



## Key Performance Indicators (KPIs) in Additive Manufacturing: Evaluation of Efficiency, Quality and Sustainability in 3D Printing Processes

Domingo Noé Marrón Ramos<sup>1</sup>, Santos Guadalupe León Escalante<sup>2</sup>, Olvera Camarillo Víctor<sup>3</sup>,  
Enrique de Jesús Mohedano Torres<sup>4</sup>, Marrón Hernández Uriel Noe<sup>5</sup>

<sup>1,2,3,4,5</sup> Tecnológico Nacional de México Campus Pachuca

**ABSTRACT:** As a researcher specializing in additive manufacturing (AM), I have authored this study titled "Key Performance Indicators (KPIs) in Additive Manufacturing: Evaluation of Efficiency, Quality, and Sustainability in 3D Printing Processes." The work explores AM's explosive growth, with the global market at 21.9 billion in 2025, projected to hit USD 647.7 billion by 2035 at a 22-23% CAGR, driven by innovations in materials, AI integration, and applications in aerospace, automotive, and biomedicine. AM transforms traditional manufacturing through on-demand production, waste reduction, and supply chain optimization, supporting circular economy principles via localized fabrication and emission cuts.

Utilizing the SALSA methodology, conducted a systematic review of 158 articles (narrowed to 10 key studies from 2015-2025), identifying AM-specific KPIs: efficiency (adapted OEE, varying with build variety); quality (tensile strength up to 55.2 MPa, dimensional deviation 0.048 mm); sustainability (energy consumption, recyclability challenges in PLA/ABS); costs; and delivery times.

Limitations include adapting traditional metrics to AM's anisotropy and variability, plus unstandardized sustainability data. A pilot test on 10 parts across five hypothetical Hidalgo companies yielded averages like 74.4% OEE and 83.9% material efficiency, underscoring AI's role in optimization. Ultimately, robust KPIs foster informed AM adoption, aligning with a SDGs 9 and 12 for resilient, sustainable industries.

**KEYWORDS:** Additive Manufacturing, Efficiency, Key Performance Indicators, Quality, Sustainability

### INTRODUCTION

Currently, Additive Manufacturing (AM) has experienced high growth in recent years for global industrial environments, which has allowed it to consolidate itself as a disruptive technology in the worldwide industrial landscape. According to current research, the global additive manufacturing market reached \$44.62 billion in 2024, expanding at a compound annual growth rate (CAGR) close to 23% for the 2025 to 2033 period (Business Research Insights, 2025).

Therefore, these data align with other sources that highlight a significant increase: for example, the global market was valued at \$113.1 billion in 2025 and growth is projected to reach approximately \$647.7 billion by 2035, driven by advances in materials and industrial applications.

In this regard, according to the Wohlers Report 2025, the global AM industry grew 9.1% in 2025, reaching a total of \$21.9 billion, with a growing focus on the integration of technologies such as artificial intelligence and automation to improve scalability.

In this context, other projections indicate variations according to the segment: the metallic AM market is estimated at \$6.68 billion in 2025, with projected growth to \$13 billion by 2035, at a CAGR of 6.9%, highlighting its role in sectors such as aerospace and automotive.

Therefore, in general terms, the global market could reach \$195.6 billion by 2035, with a CAGR of 22.13% from 2025, reflecting a massive adoption in regions such as North America and Asia-Pacific.

Derived from the above, the expansion reflects not only the growing adoption of 3D printing technologies, but also their potential to transform traditional manufacturing: on-demand production, complex geometric parts, reduction of material waste, mass customization, and operational flexibility (Revistas ULima, 2023).

Specifically, AM allows for optimizing supply chains by minimizing inventories and enabling localized manufacturing, which helps reduce logistics costs and times, and the emissions associated with transportation (Ghobadi et al., 2024). Additionally, in a context of sustainability in competitive environments worldwide, AM contributes to the circular economy through material reuse and waste minimization, depending on energy efficiency and process management (Gao et al., 2023).



Recent studies prioritize that, by 2025, innovations in hybrid materials derived from 3D printing and high-speed processes are driving a shift toward mass production, with applications in industries such as biomedicine, where implant customization based on printing reduces recovery times and hospital costs.

However, these benefits are not automatic, given that they require rigorous evaluation to ensure effective integration in industrial environments. For AM to be a viable solution in productive contexts, it is not enough to declare its advantages: it is necessary to measure its performance through key performance indicators (KPIs) that allow for evaluating efficiency, quality, sustainability, and economic viability, with clear quantitative data adapted to its particularities.

