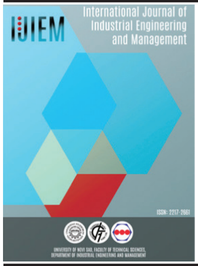
ISSN 2683-345X



journal homepage: http://ijiemjournal.uns.ac.rs/

International Journal of Industrial Engineering and Management

Volume 15 / No 2 / June 2024 / 109 - 124

Original research article

Application of a proposed additive manufacturing performance measurement system in a Brazilian industry

A. Neuenfeldt Júnior[a,*] 0000-0002-6492-6342, P. Nogueira[a] 0000-0002-9001-3256, M. Francescatto[a] 0000-0001-7554-9637, J. Siluk[a] 0000-0001-6755-7186, S. De Paris[a] 0000-0002-8145-0649, M. Mandlhate[a] 00009-0008-4880-8988

[a] *Federal University of Santa Maria, Santa Maria, Brazil*

ABSTRACT

Additive manufacturing as a new manufacturing process contributes to production systems progress, decreasing the lead time between product requests and customer delivery. The article presents a measurement system to verify the additive manufacturing performance in a Brazilian metal-mechanical industry, stratified methodologically in a top-down hierarchical decision-making structure with critical success factors and key performance indicators based on the Analytic Hierarchy Process to obtain the performance index. The performance measurement system was applied in a multinational metal-mechanical manufacturer of motorized tools from Brazil. The results show a neutral performance for the tooling sector, emphasizing key performance indicators related to new product research and development, importation cost rate, and traditional manufacturing processes reduction. Also, according to the experts consulted, the main factors related to additive manufacturing in developing countries' production chains are new product development, workforce training, and export activity.

ARTICLE INFO

Article history:

Received September 21, 2023
Revised March 8, 2024
Accepted March 20, 2024
Published online April 3, 2024

Keywords:
Additive manufacturing;
Competitiveness;
Performance measurement system;
Key performance indicators

*Corresponding author:
A. Neuenfeldt Júnior
alvaro.junior@ufsm.br

1. Introduction

The development of industries focused on consumer goods, aviation, defense, and health, generates specific demands for processes and technologies, as well as business-to-customer products. For the automotive industry, in addition to stamping and forming processes, additive manufacturing is used with composite materials (carbon fiber and cellulose nanocrystals) to reinforce glass or basalt fibers, providing good mechanical properties and weight reduction [1]. The potential to exploit additive manufacturing is enabled by component generation flexibility, exceeding industrial limits, and acting in areas of industrial, human, and technological development, by adding layers of material through three-dimensional models [2]-[5].

Research and technologies developed from the 1970s onwards combined with technology patents expired between 2009 and 2014, created a favorable environment for new manufacturing technologies related to additive manufacturing, mainly emphasizing the fused deposition process and the selective laser sintering process [6]-[9]. Processes and technologies including stereolithography, powder sintering, selec-

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

http://doi.org/10.24867/IJIEM-2024-2-351

tive sintering laser, filament extrusion, and layer lamination area also contributed to expanding additive manufacturing use [10].

Additive manufacturing, although highly promising, presents difficulties related to process type, inconsistency when applied in large-scale production, dimensional variations, and structural variations. However, compared to conventional manufacturing, additive manufacturing provides customization and innovation, generating freedom in product design [11], [12].

Emerging technologies guide the identification of areas not yet explored, visualizing opportunities and threats related to investment decisions (i.e., when, how much, and why), given the challenges for decision-making to invest in new technologies implementation such as additive manufacturing in emerging countries [13].

Therefore, a measurement system to verify additive manufacturing performance in a Brazilian metal-mechanical industry is presented. This research main contributions are: (i) Identify the main critical factors related to additive manufacturing success or potential failure to replace traditional manufacturing processes in a developing country production chain; (ii) Contribute to the academic community by bringing a methodological scientific contribution, systematizing by a performance measurement system approach, factors considered critical to additive manufacturing success, meeting expectations and practices adopted in metal-mechanical industries; (iii) Develop a performance measurement system replicable to different types of Brazilian or Latin American industries, despite the measurement system being mainly focused on serving national and multinational metal-mechanical industries, where additive manufacturing is already incorporated in the manufacturing process.

The article is structured as follows: Section 2 describes the proposed performance measurement system methodological steps; Section 3 shows the results obtained with the performance measurement system application in a multinational industry; and in Section 4, the research conclusion is presented.

2. Method

The Performance Measurement System (PMS) stratifies the research objective into a hierarchical decision-making structure [14]-[16], developed with a top-down orientation. As verified in Figure 1, the objective is located at the top, named "additive manufacturing measure", detailed in a second level in six Critical Success Factors (CSFs) based on [17]-[19], for a more refined description of the PMS objective main characteristics.

The third level is divided into 13 subfactors (SFs), detailed according to each CSF conceptual specification. In the fourth hierarchical structure level, 21 Key Performance Indicators (KPIs) are proposed to quantitatively measure the specific SF and, consequently, CSF competitiveness. Finally, a function aggregates the KPIs attributes and the SFs' importance, based on [20]-[22], combining the 21 KPIs performance measured individually to obtain the performance index, representing the overall "additive manufacturing measure" performance.

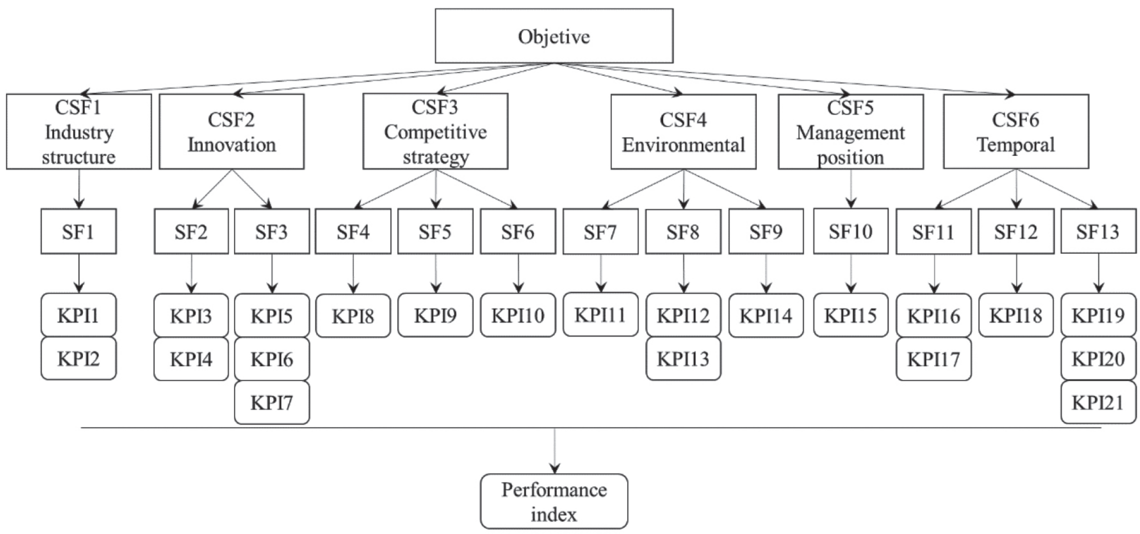


Figure 1. General top-down PMS hierarchical decision-making structure levels for additive manufacturing measure

