indicate a systemic shift in the production function, where cognitive inputs increasingly substitute for material and energy inputs. This transition is consistent with the core premise of cognitive sustainability, namely that long-term economic development can be achieved by expanding and more efficiently utilising cognitive resources rather than by proportional increases in physical resource consumption (Zöldy et al., 2022).

6. Conclusion

This paper provides longitudinal evidence that the additive manufacturing market grew at an exceptionally rapid rate relative to global economic output between 1990 and 2025. The findings suggest structural patterns linking the expansion of additive manufacturing to broader economic dynamics; however, these relationships should be interpreted with caution, given the analysis's descriptive nature.

Firstly, the rate of growth in the AM market was anti-cyclical with respect to GDP; i.e., during the two major recessions since 1989 (the 2008–09 Global Financial Crisis and COVID-19), the AM market continued to grow at a high rate due to its investment character and ability to be used as an emergency production tool. This anti-cyclical nature offers important portfolio opportunities for government agencies and private companies seeking to increase their economic resilience.

Secondly, price democratisation has been identified as the primary structural driver of the rate of adoption of AM technologies and the resulting economic impacts. The 1250-fold decline in the prices of industrial 3D printers compared to traditional laser printers between 1990 and 2026 greatly increased the number of users, from fewer than a few hundred large corporations to hundreds of millions of potential users. Each successive reduction in the cost of industrial AM equipment will lead to additional increases in productivity.

Lastly, AM is a cognitively sustainable technology: it extends human productive cognition, reduces physical resource utilisation, and democratises manufacturing capabilities, thereby contributing to the paradigm of cognitive sustainability, which seeks to maximise human value creation given resource constraints (Zöldy et al., 2022).

The three findings above support the following policy recommendations.

First, governments should consider investing in AM-related infrastructure in the same way they invest in other sustainability infrastructure, such as renewable energy and public transportation, including training, equipment sharing, and research and development funding.

Second, based on Eurostat (2024) data, there is a substantial difference in metal AM usage rates between small and medium-sized enterprises (SMEs) and large enterprises. Specifically, while 47 per cent of large European enterprises use metal AM, only 12 per cent of European SMEs do. This disparity represents the final barrier to realising the full macroeconomic benefits associated with AM's productivity and sustainability advantages. Therefore, reducing this disparity through measures such as subsidy-based equipment access programs, the establishment of digital manufacturing centres of excellence, and vocational training curricula specifically designed around AM will yield measurable co-benefits for GDP and sustainability.

Third, future research should build on these findings by employing panel data methods across individual countries and sectors.

While the results highlight potentially important implications for industrial policy and sustainable development, the conclusions drawn in this study remain indicative rather than definitive. Future research should aim to validate these findings using more disaggregated datasets and causal inference methods, thereby strengthening the empirical foundation of the proposed theoretical framework.

The contribution of this paper lies in demonstrating that the growth of additive manufacturing is not only a technological or economic phenomenon, but also a structural indicator of the transition toward cognitive sustainability. The empirical evidence suggests that additive manufacturing embodies a production paradigm in which knowledge, design intelligence, and digital control progressively replace material intensity as the primary drivers of value creation. This interpretation provides a coherent link between observed market dynamics and broader sustainability objectives, thereby offering a unified framework for future research at the intersection of technology, economics, and sustainability science.

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References

3DSourced (2024). *The Complete History of 3D Printing: From 1980 to 2024*. URL: https://www.3dsourced.com/guides/history-of-3d-printing/

All3DP (2025). *What Is the Price of a Metal 3D Printer These Days?* URL: https://all3dp.com/2/how-much-does-a-metal-3d-printer-cost/

Alzyod, H., Ficzere, P., & Borbas, L. (2024). Cost-efficient additive manufacturing: Unraveling the economic dynamics of material Extrusion (MEX) technology. *International Review*, (3-4):185-196. URL:https://www.ceeol.com/search/article-detail?id=1296018