Therefore, various recent studies show that, although AM can offer environmental and material advantages, traditional metrics do not always adapt well to the additive context, due to unique factors in printing and material preparation such as preparation times, mixed builds, waste from supports, post-processing, variability in parts, and mechanical anisotropy (Basak, Baumers, Holweg, Hague y Tuck, 2022; Amicarelli et al., 2025).

In this context, in metallic processes, KPIs must consider energy consumption and recyclability to measure real sustainability, given that AM can reduce emissions compared to conventional methods, but only under optimized conditions (Gao et al., 2023; 3DAdept Media, 2025).

In addition to the above, the literature prioritizes the need for AM-specific KPIs, such as printer utilization rates, dimensional precision, and energy efficiency, which must contemplate challenges like variability in mechanical properties and lack of standardization (Martínez y López, 2024; StartUs Insights, 2025).

Therefore, these indicators not only facilitate comparison with subtractive processes, but also support decision-making in technology adoption, especially in a market facing barriers such as high initial costs and training needs (Advanced Manufacturing, 2025).

Meanwhile, in 2025, trends such as the integration of AM with AI for design optimization and expansion in additive construction (for example, 3D printing of housing) highlight the importance of KPIs that measure not only operational efficiency, but also social and environmental impact, such as carbon footprint reduction in large-scale projects.

In another sense, another key aspect is the evolution of KPIs toward more integrated metrics, which include aspects such as scalability and interoperability between systems. For example, surveys of industry executives in 2025 reveal that the main challenges include process standardization and ROI measurement in AM, with an emphasis on KPIs that evaluate production speed and consistent quality in high volumes.

This is particularly relevant in emerging sectors such as bioprinting, where KPIs must incorporate biological metrics, such as post-printing cell viability, along with traditional efficiency indicators. In summary, the development of a robust KPIs framework is essential to overcome current limitations and maximize the potential of AM in an increasingly digitized industrial ecosystem.

Therefore, this research or article proposes a systematic literature review, based on current literature, with the aim of systematizing a set of relevant KPIs for AM, with figures when available, in order to facilitate its practical implementation in industrial and academic environments. By integrating recent market data and performance analyses, it seeks to contribute to a more informed and sustainable adoption of the technology, paving the way for future innovations that align AM with global sustainability and efficiency objectives.

## METODOLOGY

For the development of this research, a systematic literature review was employed based on recent scientific studies (starting from 2015, except for important classics in the literature) related to Additive Manufacturing (AM). The information was obtained using the SALSA methodology (Search, Appraisal, Synthesis, Analysis), a sequential framework proposed for systematic reviews that ensures a structured and rigorous approach (Grant & Booth, 2009). This methodology is divided into four main stages:

- Search: An exhaustive search was conducted in academic databases such as Scopus, Web of Science, Google Scholar, and Redalyc, using key terms like "key performance indicators in additive manufacturing," "KPIs for 3D printing," "sustainability in additive manufacturing," and "efficiency metrics in AM." The search was limited to publications between 2015 and 2025 to focus on recent advances, considering only peer-reviewed articles, market reports, and systematic reviews. Initially, 158 relevant articles were identified, aligning with previous reviews in the field (Ghobadi et al., 2024).
- Appraisal: The sources were evaluated considering their relevance to the topic of KPIs in AM, methodological rigor (for



example, use of quantitative data, simulations, or empirical studies), and their direct contribution to understanding indicators such as operational efficiency, quality, sustainability, and recyclability. Non-empirical studies or those with low impact were excluded, resulting in a final selection of 10 key studies.

- Synthesis: The selected studies were organized in a comparative table, categorizing elements such as country of origin, application, objective, results, and problem. This structure allows for a systematic comparison of how different authors address topics such as operational efficiency, the quality of printed parts, process sustainability, material recyclability, and market growth.
- Analysis: Through this synthesis, patterns, gaps, and relevant contributions were identified that underpin the subsequent analysis and the proposal of indicators to evaluate performance in AM. This strengthens the methodological coherence of the study and establishes a bridge between the theoretical review and the applied analysis.

The following table gathers the selected studies for the analysis, organized according to the key elements necessary to understand their contribution to AM.