Section 2.1 shows the CSF theoretical conception proposed for the "additive manufacturing measure". In Section 2.2, the SFs' importance calculation definition is described, involving the hierarchical structure with CSFs, SFs, KPIs, and the peer comparisons ratio to verify the experts' judgments consistency. Section 2.3 shows the performance index formulation, aggregating the SFs' importance with the KPIs attributes from an industrial scenario on the original input data collection scale converted to a standardized scale. Section 2.4 details the procedures adopted to collect data to obtain the SFs' importance from experts and to collect the KPIs attributes from an industrial scenario.

2.1 Critical success factors and subfactors

2.1.1 CSF1: Industry structure

For CSF1 (Industry structure), additive manufacturing promotes the introduction of new processes concomitant to subtractive processes. From the identification of opportunities to use additive manufacturing, the traditional strategies tend to be readjusted based on the opportunities presented. Additive manufacturing success is related to the use of materials and equipment to reach the quality requirements demanded by customers [23].

As for SF1 (centralized/decentralized industrial base), considering additive manufacturing, supply centralization has advantages including better resource use and consequent cost reduction due to lower carbon emissions [24], [25]. However, industrial base decentralization, where the incentive to scale economies combined with the use of accelerated growth regions to reach high economic integration rates, presents advantages over the centralized industrial bases [26].

2.1.2 CSF2: Innovation

CSF2 (Innovation) presents actions and initiatives to ensure the advancement of organizations and better use of available human resources to plan and execute production system operations. However, the innovation process depends on human qualities capable of generating change and guaranteeing good levels of competitiveness [27]. In Gibson et al. [10], an overview of additive manufacturing processes was provided, showing the additive manufacturing importance in different industries. The technology development was outlined, as well as the need for further studies in the area. Each group of technologies used in additive manufacturing was described in detail. Furthermore, how additive manufacturing can be applied in different settings was explored, showing selection methods and providing guidelines for selecting the right technology considering distinct purposes. In addition, the manufacturing technologies improved over the years, creating novel applications with different industries using additive manufacturing machines and, in specific cases, considering mass customization.

For SF2 (new products or platforms development), the main types of work arrangements, including functional, by-projects, and matrix, are considered in the engineering structure. Additive manufacturing enables the increase of freedom and restrictions changes related to design and conception [27]. For example, machine and cutting tools, required on a large scale in the metal-mechanical industry [28], [29], are disregarded when a traditional subtractive manufacturing operation is replaced by an additive manufacturing operation. However, processes need improvements, such as machine development, standardization, dimensional constraints reduction, and the development of guides for print preparation and post-processing [30], [31].

Klahn et al. [32] developed two different strategies to use additive manufacturing for product development. First, a manufacturing-driven design, which allows the substitution of manufacturing processes in the product life cycle later stages, was presented. The manufacturing-driven design maintains a conventional design, complying with different manufacturing technologies design rules. Second, a function-driven design to increase the product's performance was shown. The function-driven design uses additive manufacturing freedom to eliminate major adjustments to product design when transferred to conventional manufacturing.

Considering SF3 (business model changes), with additive manufacturing introduction, the business model change and/or restructuring impacts storage cost reductions, based on the parts and components centralized and decentralized supply. For the raw materials supply, additive manufacturing enables the possibility of including new incomes to compete with traditional manufacturers [33], [34].

Guo and Leu [35] highlight the evolution achieved with research related to new additive manufacturing processes developed in recent years and applications in areas including medicine, automotive, and aerospace. Industrial processes developed such as stereolithography, fused deposition modeling, selective laser sintering, Laminated Object Manufacturing (LOM), 3D printing (3DP), and Laser Metal Deposition (LMD) were discretized, as well as the materials employed and the materials available on the market for additive manufacturing use. According to Huang et al. [36], among the technical aspects and the additive manufacturing scope are the potential for simplifying the production chain, with opportunities for significant gains in efficiency and to answer demands.

2.1.3 CSF3: Competitive strategy

In CSF3 (competitive strategy), new “players” are noticed in established and structured markets, since additive manufacturing raw material resources and the establishment of long supply chains are unnecessary [34], [37], [38]. However, the optimization process extends from idea generation to validation until the product is on the market. Sectors including the automotive industry, where components customization using additive manufacturing has been present for at least a decade, and aeronautics, where the possibility of reducing spare parts inventories and increasing availability can provide financial benefits and drastically reduce delivery times, are paths to be explored by additive manufacturing implementation [39]. As a cornerstone for competitive strategy in technology industries research, Porter [40] presents five forces to identify generic key factors related to obtaining cost leadership, differentiation, and industrial success focus (threat of new entrants, bargaining power of buyers, bargaining power of suppliers, threat of substitute products, intensity of competitive rivalry), guiding the SF4, SF5, and SF6 development.

For SF4 (production process), the production process is evaluated considering product development improvements according to customers' needs. Therefore, concerning traditional business models, additive manufacturing can be advantageous [41]. Evaluating SF5 (materials and equipment) to identify which equipment generates adherence to the previously structured business model, and assessing the processes involved in the switch to additive manufacturing, is necessary, initiating a material flow restructuring regarding external and internal supply chain [11], [42].

As for SF6 (workforce training), the production technological development, as well as the redirection of business models, demands operational human resources preparation and training. DebRoy et al. [43] developed a review related to metallic materials additive manufacturing, involving processes, structure, and metallic parts properties, such as refractory alloys, precious metals, and compositionally graded alloys. The review examines the printability of engineering alloys considering the current knowledge base of additive manufacturing, metallurgy, and fusion welding. A review related to the needs and opportunities of uncertainty quantification and uncertainty management in additive manufacturing on laser power bed fusion was presented by Hu and Madahevan [44], showing insights related to how uncertainty qualification and uncertainty management techniques could be applied to additive manufacturing.

2.1.4 CSF4: Environmental

In CSF4 (environmental), industries invest in additive manufacturing to reduce pollutant emissions [12]. The environmental uncertainty verified in metal-mechanical industries, with traditional manufacturing processes, consumption of raw materials provided with scarce natural resources, costs related to logistic activities, raw material scrap, and variability of dependence on other industries, can positively impact new technologies adoption such as additive manufacturing [45], [46].

For SF7 (external uncertainties), alterations in the exchange rate regime, excessive price fluctuations, and importation taxes can negatively impact equipment and raw materials supply [47]. However, the exchange rate difference may benefit SF8 (export activity). Despite improving advances in the Brazilian additive manufacturing production chain, the additive manufacturing technology, inputs, and raw materials continue to be mostly imported.

