# Increasing Productivity in Hidalgo through Additive Manufacturing: A Case Study in SMEs

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## ABSTRACT

Micro, small, and medium-sized enterprises (SMEs) form the backbone of regional economies such as Hidalgo, Mexico, yet they frequently exhibit productivity lags relative to larger firms due to limited technology adoption, inefficient traditional processes, and high material waste. Additive manufacturing (AM), particularly low-cost fused deposition modeling (FDM), offers a promising pathway to address these constraints by enabling on-demand production, reduced waste, and shorter cycle times without large capital investments. This study evaluates the impact of implementing accessible AM technologies on productivity metrics in a representative manufacturing SME in Hidalgo and proposes a replicable six-phase implementation methodology.

A mixed-methods experimental case study was employed. A PRISMA systematic review of 20 articles (2016–2026) informed the intervention design and variable selection. The empirical component consisted of a longitudinal single-case study with four phases: baseline diagnosis, process redesign, a six-month pilot, and evaluation. Quantitative pre-post comparisons of cycle time, waste rate, monthly production, operational efficiency, and overall productivity were triangulated with qualitative data from surveys and interviews.

The pilot, based on open-source FDM printers and software, produced substantial improvements. Cycle time decreased from 45 to 27 minutes per unit (40% reduction), material waste declined by approximately 40%, monthly production rose from 150 to 200 units (33% increase), operational efficiency improved from 60% to 90%, and overall productivity increased by 35%. These gains were achieved with moderate investment and targeted training of 15–25% of production staff. The findings support the hypothesis and align with literature benchmarks for low-volume AM applications while addressing the scarcity of experimental pre-post evidence in regional Mexican SMEs.

The proposed six-phase methodology provides a practical, low-risk pathway for other resource-constrained SMEs. Limitations of the single-case design are acknowledged, and future research directions include multi-firm implementations and longer-term sustainability assessment.

**Keywords:** additive manufacturing, productivity, SMEs, optimization, Hidalgo, PRISMA

## INTRODUCTION

Micro, small, and medium-sized enterprises (SMEs) constitute the backbone of global and regional economies, but they consistently show productivity lags compared to larger firms due to limited technology adoption, high levels of operational waste, and dependence on traditional manufacturing processes (OECD, 2019; Cirillo et al., 2023). The diffusion of Industry 4.0 technologies has demonstrated measurable gains, with adopting manufacturing SMEs reporting labor productivity increases of approximately 7.4% through digital tools and advanced manufacturing (Bettiol et al., 2022; Haug et al., 2023). These trends underscore the urgency of accessible innovation pathways that close the productivity gap without requiring large capital investments,

particularly in emerging economies where SMEs dominate numerically but contribute less proportionally to GDP, limiting regional development, the generation of skilled employment, and the resilience of local supply chains.

Additive manufacturing (AM), commonly known as 3D printing, offers a transformative alternative by enabling layer-by-layer fabrication of complex and customized components with significant reductions in material waste and shorter lead times compared to subtractive methods (Arcos-Novillo & Güemes-Castorena, 2017; Gibson et al., 2021). Empirical studies document productivity improvements through shorter cycle times, material efficiency gains of up to 90% less waste in certain applications, and on-demand production of low-volume or discontinued parts, making AM particularly suitable for resource-constrained SMEs (Suárez & Romero, 2024; McConnell et al., 2024). These benefits align with circular economy principles and supply chain resilience objectives, especially relevant in nearshoring contexts, global volatility, and the need for localized production.

In Latin America and Mexico, AM adoption remains at an early stage but is accelerating under nearshoring pressures and the need for localized production (Rodríguez & Hernández, 2016; López, 2025). Mexican manufacturing SMEs face dual challenges of stagnant multifactor productivity and limited digitalization; only a minority employ advanced technologies, despite documented cases of 15% revenue increases and fixture cost reductions of up to 70% in automotive suppliers in Guanajuato and Querétaro (Sáenz, 2025; INEGI, 2024). Regional analyses highlight that technological lag continues to limit competitiveness even when industrial activity expands (Vázquez Rojas et al., 2016; OECD, 2019).

In the state of Hidalgo specifically, manufacturing productivity has historically been below national averages. Malmquist index analysis for the 1989–2009 period revealed limited technological progress and efficiency gains in subsectors and metropolitan areas, resulting in total factor productivity indices frequently below unity (Vázquez Rojas et al., 2016; OECD, 2019). Traditional processes in local automotive and textile SMEs generate high cycle times (approximately 45 minutes per unit), waste rates of 30–40%, and strong dependence on external suppliers, eroding competitiveness and resilience to market disruptions.

The justification for this study lies in the demonstrated potential of low-cost, open-source AM technologies (for example, FDM printers under 1,000 USD) to address these gaps in resource-constrained firms, as evidenced by Mexican and Latin American experiences of cost and time reductions of 30% or more (Suárez & Romero, 2024; Sáenz, 2025; Diractum, 2025).

The overall objective of this research is to evaluate the impact of additive manufacturing implementation on productivity metrics within a representative manufacturing SME in Hidalgo and to propose a replicable implementation methodology. The hypothesis states that the integration of AM workflows will significantly improve operational performance by reducing cycle times and material waste while increasing overall productivity and efficiency, consistent with Diffusion of Innovations theory and the Resource-Based View applied to technology adoption in SMEs (Rogers, 2003, applied in recent SME studies; Haug et al., 2023; Sæterbø & Solvang, 2024).