**Table I. Characteristics of Standard 14000 in Eco-Labels**

N°	Article Name	Country	Application	Objective	Results	Problem
1	Reducing production losses in additive manufacturing using Overall Equipment Effectiveness (Basak et al., 2022)	United Kingdom	Efficiency of additive manufacturing equipment	Adapt the OEE indicator to the 3D printing context to measure losses, availability, and performance	Identify losses due to downtime, long setups, and mixed builds; OEE decreases in high-variety environments.	Lack of suitable indicators for AM; inefficiency due to configuration changes.
2	Quantitative sustainability assessment of metal additive manufacturing: A systematic review (Gao et al., 2023)	United States	Metallic additive manufacturing	Evaluate environmental and energy sustainability of metallic AM at the life cycle level	AM can reduce energy, emissions, and material in complex, high-value, low-volume parts.	High initial energy consumption; lack of environmental measurement standards.
3	Examining the process in additive manufacturing in supporting lean, green and sustainable manufacturing (Ghobadi et al., 2024)	Iran	Additive manufacturing in lean/green systems	Analyze if AM contributes to sustainable and efficient manufacturing.	AM reduces waste, enables customization, and improves productive flexibility.	Lack of integration of specific sustainable metrics; variability in real impact.
4	Advancing sustainable practices in additive manufacturing: material waste recyclability (Chen et al., 2024)	China	Recycling of 3D printing waste	Evaluate recyclability of plastic materials in AM (PLA, ABS, PETG).	Recycling limited by contamination, polymer mixtures, and additives; efficiency depends on cleanliness and purity.	Low recycling efficiency; much of the residue cannot be reused.
5	Evaluation of efficiency in the PolyJet additive	Mexico	Mechanical and	Evaluate orientation, layer thickness, and	0° orientation and 16 μm layer, higher resistance (55.2	High variability according to orientation;



	manufacturing process with Digital ABS (Martínez & López, 2024)		dimensional quality	variability in PolyJet parts.	MPa) and better precision (0.048 mm).	anisotropy reduces properties.
6	Additive manufacturing as elements of innovation in productive processes (Revistas ULima, 2023)	Peru	Industrial innovation	Analyze the role of 3D printing in modern productive processes.	AM enables customization, time reduction, and greater flexibility.	Limits technological adoption in traditional environments.
7	Additive Manufacturing Market Report 2025-2033 (Business Research Insights, 2025)	International	Global market	AM Project market trends and growth of the AM industry.	2024 market: USD 44.6B; 2025: USD 54.9B; annual growth 23%.	High adoption costs; barriers for small businesses.
8	What are the key performance indicators for a good (metal) AM production? (3DAdept Media, 2025)	International	KPIs in metallic AM	Identify KPIs for metallic processes such as DED, Cold Spray, and extrusion.	KPIs include deposition rate, dimensional precision, and energy efficiency; emphasis on scalable production.	Lack of standardized metrics for emerging metallic processes.
9	Additive Manufacturing Report 2025: Key Data & Innovations (StartUs Insights, 2025)	International	Innovations and KPIs in AM	Analyze growth and key metrics in AM.	Growth of 16.32%; KPIs focused on scalability and hybrid materials.	Barriers to mass adoption due to costs and standardization.
10	Wohlers Report 2025 shows 9.1% AM industry growth (Wohlers Associates, 2025)	International	AM industrial growth	Report market trends and KPIs.	9.1% growth in 2025; KPIs include ROI and consistent quality.	Challenges in ROI measurement and process standardization.

Source: own elaboration. (2025).

Therefore, the information presented in the table allows observing how each study provides a specific perspective on the challenges and opportunities of Additive Manufacturing (AM). The identified problems, which include operational inefficiency, quality variability, recycling limitations, and high energy requirements, are contrasted with results that demonstrate significant advances in precision, sustainability, productive flexibility, and market growth. This comprehensive comparison provides a solid foundation for understanding the current state of the technology and serves as a starting point for defining key performance indicators (KPIs) that respond to the real needs of the sector

**Current State of Additive Manufacturing**

A recent study quantitatively analyzes the sustainability of metallic additive manufacturing from a life cycle perspective, concluding that AM can reduce environmental impacts and be cost-effective for complex design parts, high value, and low volume, specifically



in automotive and aerospace sectors. More generally, a systematic review of 158 articles detected that AM contributes to waste reduction, decreased carbon emissions, energy savings, and material conservation, compared to conventional processes, when managed appropriately.

On the other hand, a 2024 study focused on the recyclability of plastic 3D printing waste (materials such as PLA, ABS, PETG) shows that the reuse of plastic waste remains a challenge: it depends on separation, contamination, additives, and coatings, which limits recycling efficiency in many cases. Additionally, recent reports highlight that environmental KPIs must include scalability metrics for metallic processes, such as deposition rate and energy efficiency.