Regarding SF9 (industry size), the production processes and systems complexity, related costs, and the distribution and inventory of spare parts can be impacted by additive manufacturing through scale gains [2], [10]. In Atzeni and Salmi [48], a comparison between the production costs using additive manufacturing and the production costs involved in the high-pressure casting process, with tooling construction and processes for aircraft metal components, is presented.

2.1.5 CSF5: Management position

For the evolution of new technologies, managers must be able to perform activities safely and must be able to work in interconnected and automated technological environments. Evaluations related to the replacement of traditional manufacturing processes by additive manufacturing and the production chain understanding can help maintain and improve business models, bringing industries closer to new manufacturing technologies and market shares [41], [49].

Regarding SF10 (vision and management training), additive manufacturing introduction in industrial systems requires extensive knowledge from managers to decide when, how, and where to use additive manufacturing, aiming to level productive characteristics and specialize employees [50], [51].

2.1.6 CSF6: Temporal

For CSF6 (temporal), evaluating a business model through the technologies used over time helps establish continuity. Understanding and identifying points of convergence considering technological evolution enable the detection of strengths and points to be developed for business continuity benefit.

Changes in consumption and the need to maintain competitive potential over time demand the search for new solutions and technologies for production processes and systems [52]-[54]. Understanding the correct industry positioning for a possible new technology change or implementation is relevant, presenting opportunities beyond the technical sphere related to materials and equipment used, opening the way for advances in the reduction of energy and raw material consumption, as well as product availability improvement [55].

Evaluating SF11 (additive manufacturing implementation) enables an increase in the capacity for innovation and customization, changing competitive and strategic industrial aspects [56]. The gain in speed and the simplification of production, storage, and distribution processes initiate production chain restructuring. In Pereira et al. [57], a review related to how the current additive manufacturing scenario can compete or add to established traditional manufacturing regions was proposed, considering additive manufacturing and subtractive manufacturing in an economic and quality management context. The cost models for high production volumes are better suited for traditional manufacturing, while the higher complexity or customization required is better suited for additive manufacturing. Furthermore, the requirements for the penetration of additive manufacturing in the commercial market include high process stability, a database containing properties of additive manufacturing materials, online quality control processes, continuous certification, and design rules provision. Also, Sun et al. [54] proposed a review article about the additive manufacturing technologies status in nuclear energy, battery, fuel cell, oil, and gas industries.

SF12 (industry 4.0) relates to Information Technology and the structuring of processes based on additive manufacturing. Production systems change, and additive manufacturing helps drive the migration to computerized and autonomous environments, providing levels of integration between productive sectors [41], [58]-[62]. Haleem and Javaid [63] presented a literature review on additive manufacturing applications in Industry 4.0, exploring how additive manufacturing is contributing to the fourth industrial revolution.

Finally, SF13 (impact of additive manufacturing) evaluates additive manufacturing through innovation and customization, without losing the quality standards and structural requirements practiced in traditional manufacturing [2]. Piller et al. [49] discussed the economic effects of additive manufacturing considering an innovation and production context.

2.2 Subfactors importance

With the CSFs and respective SFs explained, the PMS hierarchical structure is detailed according to what each KPI must assess to measure the additive manufacturing performance, as described in Table 1, developed following the methodological structure proposed in Gerhardt et al. [64], Neuenfeldt-Júnior et al. [65], Silva Júnior et al. [66], Neuenfeldt-Júnior and De Oliveira [67], Silva Júnior et al. [68], Gerhardt et al. [69], Alecio et al. [70], and Siluk et al. [71]. Also, KPIs are used to support the decision-making on SFs and CSFs quantitative analysis.

The measurement unfolding is the SFs importance verification, based on additive manufacturing experts' opinion, using the input data collection instrument named "diagnostic 1" (see Section 2.4), converted in a scale of importance based on Saaty [72] fundamental scale, where score 1 corresponds to an SF with little relevant to additive manufacturing performance and score 9 corresponds to an SF extremely relevant to additive manufacturing performance.

The score is non-restrictive and independent between SF. A square matrix A_{13x13} (Eq. 1) is developed from each expert score, based on the Analytic Hierarchy Process (AHP), where the number of columns and the number of rows correspond to the 13 SF proposed in the PMS (sf) and parity comparisons between the scores designated by the expert are performed with the square matrix A_{13x13} [72], [73].

$$A_{13x13} = \begin{bmatrix} a_{11} & \cdots & a_{113} \\ \vdots & \ddots & \vdots \\ a_{131} & \cdots & a_{1313} \end{bmatrix} \quad (1)$$

Table 1. PMS hierarchical decision-making structure with a brief contextualization of the information assessed by each KPI

SFs	KPIs	What does it assess?
	CSF1: Industry structure	
SF1: Centralized/decentralized industrial base	KPI1: Domestic production chain utilization KPI2: Foreign production chain utilization	Supply chain, business structuring, and strategic plan development
	CSF2: Innovation	
SF2: New products or platforms development	KPI3: New products research and development KPI4: New products development	New products and/or platforms development and implementation
SF3: Business model changes	KPI5: Production for stocks KPI6: Finished products availability KPI7: Storage cost rate	Finished products availability and inventory utilization
	CSF3: Competitive strategy	
SF4: Production process	KPI8: Products from additive manufacturing	Industry potential competitiveness
SF5: Materials and equipment	KPI9: Modernization	Industry potential competitiveness
SF6: Workforce training	KPI10: Additive manufacturing knowledge by the workforce	Workforce preparation and training
	CSF4: Environmental	
SF7: External uncertainties	KPI11: Importation cost rate	Input and raw material costs
SF8: Export activity	KPI12: Exportation rate KPI13: Stocked products availability	Export potential
SF9: Industry size	KPI14: Market share	Industry market size and share
	CSF5: Management position	
SF10: Vision and management training	KPI15: Additive manufacturing knowledge by managers	Managers' preparation and training
	CSF6: Temporal	
SF11: Additive manufacturing implementation	KPI16: Efficiency KPI17: Raw material availability	Additive manufacturing implementation speed
SF12: Industry 4.0	KPI18: Integrated management system level	New technologies and systems use
SF13: Impact of additive manufacturing	KPI19: Traditional manufacturing processes reduction KPI20: Operational effectiveness KPI21: Time between order entry and product delivery	Additive manufacturing implementation and use gains

The SF importance (w_{sf_f}) is the sum of the parity comparisons in the square matrix A_{13x13} lines, as shown in Eq. 2, where index f represents the experts interviewed during the PMS application.

$$w_{sf\,f} = \frac{\sum_{j=1}^{13} a_{ij}}{\sum_{i=1}^{13} \sum_{j=1}^{13} a_{ij}} \qquad (2)$$

Since parity comparisons and the square matrix A_{13x13} are developed individually for each expert, and the SF importance aggregation is developed using an additive function (w_{sf}) [20]-[22], as shown in Eq. 3, where (δ_f) is used to quantify possible differences if the experts' profile (z) is heterogeneous [74].

$$w_{sf} = \sum_{f=1}^{z} \delta_f \, x w_{sf\,f} \qquad (3)$$

To verify the consistency of peer comparisons, the consistency ratio of each parity matrix A_{13x13} must be calculated. According to Saaty [72], a consistency ratio below 10% indicates a coherent experts' judgments and, if the consistency ratio is greater than 10%, the expert should correct the inconsistency verified or the calculated importance should be disregarded.