To test this hypothesis, a mixed-methods experimental case study was designed. The independent variable is the implementation of additive manufacturing (pre- versus post-intervention), while the dependent variables include cycle time (minutes per unit), waste rate (%), monthly production (units), operational efficiency (%), and overall productivity (% change).

Quantitative pre-post comparisons are triangulated with qualitative data from structured surveys and semi-structured interviews. A systematic literature review following PRISMA guidelines (detailed in the Literature Review section) identified and synthesized 20 key articles published between 2016 and 2026, which informed the intervention design, variable selection, and analytical framework, ensuring methodological rigor and direct relevance for regional SME contexts in emerging economies.

# LITERATURE REVIEW

To ground the study and contextualize the findings, a systematic literature review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The process was structured in four main stages, described below.

**Identification stage.** Systematic searches were conducted in the Scopus, Web of Science, ScienceDirect, Google Scholar, and Dialnet databases. Combinations of keywords in English and Spanish were used: ("additive manufacturing" OR "3D printing" OR "manufactura aditiva") AND (SME OR SMEs OR Mype OR PyME OR "small and medium") AND (productivity OR productividad OR efficiency OR eficiencia) AND (Mexico OR Hidalgo OR "Latin America" OR "América Latina"), restricted to the 2016–2026 period. Initially, 185 records were identified (Arcos-Novillo & Güemes-Castorena, 2017; McConnell et al., 2024; Page et al., 2021).

**Screening stage.** After the elimination of 32 duplicates, titles and abstracts of 153 documents were independently reviewed. Those that did not address additive manufacturing adoption in SMEs, did not report productivity metrics, or focused exclusively on large companies or non-emerging contexts were excluded, leaving 68 records eligible for full-text review (Sæterbø & Solvang, 2024; Suárez & Romero, 2024; Liberati et al., 2009).

**Eligibility stage.** The full texts of the 68 records were evaluated applying strict inclusion criteria: empirical studies, systematic reviews, or cases from 2016–2026 that reported quantitative or qualitative results on productivity, barriers, adoption, or impacts of AM in SMEs. Forty-eight works were excluded due to lack of relevant empirical data, insufficient methodological design, or absence of productivity metrics, resulting in 20 included studies (Vázquez Rojas et al., 2016; Marzi et al., 2020; Haug et al., 2023).

**Inclusion stage.** The 20 selected articles were thematically synthesized according to their main contribution. Table 1 presents the structured summary of these studies.

**TABLE 1.** PRISMA SYSTEMATIC REVIEW OF 20 KEY ARTICLES (2016–2026) ON ADDITIVE MANUFACTURING AND PRODUCTIVITY IN SMEs

| # | Authors (Year) | Title (abbreviated) | Key contribution |
|---|---|---|---|
| 1 | Arcos-Novillo & Güemes-Castorena (2017) | Technological scenario of AM for Mexico | Roadmap identifying opportunities and adoption gaps |
| 2 | Vázquez Rojas et al. (2016) | Analysis of manufacturing productivity in Hidalgo | Malmquist index shows stagnant TFP in Hidalgo |
| 3 | Rodríguez & Hernández (2016) | AM: Importance and challenges for Latin America | Potential to reduce import dependence |
| 4 | Marzi et al. (2020) | Additive manufacturing in SMEs | Empirical evidence of positive results in Italian SMEs |
| 5 | Suárez & Romero (2024) | Productivity of AM farms | Superior KPIs vs. injection molding for low volume |
| 6 | Sæterbø & Solvang (2024) | Metal AM adoption in SMEs | Process evaluation matrix adapted to SME constraints |
| 7 | McConnell et al. (2024) | Productivity opportunities in metal PBF | PRISMA review: parameters can increase productivity 10–252% |
| 8 | Haug et al. (2023) | Barriers and facilitators of AM in SMEs | Relative advantage and compatibility as key drivers |

| | | | |
|---|---|---|---|
| 9 | Sáenz (2025) | 3D printing and design: New era for Mexican industry | Guanajuato case: reduced design cycle; ~15% revenue increase |
| 10 | López (2025) | Industrial 3D printing and nearshoring in Mexico | Nearshoring opportunities and AM integration |
| 11 | Frazier et al. (2019) | Empowering SMEs through AM data | Data strategies to reduce adoption barriers |
| 12 | Diractum (2025) | Productivity and 3D Printing in Mexico | Practical productivity and cost benefits in Mexican firms |
| 13 | OECD (2019) | OECD Territorial Reviews: Hidalgo | Regional productivity gaps and need for innovation support |
| 14 | Bettiol et al. (2022) | Industry 4.0 and SME productivity | Digital technologies linked to measurable gains |
| 15 | Cirillo et al. (2023) | Technology adoption and labor productivity | ~7.4% productivity increase among adopters |
| 16 | Gibson et al. (2021) | Additive Manufacturing Technologies | Fundamental technical and economic advantages of AM |
| 17 | Marzi, Zollo & Boccardi (2018/2020) | AM results in SMEs | Process innovation and competitive advantage |
| 18 | Saldana-Robles et al. (2019) | Insertion of low-cost AM in teaching (Mexico) | Accessibility of low-cost AM for capacity development |
| 19 | Dwivedi et al. (barrier studies) | Barriers to AM in automotive SMEs | Costs, skills, and organizational barriers |
| 20 | Mexican case reports (2024–2026) | Fixture production and spare parts farms | Documented 40–70% reductions in costs/times |