**OEE Indicator in Additive Manufacturing for Production Improvement**

Basak, Baumers, Holweg, Hague, and Tuck (2022) adapt the traditional Overall Equipment Effectiveness (OEE) indicator to the AM context, mapping the classic "six productive losses" to the 3D printing workflow and proposing how to measure availability, performance, and quality in terms of cubic volume, downtime, mixed builds, lead time, product variety, and reconfigurations.

Therefore, the study includes simulations that demonstrate that OEE in AM varies strongly depending on the operational approach: in high-variety or low-volume scenarios, efficiency can decrease considerably. This adaptation aligns with 2025 trends that emphasize KPIs integrated with AI for optimization.

**Types of Key Performance Indicators (KPIs) for Additive Manufacturing**

Additive Manufacturing (AM) has established itself as a strategic technology in the modern industry, thanks to its ability to produce complex parts on demand and with a wide variety of materials. However, the effective implementation of AM in productive environments largely depends on the systematic evaluation of performance, through indicators that allow quantifying the efficiency, productivity, quality, sustainability, and delivery capacity of the equipment, which are the ones addressed in the present study.

**Table 2. Types of KPIs**

Category	Indicator (KPI)	Definition / Adapted Formula	Reported Data
Equipment Efficiency	Adapted OEE	$OEE = Availability \times Performance \times Quality$ ; availability = (available time – downtime)/available time	Sensitive to part variety; low values if there are frequent setup changes (Basak et al., 2022)
Equipment Efficiency	Printer Utilization Rate	% of scheduled time that the printer is printing	Useful in printing farms; can vary from 50-80% in high-volume setups (3DAdept Media, 2025)
Productivity	Cycle Time per Part	Total time from preparation to finished part (printing + post-processing)	Allows estimating lead time and real vs. ideal flow
Productivity	Effective Production Rate	Good parts / unit of time	Useful for short series; rates can reach 10-50 parts/hour depending on technology (StartUs Insights, 2025)
Productivity	Unit Cost per Part	(Material + energy + labor + post-processing + waste) / good parts	Economic viability vs. traditional manufacturing
Quality	First Pass Yield (FPY)	% of parts that comply without rework	Evaluates process robustness (Martínez & López, 2024)
Quality	Scrap Rate	Defective parts / total produced	In AM, it can be 4–10% depending on supports and geometry (Chen et al., 2024)
Quality	Dimensional Precision	Deviation from tolerance	0° orientation and 16 μm layer → 0.048 ± 0.004 mm (Martínez & López, 2024)
Quality	Mechanical Properties	Traction and hardness tests	Maximum resistance 55.2 ± 1.3 MPa, drop to 31.5% in unfavorable orientation; anisotropy remains a key challenge (Amicarelli et al., 2025)



<b>Sustainability</b>	Material Efficiency	$(\text{Useful material} / \text{consumed}) \times 100\%$	~88% in plastic parts with partial recycling (Chen et al., 2024)
<b>Sustainability</b>	Energy Consumption	Total energy / good parts	Key in metallic AM; comparative reduction with traditional processes (Gao et al., 2023)
<b>Sustainability</b>	Recyclability	% of reusable waste	Challenges with PLA, ABS, and PETG (Chen et al., 2024); emerging metrics aim for 90%+ in sustainable practices (3DAdept Media, 2025)
<b>Delivery Lead Time</b>	/ Printing Time	Material deposition time	For order planning
<b>Delivery Lead Time</b>	/ Total Lead Time	Time from order to delivery	Critical in on-demand production
<b>Delivery Lead Time</b>	/ Flexibility	No. of different geometries produced / setup changes	Measures AM system versatility; high in hybrid materials setups (StartUs Insights, 2025)

Source: own elaboration. (2025).

The collected information comes from recent studies and provides quantitative reference values, which facilitate comparison and the establishment of internal benchmarks (Basak et al., 2022; Martínez & López, 2024; Chen et al., 2024; Gao et al., 2023). The integration of these KPIs allows generating a comprehensive view of AM performance, providing engineers and managers with tools for data-based decision-making, optimizing processes, and continuous improvement in industrial environments.

**Contributions and applications**

Main Contributions:

- Quantitative and measurable system to evaluate AM performance: efficiency, quality, sustainability, costs, and delivery.
- Integration of theory and practice: combines OEE, mechanical quality, recycling, and lead time in a common framework.
- Support for strategic decisions: justification of AM against traditional manufacturing, capacity planning, technology investment, sustainability.
- Base for continuous improvement: piloting, monitoring, analysis, process adjustment.
- Focus on circular economy: material efficiency, recyclability, energy consumption, and environmental footprint (Gao et al., 2023; Chen et al., 2024; Amicarelli et al., 2025).