2.3 Performance index

With the hierarchical structuring, the KPIs' attributes were developed relating to the SFs' potential impact on the analyzed industry (a), obtained using the input data collection instrument named "diagnostic 2" (see Section 2.4), by metrics described in the original scales (v'_{kpi_a}), as shown in Table 2. All KPIs'attributes on the original input data collection scale were reported by industrial managers.

Table 2. KPIs metrics definition and original input data collection scales (v'_{kpi_a}) from industrial managers

KPIs	Metrics	Original scale (v'_{kpi_a})
	SF1: Centralized/decentralized industrial base	
KPI1: Domestic production chain utilization	Inputs purchased in the domestic market/Total inputs purchased	Percentage
KPI2: Foreign production chain utilization	Inputs purchased on the foreign market/Total inputs purchased	Percentage
	SF2: New products or platforms development	
KPI3: New products research and development	Research and development investments/New products or platforms investments	Percentage
KPI4: New products development	Number of new products/Number of existing products	Percentage
	SF3: Business model changes	
KPI5: Production for stocks	Stocked products/Manufactured products	Percentage
KPI6: Finished products availability	(Finished + Stocked) products/Manufactured products	Percentage
KPI7: Storage cost rate	Storage cost/Fixed cost	Percentage
	SF4: Production process	
KPI8: Products from additive manufacturing	Products manufactured using addictive manufacturing/Manufactured products	Percentage
	SF5: Materials and equipment	
KPI9: Modernization	Materials and equipment modernization investments/Total in investments	Percentage
	SF6: Workforce training	
KPI10: Additive manufacturing knowledge by the workforce	1-Little knowledge 2-Knows, but does not apply 3-Knows and apply 4-Masters the technology 5-Master and develop the technology	Absolute
	SF7: External uncertainties	
KPI11: Importation cost rate	Imported raw material cost/Total raw material cost	Percentage
	SF8: Export activity	
KPI12: Exportation rate	Exported products/Manufactured products	Percentage
KPI13: Stocked products availability	Stocked products/Manufactured products	Percentage
	SF9: Industry size	
KPI14: Market share	Manufactured products sold value/Market size	Percentage
	SF10: Vision and management training	
KPI15: Additive manufacturing knowledge by managers	1-Little knowledge 2-Knows, but does not apply 3-Knows and apply 4-Masters the technology 5-Master and develop the technology	Absolute
	SF11: Additive manufacturing implementation	
KPI16: Efficiency	Time spent on operation/Total time available	Percentage
KPI17: Raw material availability	Raw material consumption/Raw material available	Percentage
	SF12: Industry 4.0	
KPI18: Integrated management system	1-Little knowledge 2-Knows, but does not apply 3-Knows and apply 4-Masters the technology 5-Master and develop the technology	Absolute
	SF13: Impact of additive manufacturing	
KPI19: Traditional manufacturing processes reduction	Processes after additive manufacturing implementation/Processes before additive manufacturing implementation	Percentage
KPI20: Operational effectiveness	Operational effectiveness after additive manufacturing implementation/ Operational effectiveness before additive manufacturing implementation	Percentage
KPI21: Order entry and product delivery	Lead time after the additive manufacturing implementation/Lead time before the additive manufacturing implementation	Percentage

To transform real situations into a parameterized numeric scale, attributes on the original scale were converted to a standardized scale (v_{kpi_a}), determining the optimal, intermediate, and minimally acceptable points of performance, distributed in five classes from 1 to 5. An attribute equal to 1 refers to a completely unsatisfactory performance, while an attribute equal to 5 is related to a completely satisfactory performance, with a positive linear variation of 1 value between intermediate classes. The distribution in five classes, as well as the original and the standardized limits, were structured according to Neuenfeldt-Junior et al. [62], Ramirez et al. [74], and Leal et al. [75] during PMS development. Therefore, the attributes were converted from the original scale to the standardized scale according to Table 3. Also, considering the standardized scale, each SF performance (v_{sf_a}) is calculated by its KPIs' attributes arithmetic mean.

To measure the analyzed industry, the performance index (I_a) aggregates the KPIs' attributes and the SFs' importance, as shown in Eq. 4, expressed on the same scale of values as the KPIs, ranging from a completely unsatisfactory performance (equal to 1) to a completely satisfactory performance (equal to 5).

$$I_a = \sum_{sf=1}^{13} v_{sf\,a}\, x w_{sf} \tag{4}$$

Thus, PMS enables the evaluation of an entire industry or a specific sector (tooling, machining, welding, assembly, etc.) from a strategic point of view. Regardless of the total or partial KPIs usage for further measurement, PMS can provide the necessary support for decision-makers. Therefore, the SFs importance (w_{sf_f}) not included in the performance measurement of a specific sector must be linearly redistributed among the SFs, where the sum of SFs importances used is equal to 100%.

2.4 Data collection procedures

Two quantitative instruments were developed for PMS data collection. The first instrument, named "diagnostic 1", is used to obtain all input data for SFs' importance measure, containing 13 questions, one for each SF, where the expert must adopt one of the five qualitative options available (little relevant, low relevant, relevant, high relevant, and extremely relevant). As described in Section 2.2, the input data informed in the qualitative format is converted to a quantitative scale (from 1 to 9 values, separated by a gap of 2 values), defining the SFs' importance based on the AHP. A version of the "diagnostic 1" available online, in Portuguese[1].

The second instrument, named "diagnostic 2", was developed to obtain all input data related to the analyzed industry situation, containing 34 questions related to all input data required to calculate the 21 KPIs' attributes metrics (Table 4). The answers format follows the standard required for the original scale of each KPI. Also, the recommended evaluation period is the last complete year or year to date since the input data collection.

"Diagnostic 1" can be applied online for experts, while "diagnostic 2" should be applied, preferably, in person with industry managers to obtain the KPIs' attributes input data and the qualitative perception regarding additive manufacturing adoption compared to traditional manufacturing formats.