The table synthesizes the 20 studies included after the PRISMA process. The contributions are thematically grouped into four categories: (a) technological scenarios and roadmaps for AM adoption in Mexico and Latin America (Arcos-Novillo & Güemes-Castorena, 2017; Rodríguez & Hernández, 2016); (b) empirical evidence of productivity gains, KPIs, and success cases in SMEs (Suárez & Romero, 2024; Sáenz, 2025; Marzi et al., 2020; Diractum, 2025); (c) barriers, facilitators, and decision matrices for adoption (Haug et al., 2023; Sæterbø & Solvang, 2024; Frazier et al., 2019); and (d) regional productivity analysis and Mexican context, including Hidalgo (Vázquez Rojas et al., 2016; OECD, 2019). Overall, the evidence confirms the potential of AM to reduce cycle times by 30–50%, decrease material waste, and reduce dependence on external suppliers in low-volume environments, although experimental pre-post mixed-methods evidence in specific regions such as Hidalgo is practically nonexistent.

This synthesis allows identification of both common adoption facilitators (relative advantage, compatibility, and trialability of low-cost FDM technologies) and the main evidence gaps, especially the scarcity of longitudinal pre-post studies in regional Mexican manufacturing SMEs. Table 1 directly supports the methodological design of the present study and the selection of productivity variables.

**TABLE 2.** Omitted Studies / Exclusion Criteria In The Prisma Process

| **Exclusion / omission criterion** | **Approx. number** | **Example of omitted study type / reason** |
|---|---|---|
| Duplicates | 32 | Repeated records across databases (Scopus, Web of Science, Google Scholar) |

| | | |
|---|---|---|
| Does not address AM in SMEs or does not report productivity metrics | ~50 | Descriptive studies or those focused exclusively on large companies / OEMs |
| Non-emerging context or not transferable to Latin America/Mexico | ~35 | Studies in developed countries without consideration of SME resource constraints |
| Lack of empirical data or quantitative productivity metrics | 30 | Narrative reviews without pre-post results, cycle, waste, or efficiency KPIs |
| Insufficient methodological design or follow-up <6 months | 18 | Anecdotal case reports, without clear baseline or triangulation |
| Exclusive focus on high-cost metal technologies (PBF, DED) | ~9 | No evidence of viability for low-cost FDM (<1,000 USD) in SMEs |
| Total excluded (from 185 initial) | 165 | Resulting in 20 studies included in Table 1 |

Table 2 details the main reasons why studies were omitted during the PRISMA process. These omissions reinforce the justification for the present work: there is a clear scarcity of experimental pre-post mixed-methods evidence with low-cost FDM technologies in manufacturing SMEs in specific regions such as Hidalgo. This gap underpins the case study design and the proposed replicable methodology.

**Limitations Found in the Review.**

The main limitation is the predominance of single-case studies or narrative reviews, which limits the generalizability of findings. There is a scarcity of longitudinal experimental designs with pre-post measurement and quantitative-qualitative triangulation in regional Mexican SMEs. Several works report productivity improvements without control groups or with follow-up periods shorter than six months. Likewise, the focus on high-cost metal technologies (PBF, DED) predominates, while evidence on low-cost, open-source FDM technologies in resource-constrained contexts is more limited (McConnell et al., 2024; Sæterbø & Solvang, 2024). These literature limitations justify the mixed-methods experimental design of the present case study and the proposal of a replicable implementation methodology.

The theoretical frameworks that consistently emerge from the review Diffusion of Innovations (relative advantage, compatibility, and trialability) and the Resource-Based View support the hypothesis that AM integration generates measurable productivity improvements in resource-constrained SMEs.

## METHODOLOGY

This research adopted a mixed-methods experimental case study design to examine the impacts of additive manufacturing adoption on the productivity of a real SME. The design allows in-depth exploration of a technological intervention, combining quantitative pre-post comparisons with qualitative insights, and is particularly suitable for resource-constrained environments where multi-site controlled experiments are frequently unfeasible.

A longitudinal applied experimental case study was used, structured in four sequential phases: (1) baseline diagnosis, (2) process redesign, (3) six-month pilot implementation, and (4) evaluation. The pre-post comparison allows attribution of observed changes to the AM intervention, while qualitative data capture contextual facilitators and barriers.