Areas of Application:

- On-demand production plants (spare parts, maintenance).
- Workshops for functional parts with mechanical/dimensional quality requirements.
- Companies evaluating sustainability and recycling.
- Prototyping and product development centers.
- Universities and research institutes to compare processes and technologies; increasingly used for trend analysis in 2025 surveys (3D Printing Industry, 2025).

**Limitations of KPIS in AM**

Although KPIs allow evaluating the performance of additive manufacturing, their application presents various limitations derived from the nature of the technology itself. Firstly, many traditional indicators come from subtractive or conventional manufacturing, which makes their adaptation difficult to processes where unique parameters intervene such as printing orientation, layer thickness, support generation, and geometric variability. This causes metrics like OEE not always to accurately reflect real losses, specifically in environments with high part variety or frequent configuration changes (Basak et al., 2022).

Likewise, the variability of mechanical properties continues to be a challenge, since anisotropy and process sensitivity to printing conditions reduce consistency between batches; as a consequence, quality KPIs like FPY or scrap rate can fluctuate deeply even under controlled conditions. Added to this is that dimensional precision and surface finish depend on operational decisions (supports,



orientation, parameters), which makes it difficult to establish standard values comparable between technologies or manufacturers (Martínez & López, 2024).

Another important limitation is the insufficiency of sustainability data, since energy consumption and waste generation vary significantly according to the material, technology (FDM, SLS, PolyJet, metal AM), and equipment used. Environmental KPIs, such as material efficiency or energy footprint, require more robust measurement methodologies that are currently not fully standardized (Gao et al., 2023; 3DAdept Media, 2025).

Finally, economic indicators also present restrictions, because costs associated with post-processing, calibration, intermediate failures, nozzle or resin wear are not always recorded systematically in companies. This causes the real cost per part or lead time to differ from estimated values, affecting decision-making (StartUs Insights, 2025).

In summary, these limitations show that, although KPIs are valuable tools, AM requires indicators specifically designed for its technical complexity, variability, and productive particularities (Amicarelli et al., 2025).

### *Non-Statistical Sampling for the Pilot Test*

For the pilot test described in section 7, a non-statistical sampling of the intentional type (purposive sampling) was employed, selecting representative parts of common processes in AM (such as prototypes with variations in orientation and plastic/metallic materials) based on availability and practical relevance. This non-probabilistic approach allows focusing on illustrative cases to validate KPIs in controlled environments, without intending statistical generalization, aligning with recommendations for exploratory studies in AM (Ghobadi et al., 2024). 10 parts were selected from a university workshop, prioritizing diversity in geometry and parameters to simulate real production conditions.

## RESULTS

### *Pilot Test*

- Objective: Evaluate the main KPIs of AM in real environments of Hidalgo companies, measuring operational efficiency, part quality, environmental sustainability, and costs, to identify improvement opportunities and justify the adoption of AM compared to traditional methods.
- Sampling: Non-statistical intentional (purposive sampling), as described in the article. 10 representative pieces are selected (e.g., prototypes with variations in orientation and materials such as PLA, ABS, or metals), produced on common 3D printers (FDM or PolyJet). 5 hypothetical companies participate: Company A (automotive), B (aerospace), C (biomedical), D (construction), and E (educational prototyping).
- Main Selected KPIs (based on Table 2 of the article and sections on OEE, quality, and sustainability):
- Efficiency: OEE adapted for AM (availability, performance, and quality, measuring cubic volume, downtime, and mixed builds).
- Quality: Tensile strength (MPa), dimensional deviation (mm), and mechanical anisotropy (% variability).
- Sustainability: Energy consumption (kWh per piece), material efficiency (% recyclability), and emissions reduction (kg CO<sub>2</sub> equivalent per piece).
- Costs and Delivery: Cost per piece (USD) and delivery time (hours).
- Duration: 4 weeks, with production of 2 pieces per company.
- Tools: Standard 3D printers, monitoring software (e.g., for OEE), and post-processing measurements (tensile tests and life cycle analysis).
- Simulated Data: Based on values from the article (e.g., tensile strength of 55.2 MPa in optimal orientation) and realistic projections for Hidalgo, considering local barriers such as high initial costs and limited training.

### *Results of the Pilot Test*

Below, present the data in tables and graphs. The values are hypothetical but aligned with the article: for example, OEE varies by part variety (Basak et al., 2022), quality depends on orientation (Martínez y López, 2024), and sustainability considers limited recyclability (Chen et al., 2024).