3. PMS application

3.1 Subfactors importance calculation

Table 5 shows the results obtained for SFs' importance, considering the average importance (w_{sf}) given by nine experts using the input data collection "diagnostic 1". The data collection was performed

Table 3. Standardized scale (v_{kpi_a}) conversion using the original scale

Qualitative performance scale	Original scale (v'_{kpi_a})	Standardized scale (v_{kpi_a})
Completely satisfactory	81% to 100%	5
Satisfactory	61% to 80%	4
Neutral	41% to 60%	3
Unsatisfactory	21% to 40%	2
Completely unsatisfactory	0% to 20%	1

[1] https://www.researchgate.net/publication/378207543_Diagnostic_1_PMS_additive_manufacturing

Table 4. 34 questions from "diagnostic 2" with the adopted measure unit of measure

Question	Unit of measure
Inputs purchased in the domestic market	Monetary ($)
Inputs purchased on the foreign market	
Total inputs purchased	
Research and development investments	
New products or platforms investments	
Materials and equipment modernization investments	
Total in investments	
Storage cost	
Fixed cost	
Imported raw material cost	
Domestic raw material cost	
Total raw material cost	
Manufactured products sold value	
Market size	
Number of new products	Absolute
Number of existing products	
Stocked products	
Finished products	
Manufactured products	
Exported products	
Products manufactured using addictive manufacturing	
Processes after additive manufacturing implementation	
Processes before additive manufacturing implementation	
Additive manufacturing knowledge level by the workforce	Absolute (1 to 5)
Additive manufacturing knowledge level by managers	
Integrated management system level	
Lead time after the additive manufacturing implementation	Time (days)
Lead time before the additive manufacturing implementation	
Time spent on the operation	Time (hour)
Total time available	
Raw material consumption	Quantity/hour
Raw material available	
Operational effectiveness after additive manufacturing implementation	Percentage
Operational effectiveness before additive manufacturing implementation	

from August to October 2022, with professionals from industries involved in projects related to additive manufacturing in Brazil and academic professionals. The evaluated SFs' importance consistency ratio is below 10% and the relevance (δ_f) is equal to 1 for all experts consulted, given the similar profile verified during the input data collection.

The highest importance value is for SF2 (new products or platforms development), showing the relevance of technological evolution and the combination of areas including engineering and information technology for the production system evolution, affecting the commercialized products.

For SF8 (export activity), not identifying external opportunities results in significant losses, especially for industries operating in different world markets. Considering additive manufacturing, where internationally developed technologies and raw materials are predominant, not considering exchange rate fluctuations or incentive laws for regional industrial development can directly impact industrial processes.

3.2 Case study performance evaluation

The analyzed industry is a multinational metal-mechanical manufacturer of motorized tools for

Table 5. Results for SFs importance by expert and the average SFs importance (w_{sf}) considering the experts' opinions

SF	SFs importance by expert									Aver. w_{sf}
	1	2	3	4	5	6	7	8	9	
SF2	8.1%	8.9%	9.1%	7.4%	9.3%	8.6%	11.1%	8.4%	10.3%	9.0%
SF6	8.1%	8.9%	9.1%	9.5%	9.3%	6.7%	8.6%	8.4%	8.0%	8.5%
SF8	8.1%	6.9%	9.1%	7.4%	7.2%	6.7%	11.1%	8.4%	8.0%	8.1%
SF10	6.3%	8.9%	9.1%	7.4%	9.3%	8.6%	6.2%	8.4%	8.0%	8.0%
SF11	8.1%	6.9%	9.1%	9.5%	9.3%	8.6%	6.2%	8.4%	5.7%	8.0%
SF3	8.1%	8.9%	7.1%	9.5%	7.2%	6.7%	8.6%	4.7%	8.0%	7.6%
SF7	8.1%	6.9%	5.1%	7.4%	7.2%	8.6%	8.6%	8.4%	8.0%	7.6%
SF4	8.1%	8.9%	7.1%	7.4%	7.2%	8.6%	6.2%	6.5%	8.0%	7.6%
SF12	8.1%	6.9%	3.0%	7.4%	9.3%	8.6%	8.6%	8.4%	5.7%	7.3%
SF5	6.3%	6.9%	9.1%	7.4%	7.2%	8.6%	3.7%	8.4%	8.0%	7.3%
SF9	8.1%	6.9%	7.1%	5.3%	5.2%	6.7%	8.6%	8.4%	8.0%	7.1%
SF13	8.1%	6.9%	9.1%	7.4%	7.2%	6.7%	3.7%	6.5%	8.0%	7.1%
SF1	6.3%	6.9%	7.1%	7.4%	5.2%	6.7%	8.6%	6.5%	5.7%	6.7%

forestry, agricultural, construction, conservation, and gardening segments, based in Germany. The PMS was applied in the Brazilian branch, specifically in the tooling sector, where additive manufacturing is widely used for mold cooling channel production to gain productivity, reduce cycle time, improve injected parts quality, increase injection process speed, and improve final product quality. The tooling sector is a key part of the business model, as the renovation, development, and new injection mold implementation allow continuous advancement.

To adapt the PMS to measure the tooling sector performance, SF3 (business model changes), SF4 (production process), SF8 (export activity), and SF9 (industry size) were not evaluated. As a specific and technical sector, the evaluated CSF contemplates characteristics focused on restricted machines, materials, labor, and technologies usage. As proposed in the PMS, the SFs importance not included in the tooling sector performance measurement must be redistributed among the measured SFs. Table 6 shows the recalculated importance of SF2 (new product or platform development), SF1 (centralized/decentralized industrial base), SF5 (materials and equipment), SF7 (external uncertainties), SF11 (additive manufacturing deployment), and SF13 (impact of additive manufacturing).

Table 7 shows the results obtained with the additive manufacturing performance measurement, collected using the "diagnostic 2", in December 2022, for the multinational metal-mechanical manufacturer tooling sector, with KPIs' attributes values equal to 5 related to new products research and development, importation cost rate, and traditional manufacturing processes reduction. KPIs' attribute values equal to 4 are concentrated in aspects focused on foreign pro-

Table 6. Recalculated SFs' importance to adapt the PMS to measure the tooling sector performance

SF	w_{sf}	w_{sf} (Recalculated)
SF1	6.70%	9.65%
SF2	9.00%	12.97%
SF5	7.30%	10.49%
SF6	8.50%	12.24%
SF7	7.60%	10.92%
SF10	8.00%	11.53%
SF11	8.00%	11.47%
SF12	7.30%	10.56%
SF13	7.10%	10.17%
Total	69.50%	100%

Table 7. Tooling sector additive manufacturing performance index result

KPI	v_{kpi_a}	I_a	Qualitative scale
KPI1: Domestic production chain utilization	1		
KPI2: Foreign production chain utilization	4		
KPI3: New products research and development	5		
KPI4: New products or platforms development	1		
KPI9: Modernization	1		
KPI10: Additive manufacturing knowledge by the workforce	4	3.40	Neutral performance
KPI11: Importation cost rate	5		
KPI15: Additive manufacturing knowledge by managers	4		
KPI17: Efficiency	3		
KPI18: Integrated management system level	3		
KPI19: Traditional manufacturing processes reduction	5		

duction chain utilization and additive manufacturing knowledge by the workforce. In opposite, KPIs' attributes with completely unsatisfactory performance (equal to 1) are focused on domestic production chain utilization, new products or platforms development, and modernization aspects. An evaluation based on the best and worst performances is proposed for the SFs.