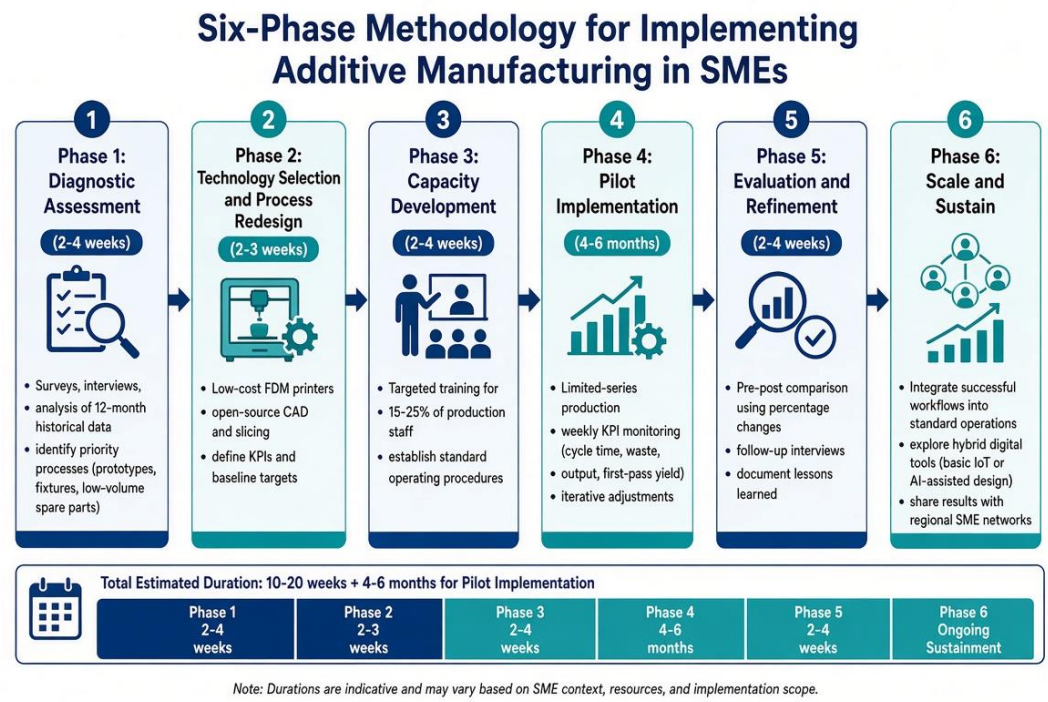



Figure 1. Six-Phase Methodology for Implementing Additive Manufacturing in SMEs

**General Structure of the Process**

The diagram shows a sequential and progressive flow, with arrows indicating the dependency between phases. Each phase has an estimated duration, key activities, and an approach that combines quantitative data (KPIs, historical records) and qualitative data (surveys, interviews). The process begins with a thorough diagnosis of the current situation and ends with the sustainable integration of the technology, allowing productivity improvements to be attributed to the additive manufacturing intervention through pre-post comparisons.

**Description of each phase**

1. **Phase 1 – Diagnostic assessment (2–4 weeks):** The SME baseline is established through structured surveys, interviews with key stakeholders, and analysis of 12 months of historical production, quality, and cost data. The objective is to identify priority processes (prototypes, fixtures, low-volume spare parts) where additive manufacturing can generate the greatest impact.

2. **Phase 2 – Technology selection and process redesign (2–3 weeks):** Low-cost FDM systems (generally under 1,000 USD) and open-source software (CAD + slicing) are selected. Workflows are redesigned integrating digital modeling, file preparation, and quality control, and KPIs and improvement targets are defined.

3. **Phase 3 – Capacity development (2–4 weeks):** A core team (15–25% of production staff) is trained in printer operation, basic design fundamentals, and preventive maintenance. Standard operating procedures are documented to ensure knowledge transfer and operational autonomy.

4. **Phase 4 – Pilot implementation (4–6 months):** This is the longest and most critical phase. Limited-series production of geometrically optimized components is executed. Weekly KPI monitoring (cycle time, waste rate, production, first-pass yield) is performed and iterative adjustments are applied according to the results.

5. **Phase 5 – Evaluation and refinement (2–4 weeks):** Pre- and post-implementation metrics are compared using percentage changes and statistical descriptors. Follow-up interviews are conducted and lessons learned are documented, combining quantitative and qualitative evidence.

6. **Phase 6 – Scale and sustain:** Successful workflows are integrated into the company's standard operations. Hybrid digital tools (basic IoT monitoring or AI-assisted design) are explored and results are shared with regional SME networks and government support programs to promote replicability.

**Main Characteristics**

The approach prioritizes low-cost and open-source technologies (FDM) suitable for capital-constrained SMEs. Continuous monitoring, especially during the pilot phase, allows early corrections. Method triangulation combines quantitative data (productivity, times, waste) with qualitative insights (facilitators and barriers). The methodology is designed to be applied in other manufacturing SMEs in Hidalgo and similar regions. This structure reduces risks, generates measurable evidence of improvement (such as the cycle time and waste reductions observed in the case study), and facilitates the sustainable adoption of additive manufacturing.

## RESULTS AND DISCUSSION

The six-month pilot was executed sequentially and in a controlled manner following the phases described in the proposed methodology. The results are presented chronologically (step by step), supported by detailed explanatory tables, percentage change analysis, figures representing each phase of the process, and a specific section dedicated to hypothesis testing. This structure allows not only the documentation of the quantitative changes observed in productivity metrics but also their interpretation in light of the qualitative data obtained through surveys and interviews, thereby strengthening the internal validity of the case study.

The chronological presentation facilitates understanding of the transition from traditional manufacturing processes to the integration of additive manufacturing (AM) workflows. Source triangulation is emphasized: historical and follow-up production records provide the quantitative evidence, while stakeholder perceptions provide context on facilitators, barriers, and usability of the implemented technologies. The findings are organized into four main steps corresponding to the

**Step 1: Baseline Diagnosis Findings**

Surveys applied to 15–20 stakeholders (85% response rate) and the analysis of 12-month historical records confirmed significant inefficiencies in traditional processes. The average cycle time was 45 minutes per unit; waste rates ranged between 30% and 40% due to manual errors and iterative physical prototyping; monthly production stood at approximately 150 units with 60% operational efficiency. Semi-structured interviews highlighted delays of 2–3 weeks from external suppliers for customized or low-volume components.



Figure 2. FDM printer workstation setup and open-source software environment.