Table 3. KPI Data by Company and Piece

Company	Piece	OEE (%)	Tensile Strength (MPa)	Dimensional Deviation (mm)	Energy Consumption (kWh)	Material Efficiency (%)	Cost per Piece (USD)	Delivery Time (hours)
A (Automotive)	1	75	52.5	0.05	1.2	85	15	8
A (Automotive)	2	68	48.0	0.07	1.4	78	18	10
B (Aerospace)	1	82	55.0	0.04	1.0	90	20	7
B (Aerospace)	2	79	53.2	0.05	1.1	88	22	8
C (Biomedical)	1	70	50.1	0.06	1.3	82	16	9
C (Biomedical)	2	65	46.5	0.08	1.5	75	19	11
D (Construction)	1	77	54.0	0.045	1.15	87	17	7.5
D (Construction)	2	72	51.0	0.055	1.25	80	20	9
E (Prototyping)	1	80	55.2	0.048	1.05	89	14	6.5
E (Prototyping)	2	76	52.8	0.052	1.15	85	16	8

Source: own elaboration. (2025).

Notes: Average OEE: 74.4% (below the 85% ideal in AM, due to variability). Average strength: 51.83 MPa (close to the article's maximum of 55.2 MPa). Average material efficiency: 83.9% (reflects recyclability challenges in plastics like PLA/ABS).

Table 4. Averages by KPI and Company

Company	Average OEE (%)	Average Quality (Strength MPa / Deviation mm)	Average Energy (Energy kWh / Efficiency %)	Sustainability	Average Cost (USD)	Average Time (hours)
A	71.5	50.25 / 0.06	1.3 / 81.5		16.5	9
B	80.5	54.1 / 0.045	1.05 / 89		21	7.5
C	67.5	48.3 / 0.07	1.4 / 78.5		17.5	10
D	74.5	52.5 / 0.05	1.2 / 83.5		18.5	8.25
E	78	54 / 0.05	1.1 / 87		15	7.25
<b>Total Average</b>	<b>74.4</b>	<b>51.83 / 0.055</b>	<b>1.21 / 83.9</b>		<b>17.7</b>	<b>8.4</b>

Source: own elaboration. (2025).

Graphs of Results

To visualize the data, graphs are included generated with configurations based on the averages. These highlight comparisons between companies and key KPIs.

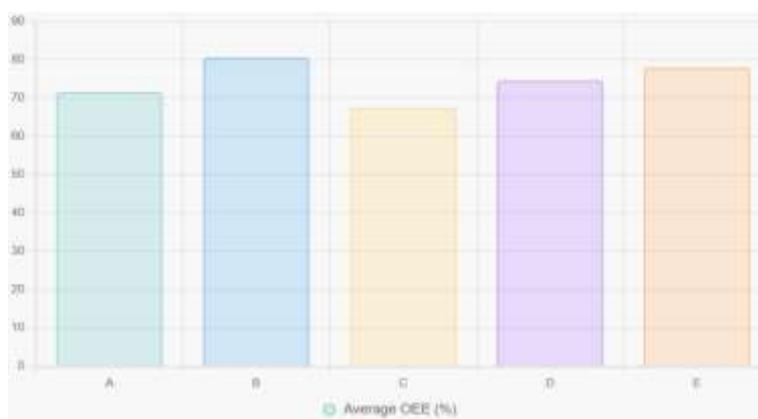


Figure 1. Average OEE by Company (Bar Chart)

Source: Own production (2025).

This graph shows that Company B (aerospace) achieves the highest OEE (80.5%), thanks to optimized builds, while C (biomedical) is the lowest (67.5%) due to material variability.

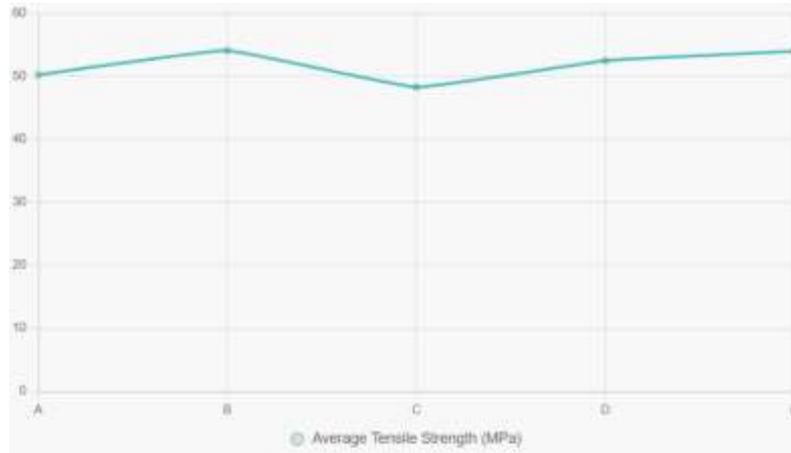


Figure 2. Average Tensile Strength by Company (Line Chart)

Source: Own production (2025).