For SF2 (new products or platforms development), the industry applies a planned annual investment for research and development towards modernization, application, and introduction of new ideas and products, with a 3% increase in the number of different molds produced, compared to previous years. As verified by Liu et al. [76], additive manufacturing provides freedom for design structures, exhibiting uncertainties in the product design concept [77], but mainly due to material properties. In SF5 (materials and equipment), the modernization investments are 2% of the total tooling sector investments, as verified in Babu et al. [78] for high-cost preprocessed plastic components polymer filaments (USD$1.40/kg) compared with reinforced acrylonitrile butadiene styrene carbon-fibers (US$11/kg). Another example is found in ceramic additive manufacturing [79], which allows the manufacturing of complex parts without the high mold-associated costs (equipment and feedstock) from traditional ceramic manufacturing.

Regarding investment in workforce training rate, considering SF6 (workforce training), 63% of all 2020 planned investment was used on international and national trips for technical visits and congress participation, despite COVID-19. A trained industrial workforce knowing how to apply new technologies to solve real-world problems is an increasing and continuous demand to be invested. In Simpson et al. [80], five key educational themes were identified as fundamental to developing the workforce: (i) additive manufacturing processes and processes and materials relations; (ii) engineering fundamentals with an emphasis on materials science and manufacturing; (iii) professional skills for problem-solving and critical thinking, (iv) design practices and tools that leverage the design freedom enabled by additive manufacturing, and (v) cross-functional teaming and ideation techniques to nurture creativity. A manufacturing industry can familiarize employees with additive manufacturing with low investment and minimal training cost. Also, small investment initiatives can be associated with university partnerships. For SF10 (vision and management training), the knowledge about additive manufacturing covers both operational and strategic workforce, due to the need to invest in training and capacity, reaching a strategic status and satisfactory performance. Demand for new management approaches is described in Patalas-Maliszewska and Topczak [61], based on additive manufacturing technologies and Industry 4.0 requirements to increase competitive advantage by reducing waste.

SF11 (additive manufacturing implementation) is performance neutral, where the technology complexity demands a relatively long learning curve for new developments. The total available hours allocated to develop activities is 50%, composed of meetings and case discussions. Thus, the additive manufacturing implementation speed is relatively short [61]. However, technical challenges must be solved for additive manufacturing implementation, including materials standardization and interfacial bonding quality between the deposited layers [81]. Even with follow-up activities being developed, the activities' complexity involved is relevant and demands support from different sectors and a consistent manufacturing structure, as verified for light and high-tech small and medium-sized manufacturing industries in the Netherlands [82] or for defense industries in the United States [83].

As for SF7 (external uncertainties), the raw material cost indicator is ineffective, since the raw material used in additive manufacturing comes heavily from external suppliers. Zaidia and Hasana [84] shows an information-sharing and risk mitigation framework among supply chain departments, being labor strikes and government regulations as the top risk priorities. Compared to other regions and countries, considering the necessary financial investment, Brazil is not competitive, which is a barrier to additive manufacturing adoption. When considering the global network and the current supply chain complexity, where raw materials are mined in one country, processed at another location, and assembled into an array of multiple products and sites, it is possible to understand the high entry barrier for additive manufacturing to replace traditional industries processes in a short-term period [5]. To identify and create strategies to overcome external uncertainties, the development of learning factories can be an effective solution to approach new technologies, as verified in the Brazilian context [85].

Therefore, CFS4 (environmental) has a disadvantage due to its dependence on raw materials supplied from abroad. From one perspective, there is applicability and the need to establish increasing levels of competitiveness for the domestic industry. However, a technological gap in the Brazilian production chain is verified. Rejeski et al. [86] outlines some potential environmental implications related to additive manufacturing as energy use, occupational health, waste, lifecycle impact, and cross-cutting and policy issues. In SF13 (additive manufacturing impact), additive manufacturing requires the improvement and simplification of the manufacturing processes involved, since the number of molds reduces the number of processes in the product line by 97% compared to traditional manufacturing, increasing the molds' use efficiency. Thus, additive manufacturing improves the life cycle environmental performance by redesigning components for weight reduction. However, a clean electricity source is required as well as technological development allowing for large components manufacturing, with low-impact raw materials [87]. Peng et al. [55] provides an additive manufacturing sustainability overview focused on energy and environmental impacts. Resource consumption is identified as the most important aspect, but also design, material preparation, manufacturing, usage, and end-of-life treatment are aspects to be considered.

Finally, for SF1 (centralized/decentralized industrial base), 20% of the financial resources available are invested in the regional production chain (Brazil) and 80% in the global production chain (one or more countries). The difference verified between national and global production chains is confirmed by the low Brazilian additive manufacturing competitiveness, specifically by the low inputs availability. Since the evaluated industry is multinational, the input acquisition in the international market is guaranteed, facilitating acquisition and negotiation, and providing competitiveness by a variety of first-line inputs. However, for Manco et al. [88], the adoption of a centralized or a decentralized supply chain remains an open issue, parametrized depending on strategic decisions impacted by economic and environmental sustainability. The results show that fully decentralizing production by renting production capacity and outsourcing post-processing activities is a good solution, mainly considering green supply chain aspects. Thus, for a short-term production demand forecast, the complete regional production chain compared with the global production chain use is not feasible.

3.3 Improvement suggestions

For CSF1 (industry structure), which encompasses KPI1 (domestic production chain utilization) and KPI2 (foreign production chain utilization), expanding the knowledge about additive manufacturing impact in centralized and decentralized models could be a good alternative to address. Identifying or developing regional suppliers with the same inputs availability and quality comparable to foreign inputs would improve the results for KPI1 attribute (regional production chain (Brazil) utilization rate) to a neutral or satisfactory qualitative scale.

In CSF2 (innovation), composed of KPI3 (new products research and development) and KPI4 (new products or platforms development), increasing the understanding achieved by integrating new technologies including the internet of things, artificial intelligence, cloud computing, blockchain, and virtual simulations are improvement possibilities for additive manufacturing [89]. Since KPI3 (new products research and development) presents a performance classified as completely satisfactory, consequently, the investment distribution and concentration of efforts in additive manufacturing application and expansion increases the KPI4 performance (new products or platforms development). Additive manufacturing technologies may require an increase in investment levels for research and development, presenting a high return rate, since the options for exploring additive manufacturing are wide and unrestricted [90].