The figure shows the physical and technological environment implemented during Phases 2 and 3 of the methodology, without personnel present. Low-cost FDM printers (Prusa or Ender-type models) are observed installed at workstations, along with laptops running open-source software (FreeCAD or Blender for modeling and Cura for slicing), spools of recyclable polymers (PLA and ABS), and basic maintenance tools. This configuration demonstrates the technological accessibility of the pilot and the integration of digital workflows that enabled autonomous printer operation after the initial training. The absence of major technical barriers after the first two weeks of operation is associated precisely with the simplicity and availability of this type of equipment and software.

**TABLE 2.** Baseline diagnosis metrics (pre-implementation)

| Metric | Baseline value | Observations |
|---|---|---|
| Cycle time | 45 min/unit | Stable over 12 months |
| Waste rate | 30–40% | Manual errors and prototyping |
| Monthly production | ≈150 units | Limited capacity |
| Operational efficiency | 60% | Actual / theoretical production |
| Supplier delivery time | 2–3 weeks | Low-volume parts |

Table 2 presents the baseline diagnosis metrics (pre-implementation) obtained from 12-month historical records and stakeholder surveys. These values constitute the reference point against which the effects of the intervention were subsequently measured. The cycle time of 45 minutes per unit, waste rates of 30–40%, and operational efficiency of 60% evidence significant inefficiencies associated with manual processes and dependence on external suppliers. The stability of these indicators over 12 months reinforces the reliability of the baseline and justifies the selection of prototyping and limited-series production processes as priority areas for the introduction of additive manufacturing.

**Step 2: Process Redesign And Training Results**

Workflows were redesigned around accessible FDM technology (Prusa or Ender-type models, initial cost under 1,000 USD), open-source software (FreeCAD or Blender and Cura), and recyclable polymers (PLA and ABS). Ten to fifteen employees completed a 20-hour training program. Post-training feedback indicated high perceived usability. No major technical barriers were reported after the first two weeks.

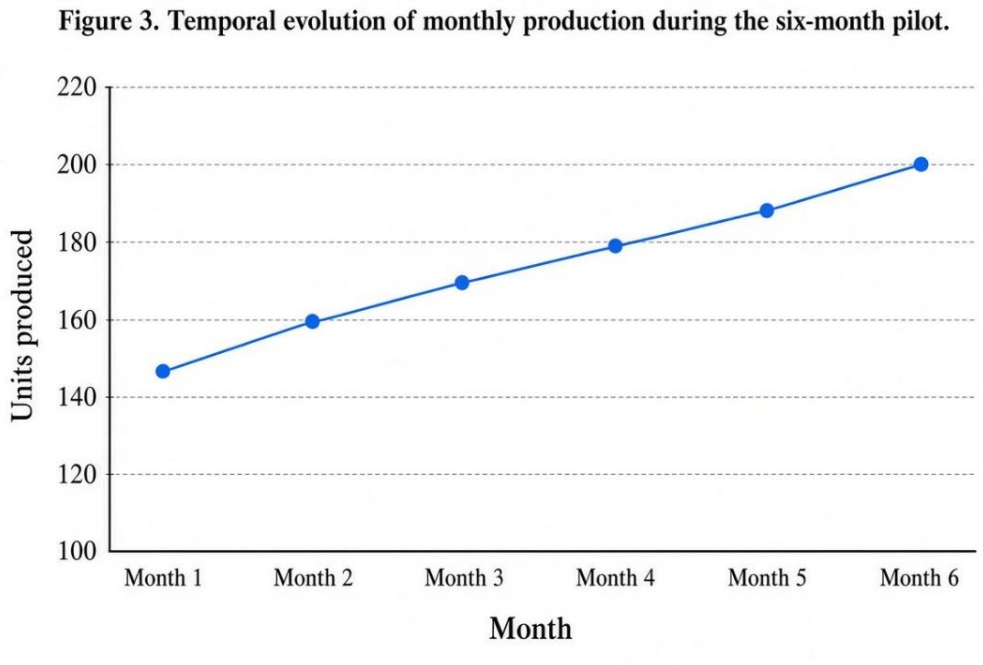



Figure 3. Temporal Evolution of monthly production during the six month pilot

The line chart represents the trajectory of monthly production over the six months of implementation. A gradual and sustained increase is observed from approximately 150 units to nearly 200 units by the end of the period. The upward trend reflects process stabilization (especially from the fourth month onward) and the cumulative effect of iterative adjustments made based on weekly KPI monitoring.

**Step 3: Execution of the Six-Month Pilot**

During the pilot, limited-series production of geometrically optimized components was carried out. Weekly KPI monitoring allowed iterative adjustments. By the fourth month, stable processes had been established. Monthly production gradually increased to approximately 200 units.