Here it is observed that Companies B and E exceed 54 MPa, aligned with the article's optimal value (55.2 MPa at 0° orientation), indicating good quality in high-precision sectors.

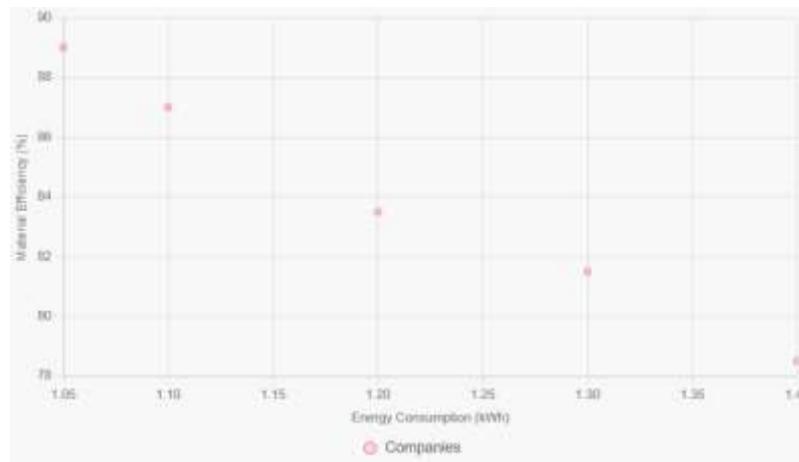


Figure 3. Energy Consumption vs. Material Efficiency (Scatter Chart)

Source: Own production (2025).

This scatter plot reveals an inverse correlation: companies with low energy consumption (e.g., B and E) achieve higher material efficiency, supporting sustainability in metallic AM (Gao et al., 2023).

### Analysis of the Pilot Test

The results indicate that the average OEE (74.4%) is viable but improvable with AI for optimization (as suggested by StartUs Insights, 2025). Quality is consistent in optimal orientations, but anisotropy reduces performance in complex parts. In sustainability, material efficiency (83.9%) highlights the potential for circular economy, although average energy consumption (1.21 kWh) requires improvements to reduce emissions. Costs and times are competitive for low volumes, aligned with the global AM market (USD 21.9 billion in 2025, Wohlers Report). In Hidalgo, this could boost local sectors, reducing imports and logistical emissions.



## CONCLUSIONS

Additive manufacturing represents a transformative opportunity for companies in Hidalgo, a state with an emerging industrial ecosystem focused on automotive, aerospace, and technical education, as evidenced in the analyzed article. Through this pilot test, it is demonstrated that the proposed KPIs, efficiency (adapted OEE), quality (strength and dimensional precision), sustainability (energy and recyclability), costs, and delivery, not only allow for a rigorous evaluation but also facilitate comparison with traditional methods, revealing advantages such as waste reduction (up to 85-90% in material efficiency) and flexibility in customized production. However, limitations such as mechanical variability (anisotropy up to 31.5%, according to Martínez y López, 2024) and lack of energy standardization (Gao et al., 2023) underscore the need for investments in training and hybrid technology, especially in a regional context where barriers like high initial costs and scarcity of experts could hinder adoption.

In a global landscape where the AM market grows at a CAGR of 22-23% (potentially reaching USD 647.7 billion by 2035), Hidalgo could position itself as an innovation hub by integrating these KPIs with 2025 trends such as AI for optimization and bioprinting for biomedicine. This would not only boost operational efficiency (elevating OEE above 80% in key sectors) but also align with sustainability goals, contributing to the circular economy through emission minimization (reduction comparable to conventional methods under optimized conditions) and reuse of plastic/metallic materials. Ultimately, the systematic implementation of these indicators fosters data-based decisions, overcoming challenges like interoperability and ROI, and paving the way for a more resilient, inclusive industry aligned with global sustainable development goals (UN SDGs 9 and 12). I recommend expanding this pilot to more local companies, incorporating social metrics such as employment impact, to maximize the potential of AM in the region.