The CSF3 (competitive strategy), specifically KPI9 (modernization) and KPI10 (additive manufacturing knowledge by workforce) can be better explored by the analyzed industry. Developing a workforce without investing in materials and equipment modernization shows the industry's lack of preparation, which could be included as research and development goals, such as research and application of business knowledge structural aspects through workforce improvement.

CSF4 (environmental), with KPI11 (importation cost rate), presents a completely satisfactory performance. However, exploring new supply possibilities and new markets indicates a strategic option, since the industry uses imported raw materials due to the lack of local market raw materials. CSF5 (management position), composed of KPI15 (additive manufacturing knowledge by managers), is a relevant aspect to be explored when human potential is considered. Developing and preparing decision-makers regarding the use and employment of new technologies creates a synergy between knowledge and practical application, providing an expanded view of business needs. Therefore, managers' knowledge guides the decision-making related to investment levels, areas, sectors, and technologies. In CSF6 (temporal), with KPI18 (integrated management system level), improvements related to issues in expanding manufacturing processes automation in Industry 4.0, can be gradually implemented using the knowledge already acquired by the managers and the workforce.

4. Conclusion

The following arguments show the main perspectives highlighted from the proposed research:

- In this research a PMS was proposed to verify the status of the additive manufacturing use in a Brazilian metal-mechanical industry, given by the quantitative indicator performance index, hierarchically structured based on 21 KPIs from 6 CSFs;
- According to nine experts consulted, the main factors related to additive manufacturing found in a developing country's production chain are new products or platforms development (SF2), workforce training (SF6), and export activity (SF8). The experts' perception is relevant and can be influenced in the expansion, adoption, or non-adoption of additive manufacturing in metal-mechanical industries, mainly to replace traditional manufacturing processes;
- The PMS developed based on a hierarchical structure with CSFs, SFs, and KPIs is useful to measure additive manufacturing performance, bringing a methodological scientific contribution to achieve industrial expectations and practices. From the application in a Brazilian multinational metal-mechanical industry, the KPIs new products research and development (KPI3), import cost rate (KPI11), and traditional manufacturing processes reduction (KPI19) contributed significantly to obtain a 3.40 score (maximum possible 5.00) in the performance index, considered as neutral performance;
- The performance index calculation is flexible and can be adapted by adding, replacing, or removing SFs according to the industry type or sector studied, as verified for the tooling sector performance measurement developed in the analyzed industry. However, the SFs' importance must be recalculated, following the procedures described in Section 2.3;
- The main research limitations are: (i) restricted access to qualified experts capable of accurately answering the 13 questions from "diagnosis 1" to define SFs' importance; (ii) the PMS was applied in only one multinational metal-mechanical industry, being infeasible to generalize the results for all additive manufacturing Brazilian industries context;
- Understanding the new digital models offered by advances in additive manufacturing concerning applicability in emerging markets, such as Brazil or another Latin American country, can be expanded in future research. In addition, within the Industry 4.0 concept and additive manufacturing technologies, research related to decision-making can be developed based on the proposed PMS.
- Finally, the quantitative indicator performance index was developed to be easily applied to measure the status of the additive manufacturing of any Brazilian metal-mechanical industry. Also, the PMS calculation structure does not require the use of complex software to be applied in practice, in addition to the low difficulty of obtaining the input data related to the KPIs attribute.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] G. Liu, X. Zhang, X. Chen, Y. He, L. Cheng, M. Huo, and J. and Lu, "Additive manufacturing of structural materials", Mater. Sci. Eng. R: Reports, vol. 145, p. 100596, 2021, doi:10.1016/j.mser.2020.100596.

[2] S. H. Huang, P. Liu, A. Mokasdar, and L. Hou, "Additive manufacturing and its societal impact: a literature review", Int. J. Adv. Manuf. Technol., vol. 67, no. 5, pp. 1191-1203, 2013, doi:10.1007/s00170-012-4558-5.

[3] I. Campbell, D. Bourell, and I. Gibson, "Additive manufacturing: rapid prototyping comes of age," Rapid Prototyping J., vol. 18, no. 4, pp. 255-258, 2012, doi:1108/13552541211231563.

[4] D. R. Eyers, A. T. Potter, J. Gosling, and M. M. Naim, "The flexibility of industrial additive manufacturing systems", Int. J. Oper. Prod. Manage., vol. 38, no. 12, pp. 2313-2343, 2018, doi:10.1108/IJOPM-04-2016-0200.

[5] S. A. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, and C. Charitidis, "Additive manufacturing: scientific and technological challenges, market uptake and opportunities", Mater. Today, vol. 21, no. 1, pp. 22-37, 2018, doi:10.1016/j.mattod.2017.07.001.

[6] B. Vayre, F. Vignat, and F. Villeneuve, "Metallic additive manufacturing: state-of-the-art review and prospects," Mech. Ind., vol. 13, no. 2, pp. 89-96, 2012, doi: 10.1051/meca/2012003.

[7] O. A. Mohamed, S. H. Masood, and J. L. Bhowmik, "Investigation of dynamic elastic deformation of parts processed by fused deposition modeling additive manufacturing," Adv. Prod. Eng. Manage., vol. 11, no. 3, pp. 227-238, 2016. doi: 10.14743/apem2016.3.223.

[8] K. Rajaguru, T. Karthikeyan, and V. Vijayan, "Additive manufacturing–State of art," Mater. today: proceedings, vol. 21, no. 1, pp. 628-633, 2020. doi: 10.1016/j.matpr.2019.06.728.

[9] C. Wang, X. P. Tan, S. B. Tor, and C. S. Lim, "Machine learning in additive manufacturing: State-of-the-art and perspectives", Addit. Manuf., vol. 36, p. 101538, 2020, doi:10.1016/j.addma.2020.101538.

[10] I. Gibson, D. W. Rosen, B. Stucker, M. Khorasani, D. Rosen, B. Stucker, and M. Khorasani, Additive manufacturing technologies, Springer, Switzerland, 2021.

[11] S. Lim, R. A. Buswell, T. T. Le, S. A. Austin, A. G. Gibb, and T. Thorpe, "Developments in construction-scale additive manufacturing processes", Autom. Constr., vol. 21, no. 1, pp. 262-268, 2012, doi: 10.1016/j.autcon.2011.06.010.

[12] W. E. Frazier, "Metal additive manufacturing: a review," J. Mater. Eng. Perform., vol. 23, no. 6, pp. 1917-1928, 2014. doi: 10.1007/s11665-014-0958-z.

[13] Y. Jin, S. Ji, X. Li, and J. Yu, "A scientometric review of hotspots and emerging trends in additive manufacturing", J. Manuf. Technol. Manage., vol. 28, no. 1, pp. 18-38, 2017, doi: 10.1108/JMTM-12-2015-0114.

[14] R. Silvi, M. Bartolini, A. Raffoni, and F. Visani, "The practice of strategic performance measurement systems: Models, drivers and information effectiveness," Int. J. Product. Perform. Manage., vol. 64, no. 2, pp. 194–227, doi:10.1108/IJPPM-01-2014-0010.