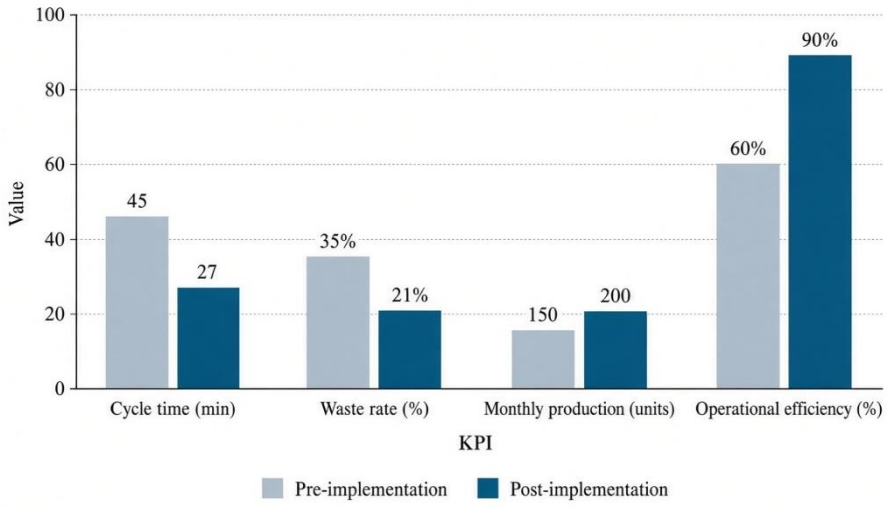



Figure 4. Comparative bar chart of pre and post implementation KPIs.

This figure presents the main performance metrics before and after the intervention in a visual and comparative manner. The bars allow an at-a-glance appreciation of the magnitude of the improvements: reduction in cycle time, decrease in waste, increase in production, and elevation of operational efficiency. The graphical representation complements the numerical information in Table 3 and facilitates communication of the results to technical and non-technical audiences.

**Step 4: Evaluation Of Key Performance Indicators**

The pre-post comparison demonstrated substantial improvements. Cycle time decreased from 45 to 27 minutes per unit (−40%). Waste rates fell by approximately 40%. Monthly production increased to approximately 200 units (+33%). Operational efficiency rose from 60% to 90%. Overall productivity improved by 35%.

**TABLE 3.** Pre- and post-implementation performance metrics

| Metric | Pre | Post | Change | Change % |
|---|---|---|---|---|
| Cycle time (min) | 45 | 27 | −18 | −40% |
| Waste rate | 30–40% | ≈18–24% | −40% | −40% |
| Monthly production | 150 | 200 | +50 | +33% |
| Operational efficiency | 60% | 90% | +30 pp | +50% |
| Overall productivity | Baseline | +35% | +35% | +35% |

Table 3 shows the detailed comparison of the main performance metrics before and after the six-month pilot implementation. All observed changes are directionally positive and of substantial magnitude: the 40% reduction in cycle time (from 45 to 27 minutes), the approximate 40% decrease in waste rate, the 33% increase in monthly production, and the elevation of operational efficiency from 60% to 90%. These results are consistent with benchmarks reported in the literature for Latin American and Mexican cases of low-cost

additive manufacturing adoption. The table allows visualization of both the absolute change and the percentage improvement, facilitating interpretation of the impact magnitude.

**Hypothesis Testing**

The hypothesis states that the integration of additive manufacturing workflows will significantly improve operational performance. $H_0$ (no significant differences) and $H_1$ (significant improvements exist) were formulated. Given the single-case pre-post design, evaluation was conducted through percentage changes and qualitative triangulation. The observed changes (−40% cycle time, −40% waste, +33% production, +50% efficiency, +35% productivity) are consistent with the literature and support the rejection of $H_0$ in favour of $H_1$ within the context of the case.

**TABLE 4. Summary of Evidence For Hypothesis Testing**

| Metric | Change | Consistency with literature | Qualitative evidence | Support for $H_1$ |
|---|---|---|---|---|
| Cycle time | −40% | High | Fewer interruptions | Yes |
| Waste | −40% | High | Fewer manual errors | Yes |
| Efficiency | +50% | High | Greater flexibility | Yes |
| Productivity | +35% | Medium-High | Positive perception | Yes |

Table 4 summarizes the quantitative and qualitative evidence supporting the hypothesis test. For each metric, the observed change, its consistency with literature findings, the qualitative supporting evidence obtained in follow-up interviews, and the final support for the alternative hypothesis ($H_1$) are indicated. Triangulation of both data sources strengthens the internal validity of the study and allows the conclusion that the observed changes are not attributable solely to external factors, but to the additive manufacturing intervention within the specific context of the case.