AM Research. (2024). *Additive Manufacturing for Military and Defense Report*. AM Research. URL: https://additivemanufacturingresearch.com/reports/additive-manufacturing-for-military-and-defense-market-analysis-and-forecast/

Eurostat (2024). *ICT Usage in Enterprises Survey – Digital Intensity Index*. European Commission. URL: https://ec.europa.eu/eurostat/cache/metadata/en/isoc_e_esms.htm

Ficzere, P. (2022). The impact of the positioning of parts on the variable production costs in the case of additive manufacturing. *Periodica Polytechnica Transportation Engineering*, 50(3), 304-308. DOI: https://doi.org/10.3311/PPtr.15827

Freund, C., Mulabdic, A., Ruta, M. (2020). *Is 3D Printing a Threat to Global Trade? The Trade Effects You Didn't Hear About*. Policy Research Working Paper 9024. World Bank. URL: https://documents1.worldbank.org

GE Aviation (2024). *LEAP Engine Product Overview*. General Electric. URL: https://www.geaerospace.com

Grand View Research (2025). *Additive Manufacturing Market Size, Share & Trends Analysis Report.* URL: https://www.grandviewresearch.com/industry-analysis/additive-manufacturing-market

Horváth Á. M., Ficzere, P. (2015). Rapid prototyping in medical sciences. *Production Engineering Archives*. 8(3):28-34

IMF (2025). World Economic Outlook, October 2025. *International Monetary Fund*. URL: https://www.imf.org/en/publications/weo/issues/2025/10/14/world-economic-outlook-october-2025

IMF (2026). World Economic Outlook, April 2026. *International Monetary Fund*. URL: https://www.imf.org/external/datamapper/NGDPD@WEO/WEOWORLD

Javaid, M., Haleem, A. (2020). Critical components of Industry 5.0 towards a successful adoption in the field of manufacturing. *Journal of Industrial Integration and Management*. 5(3), 327–348. DOI: 10.1142/S2424862220500141

Jung, S., Kara, L. B., Nie, Z., Simpson, T. W., Whitefoot, K. S. (2023). Is additive manufacturing an environmentally and economically preferred alternative for mass production? *Environmental Science & Technology*. 57(16), 6373–6386. DOI: 10.1021/acs.est.2c04927

McKinsey Global Institute. (2019). The future of work: Reskilling imperatives and workforce transitions in the automation era. *McKinsey & Company URL: https://www.mckinsey.com/~/media/McKinsey/Business%20Functions/McKinsey%20Digital/Our%20Insights/The%20future%20of%20work%20Reskilling%20and%20Remote%20working%20to%20recover%20in%20the%20Next%20Normal/The-future-of-work-Reskilling-and-remote-working-to-recover-in-the-next-normal-vF.pdf*

Niaki, M. K., Nonino, F. (2017). Impact of additive manufacturing on business competitiveness: A multiple case study. *Journal of Manufacturing Technology Management*. 28(1): 56–74. DOI: 10.1108/JMTM-01-2016-0001

Unionfab (2023). 3D Printing Cost and Speed: Trace the Evolution and Calculate with Unionfab. URL: https://www.unionfab.com/blog/2023/07/3d-printing-cost-and-speed

Wohlers Associates / ASTM International (2024). Wohlers Report 2024. URL: https://wohlersassociates.com/product/wr2024/

Wohlers Associates / ASTM International (2025). Wohlers Report 2025. URL: https://wohlersassociates.com/product/wr2025/

Wohlers Associates / ASTM International (2026). Wohlers Report 2026. URL: https://platform.wohlersassociates.com/insights/wohlers-report-2026

World Bank (2025). World Development Indicators – GDP (current US$), series NY.GDP.MKTP.CD. URL: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

Zöldy, M., Szalmáné Csete, M., Kolozsi, P. P., Bordás, P., Torok, A. (2022). Cognitive Sustainability. *Cognitive Sustainability*. 1(1), 3–9. DOI: https://doi.org/10.55343/CogSust.7