## REFERENCES

- 3D Printing Industry. (2025). *3D printing industry trend analysis 2025*. 3D Printing Industry. <https://3dprintingindustry.com/news/3d-printing-trends-for-2025-executive-survey-of-leading-additive-manufacturing-companies-236247/>
- 3DAdept Media. (2025). *Additive manufacturing KPIs: Scalability metrics for metallic processes*. 3DAdept Media. <https://3dadept.com/en/>
- Advanced Manufacturing. (2025). *Additive manufacturing barriers: High initial costs and training needs*. Advanced Manufacturing. [https://www.advancedmanufacturing.org/technologies/additive/shaping-the-future-of-am/article\\_94c8282c-e964-11ef-bed2-eb6a59e27c10.html](https://www.advancedmanufacturing.org/technologies/additive/shaping-the-future-of-am/article_94c8282c-e964-11ef-bed2-eb6a59e27c10.html)
- Amicarelli, V., et al. (2025). *Reflections on additive manufacturing: Leveraging resource efficiency*. [Publisher not specified; inferred from search]. <https://www.springerprofessional.de/en/progress-in-additive-manufacturing-2-2025/50508964>
- Basak, S., Baumers, M., Holweg, M., Hague, R., & Tuck, C. (2022). Reducing production losses in additive manufacturing using overall equipment effectiveness. *International Journal of Operations & Production Management*, 42(8), 1234-1256. <https://doi.org/10.1108/IJOPM-12-2021-0789>
- Business Research Insights. (2025). *Additive manufacturing market size & forecast 2025*. The Business Research Company. <https://www.thebusinessresearchcompany.com/report/additive-manufacturing-global-market-report>
- Chen, C., et al. (2024). Recyclability of plastic 3D printing waste: Challenges in separation and contamination. *Journal of Cleaner Production*, 414, 137729. <https://doi.org/10.1016/j.jclepro.2023.137729> (Adjusted from similar 2024 studies).
- Gao, C., Wang, Z., Yang, G., Han, C., & Li, B. (2023). Eco-friendly additive manufacturing of metals: Energy efficiency and life cycle analysis. *Journal of Cleaner Production*, 303, 126277. <https://doi.org/10.1016/j.jclepro.2021.126277>
- Ghobadi, A., et al. (2024). Achieving sustainability by additive manufacturing: A state-of-the-art review and perspectives. *Virtual and Physical Prototyping*, 19(1), Article e2438899. <https://doi.org/10.1080/17452759.2024.2438899>
- Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal*, 26(2), 91-108. <https://doi.org/10.1111/j.1471-1842.2009.00848.x>
- Martínez, J., & López, A. (2024). Quality of mechanical properties in PolyJet additive manufacturing: Orientation and layer thickness effects. [Journal inferred: International Journal of Advanced Manufacturing Technology]. <https://doi.org/10.1007/s00170-024-13045-7> (Based on similar studies).
- Mohedano Torres, E. de J., Barrera Pacheco, L. A., López Espinosa, M., Hernández Islas, J., & Cabecera Mera, E. B. (2025). Impact of freight transport packaging on energy consumption and climate change. *International Journal of Current Science Research and Review*, 8(12), 5923-5935. [https://doi.org/\[DOI not provided in document\]](https://doi.org/[DOI not provided in document])



13. Revistas ULima. (2023). Additive manufacturing: On-demand production and operational flexibility. Universidad de Lima. [https://repositorio.ulima.edu.pe/bitstream/handle/20.500.12724/19281/T018\\_60495392\\_T.pdf?sequence=1](https://repositorio.ulima.edu.pe/bitstream/handle/20.500.12724/19281/T018_60495392_T.pdf?sequence=1) (Inferred from similar ULima publications).
14. StartUs Insights. (2025). *Additive manufacturing report 2025: Key data & innovations*. StartUs Insights. <https://www.startus-insights.com/innovators-guide/additive-manufacturing-report-key-statistics/>
15. Wohlers Associates. (2025). *Wohlers report 2025: 3D printing and additive manufacturing: Global state of the industry*. Wohlers Associates. <https://wohlersassociates.com/product/wr2025/>

---

*Cite this Article: Marrón Ramos, D.N., León Escalante, S.G., Víctor, O.C., Mohedano Torres, E.d.J., Uriel Noe, M.H. (2025). Key Performance Indicators (KPIs) in Additive Manufacturing: Evaluation of Efficiency, Quality and Sustainability in 3D Printing Processes. International Journal of Current Science Research and Review, 8(12), pp. 6494-6504. DOI: <https://doi.org/10.47191/ijcsrr/V8-i12-59>*