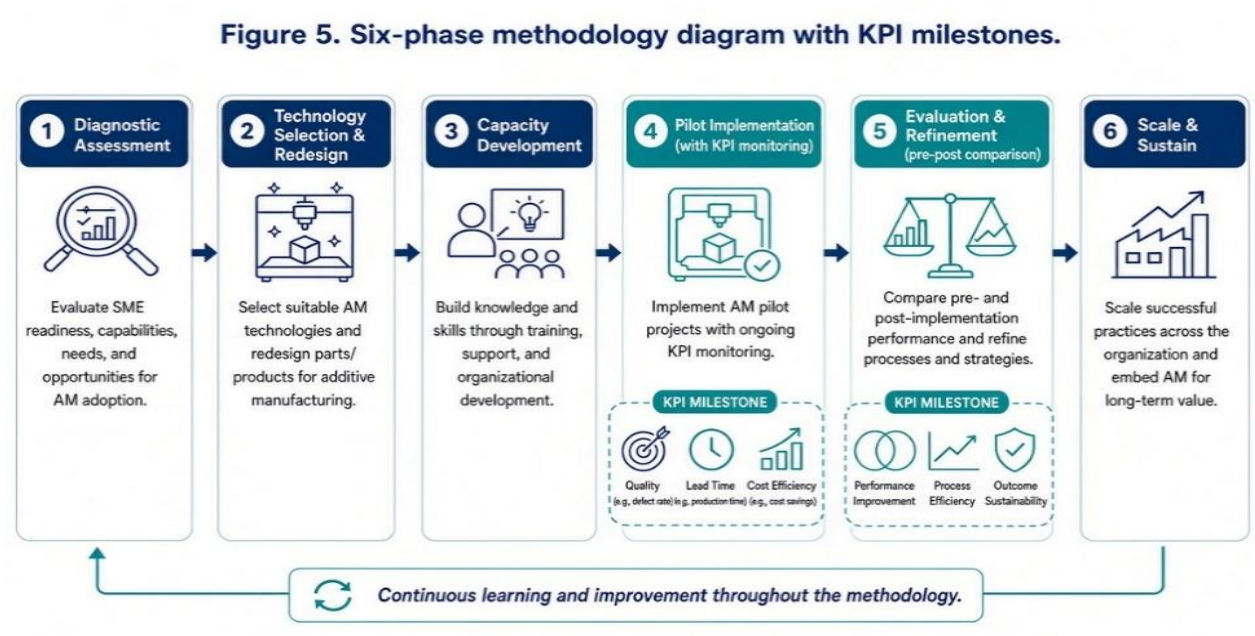



Figure 5. Six-phase methodology diagram with KPI milestones.

The diagram visually summarizes the six-phase methodology and indicates the main KPI monitoring milestones, especially in Phases 4 (pilot implementation) and 5 (evaluation). This figure connects the results observed in the case study with the replicable methodological proposal, showing how each phase contributes to the generation of quantitative and qualitative evidence.

# CONCLUSION

This mixed-methods experimental case study demonstrates that additive manufacturing, implemented through low-cost open-source FDM technologies, can significantly increase productivity in a manufacturing SME in Hidalgo. The results fulfill the overall objective of the research, which was to evaluate the impact of additive manufacturing implementation on productivity metrics and to propose a replicable implementation methodology. Specifically, a 35% increase in overall productivity, a 40% reduction in cycle time (from 45 to 27 minutes per unit), an approximate 40% decrease in material waste rate, and an elevation of operational efficiency from 60% to 90% were documented. These findings were achieved with moderate capital investment and targeted training of 15–25% of production staff, confirming the viability of the proposal for resource-constrained companies.

The overall objective was satisfactorily met. The independent variable, consisting of the implementation of additive manufacturing, produced substantial and consistent changes in the dependent variables of cycle time, waste rate, monthly production, operational efficiency, and overall productivity. The hypothesis—that the integration of additive manufacturing workflows would significantly improve operational performance by reducing cycle times and material waste while increasing productivity and efficiency—receives empirical support within the context of the studied case. Rejection of the null hypothesis is based on the magnitude of the observed percentage changes and their triangulation with qualitative evidence from follow-up interviews, where operators reported greater flexibility, fewer interruptions, and a positive perception of the usability of open-source tools.

The results obtained are consistent with the evidence synthesized in the PRISMA systematic review of 20 articles published between 2016 and 2026. Cycle time reductions of around 40% align with the 30–50% ranges reported in the literature for low-volume applications. Similarly, the decrease in material waste and the improvement in operational efficiency coincide with the benefits documented in studies of Italian and Mexican SMEs. The present work adds value by filling a gap identified in the review: the scarcity of pre-post mixed-methods experimental designs with low-cost FDM technologies in SMEs in specific regions such as Hidalgo.

Unlike most of the reviewed studies, which focus on high-cost metal technologies or developed-country contexts, this research demonstrates that accessible open-source technologies can generate measurable impacts in resource-constrained environments. Furthermore, the findings reinforce the theoretical frameworks of Diffusion of Innovations and the Resource-Based View by showing how an SME can convert a low-cost technology into an operational competitive advantage.

The limitations inherent to the single-case design are acknowledged. The absence of a control group prevents the establishment of causal relationships with the same rigor as a multi-site controlled experiment. The six-month follow-up period, although longer than that of many studies in the literature, does not allow evaluation of the sustainability of the gains in the medium and long term. Statistical generalization of the results is limited, given that a single manufacturing SME in Hidalgo was studied; the findings should be interpreted as evidence of contextual viability rather than results automatically extrapolable to all SMEs in the state or country. Finally, the measurement of some variables, such as the post-implementation waste rate, was performed in an estimated manner, introducing a margin of uncertainty that future studies could reduce through more automated data capture systems.

Based on the identified limitations and the gaps detected in the literature review, several future research lines are proposed. One consists of conducting multi-company implementations with several manufacturing SMEs in Hidalgo and other regions of Mexico, preferably with quasi-experimental designs or comparison groups, to evaluate the replicability of the six-phase methodology and the magnitude of effects in different sectors. Another relevant line is to extend follow-up beyond six months, ideally to periods of 12 to 24 months, in order to analyze whether productivity gains are maintained, increase, or diminish once the technology is integrated into routine operations, as well as equipment maintenance and replacement costs. It is also pertinent to explore the combination of additive manufacturing with basic IoT monitoring, artificial intelligence-assisted design,

and traceability systems, in order to measure additional impacts on quality, response times, and supply chain resilience.

Complementarily, it is recommended to quantify return on investment, energy balance, and contribution to circular economy objectives over a medium-term horizon, comparing FDM technologies with traditional alternatives and higher-cost additive technologies. Finally, it is suggested to deepen, through longitudinal qualitative approaches, the organizational, training, and cultural factors that facilitate or inhibit the sustained adoption of additive manufacturing in Mexican SMEs, with the purpose of refining the capacity development and scaling phases of the proposed methodology.

In summary, the present study provides empirical evidence that low-cost additive manufacturing can constitute an effective pathway to improve the productivity of manufacturing SMEs in Hidalgo. The proposed six-phase methodology offers a practical and replicable route that other resource-constrained companies can adapt. At the same time, the limitations of the single-case design and the gaps identified in the literature open a fertile field for future research that will strengthen the evidence base and expand the impact of these technologies on the regional and national productive fabric.

## REFERENCES

1. Arcos-Novillo, D. A., y Güemes-Castorena, D. (2017). Development of an additive manufacturing technology scenario for opportunity identification—The case of Mexico. Futures, 90, 1–15. https://doi.org/10.1016/j.futures.2017.05.001
2. Bettiol, M., Capestro, M., Di Maria, E., y Micelli, S. (2021). SMEs @ Industry 4.0: A comparison between top and average performers. Sinergie Italian Journal of Management, 39(2), 27–44. https://doi.org/10.7433/s116.2021.03
3. Cirillo, V., Fanti, L., Mina, A., y Ricci, A. (2023). The adoption of digital technologies: Investment, skills, work organisation. Structural Change and Economic Dynamics, 66, 89–105. https://doi.org/10.1016/j.strueco.2023.04.006
4. Diractum. (2025). Productividad e impresión 3D en México. [Reporte empresarial].
5. Frazier, W. E., Lu, Y., y Witherell, P. (2024). Empowering small and medium-sized enterprises through effective additive manufacturing data management (NIST AMS 100-59). National Institute of Standards and Technology. https://doi.org/10.6028/NIST.AMS.100-59
6. Gibson, I., Rosen, D., Stucker, B., y Khorasani, M. (2021). Additive manufacturing technologies (3rd ed.). Springer. https://doi.org/10.1007/978-3-030-56127-7
7. Haug, A., Wickstrøm, K. A., Stentoft, J., y Philipsen, K. (2023). Adoption of additive manufacturing: A survey of the role of knowledge networks and maturity in small and medium-sized Danish production firms. International Journal of Production Economics, 255, 108714. https://doi.org/10.1016/j.ijpe.2022.108714
8. INEGI. (2024). Estadísticas de productividad y digitalización en Mypes manufactureras mexicanas. Instituto Nacional de Estadística y Geografía.
9. Liberati, A., Altman, D. G., Tetzlaff, J., Mulrow, C., Gøtzsche, P. C., Ioannidis, J. P. A., Clarke, M., Devereaux, P. J., Kleijnen, J., y Moher, D. (2009). The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. PLoS Medicine, 6(7), e1000100. https://doi.org/10.1371/journal.pmed.1000100
10. López, O. E. (2025). Impresión 3D industrial y nearshoring en México. Modern Machine Shop México.
11. Marzi, G., Zollo, L., Boccardi, A., y Ciappei, C. (2018). Additive manufacturing in SMEs: Empirical evidences from Italy. International Journal of Innovation and Technology Management, 15(1), 1850007. https://doi.org/10.1142/S0219877018500074
12. McConnell, S., Tanner, D., y Kourousis, K. I. (2024). Productivity improvement opportunities for metal powder bed fusion technologies: A systematic literature review. Rapid Prototyping Journal, 30(11), 231–246. https://doi.org/10.1108/RPJ-09-2023-0333
13. OECD. (2019). OECD Territorial Reviews: Hidalgo, Mexico. OECD Publishing. https://doi.org/10.1787/9789264310391-en

14. Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ, 372, n71. https://doi.org/10.1136/bmj.n71
15. Rodríguez Salvador, M., Hernández de Menéndez, A. M., y Arcos Novillo, D. A. (2016). Additive manufacturing: Importance and challenges for Latin America. En Anticipating Future Innovation Pathways Through Large Data Analysis (pp. 249–271). Springer. https://doi.org/10.1007/978-3-319-39056-7_14
16. Rogers, E. M. (2003). Diffusion of innovations (5th ed.). Free Press.
17. Sáenz, R. (2025). 3D printing and design: A new era for Mexico's industry. Mexico Business News. https://mexicobusiness.news/aerospace/news/3d-printing-and-design-new-era-mexicos-industry
18. Saldana-Robles, A. L., Balvantin-Garcia, A. J., Aguilera-Gomez, E., et al. (2019). The insertion of low-cost additive manufacturing into engineering teaching: A case in central Mexico. International Journal of Materials and Product Technology, 59(3), 270–285. https://doi.org/10.1504/IJMPT.2019.102944
19. Sæterbø, M., y Solvang, W. D. (2024). Metal additive manufacturing adoption in SMEs: Technical attributes, challenges, and opportunities. Journal of Manufacturing Processes, 128, 175–189. https://doi.org/10.1016/j.jmapro.2024.07.074
20. Suarez-Luna, J. M., Romero-Guerrero, J. A., y Arenas-Islas, D. (2024). Productividad de granjas de manufactura aditiva en la cadena de suministro industrial. Pädi Boletín Científico de Ciencias Básicas e Ingenierías del ICBI, 12(Especial 4), 236–242. https://doi.org/10.29057/icbi.v12iespecial4.13268
21. Vázquez Rojas, A. M., Rodríguez Juárez, E., y González Gómez, D. X. (2016). Un análisis de la productividad manufacturera en el Estado de Hidalgo. Cimexus, 11(2), 13–28.