[15] C. R. Silva Júnior, J. C. M. Siluk, A. Neuenfeldt Júnior, M. Francescatto, and C. Michelin, "A competitiveness measurement system of Brazilian start-ups," Int. J. Product. Perform. Manage., doi:10.1108/IJPPM-02-2022-0098.

[16] M. Francescatto, A. Neuenfeldt Júnior, F. I. Kubota, G. Guimarães, and B. de Oliveira, "Lean Six Sigma case studies literature overview: critical success factors and difficulties," Int. J. Product. Perform. Manage., vol. 72, no. 1, pp. 1–23, doi:10.1108/IJPPM-12-2021-0681.

[17] J. Ram and D. Corkindale, "How "critical" are the critical success factors (CSFs)? Examining the role of CSFs for ERP," Bus. Process. Manage. J., vol. 20, no. 1, pp. 151–174, 2014.

[18] M. S. Bhatia and S. Kumar, "Critical success factors of industry 4.0 in automotive manufacturing industry," IEEE Trans. Eng. Manage., vol. 69, no. 5, pp. 2439–2453, 2020.

[19] M. Bongo, D. P. Abellana, S. A. Jr R. A., Caballes, C. Himang, J. J. Obiso, and C. Deocaris, "Critical success factors in implementing Industry 4.0 from an organisational point of view: a literature analysis," Int. J. Adv. Oper. Manage., vol. 12, no. 3, pp. 273–301, 2020.

[20] M. T. Escobar and J. M. Moreno-Jimenéz, "Aggregation of individual preference structures in AHP-group decision making," Group Decis. Negot., vol. 16, no. 4, pp. 287–301, 2007.

[21] A. Ishizaka, D. Balkenborg, and T. Kaplan, "Influence of aggregation and measurement scale on ranking a compromise alternative in AHP," J. Oper. Res. Soc., vol. 62, no. 4, pp. 700–710, 2011.

[22] A. Kolesárová, J. Li, and R. Mesiar, "k-additive aggregation functions and their characterization," Eur. J. Oper. Res., vol. 265, no. 3, pp. 985–992, 2018.

[23] O. Salunkhe and Å. F. Berglund, "Industry 4.0 enabling technologies for increasing operational flexibility in final assembly," Int. J. Ind. Eng. Manage., vol. 13, no. 1, pp. 38–48, 2022, doi: 10.24867/IJIEM-2022-1-299.

[24] G. A. Adam and D. Zimmer, "Design for Additive Manufacturing—Element transitions and aggregated structures," CIRP J. Manuf. Sci. Technol., vol. 7, no. 1, pp. 20–28, 2014, doi: 10.1016/j.cirpj.2013.10.001.

[25] J. Plocher and A. Panesar, "Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures," Mater. Des., vol. 183, p. 108164, 2019, doi:10.1016/j.matdes.2019.108164.

[26] R. Kleer and F. T. Piller, "Local manufacturing and structural shifts in competition: Market dynamics of additive manufacturing," Int. J. Prod. Econ., vol. 216, no. 1, pp. 23–34, 2019, doi:10.1016/j.ijpe.2019.04.019.

[27] W. Gao et al., "The status, challenges, and future of additive manufacturing in engineering," Comput. Aided Des., vol. 69, no. 1, pp. 65–89, 2015, doi:10.1016/j.cad.2015.04.001.

[28] M. Francescatto, A. L. Neuenfeldt Júnior, E. Silva, J. C. Furtado, and D. Bromberger, "Impact of minimum distance constraints on sheet metal waste for plasma cutting," PLoS One, vol. 18, p. e0292032, 2023.

[29] A. Neuenfeldt Junior, M. Francescatto, O. Araujo, D. T. Disconzi, and G. Stieler, "The machining torch movement for the rectangular plasma sheet metal cut," PLoS One, v. 18, p. e0291184-1, 2023.

[30] M. Vaezi, H. Seitz, and S. Yang, "A review on 3D micro-additive manufacturing technologies," Int. J. Adv. Manuf. Technol., vol. 67, no. 5, pp. 1721–1754, 2013, doi:10.1007/s00170-012-4605-2.

[31] D. Herzog, V. Seyda, E. Wycisk, and C. Emmelmann, "Additive manufacturing of metals," Acta Mater., vol. 117, pp. 371–392, 2016, doi:10.1016/j.actamat.2016.07.019.

[32] C. Klahn, B. Leutenecker, and M. Meboldt, "Design Strategies for the Process of Additive Manufacturing,"

Procedia CIRP, vol. 36, pp. 230–235, 2015, doi:10.1016/j.procir.2015.01.082.
[33] M. Schröder, B. Falk, and R. Schmitt, "Evaluation of cost structures of additive manufacturing processes using a new business model," Procedia Cirp, vol. 30, pp. 311–316, 2015, doi:10.1016/j.procir.2015.02.144.
[34] V. Kumar, B. R. Isanaka, S. Gupta, and V. Kushvaha, "Future Trends and Technologies in Additive and Substractive Manufacturing", In: Additive and Subtractive Manufacturing of Composites, Singapore: Springer, 2021, 227-247, doi:10.1007/978-981-16-3184-9_9.
[35] N. Guo and M. Leu, "Additive manufacturing: technology, applications and research needs," Front. Mech. Eng., vol. 8, no. 3, pp. 215–243, 2013, doi:10.1007/s11465-013-0248-8.
[36] S. H. Huang, P. Liu, A. Mokasdar, and L. Hou, "Additive manufacturing and its societal impact: a literature review", Int. J. Adv. Manuf. Technol., vol. 67, no. 1, pp. 1191–1203, 2012, doi:10.1007/s00170-012-4558-5.
[37] C. Weller, R. Kleer, and F. T. Piller, "Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited," Int. J. Prod. Econ., vol. 164, no. 1, pp. 43–56, 2015, doi:10.1016/j.ijpe.2015.02.020.
[38] M. Delić, D. R. Eyers, and J. Mikulic, "Additive manufacturing: empirical evidence for supply chain integration and performance from the automotive industry," Supply Chain Manage. Int. J., vol. 24, no. 5, pp. 604–621, 2019, doi:10.1108/SCM-12-2017-0406.
[39] G. G. Saueressig, A. de Paris, J. M. Bauer, J. Luchese, M. A. Sellitto, and J. A. Valle Antunes Jr., "Strategic Materials Positioning Matrix: An Application in the Automotive Industry in Southern Brazil", Int. J. Ind. Eng. Manag., vol. 8, no. 2, pp. 77–89, 2017, doi: 10.24867/IJIEM-2017-2-109.
[40] M. E. Porter, Competitive Strategy: Techniques for analyzing industries and competitors. New York: Free, 1980.
[41] S. K. Thomas, A. Ali, A. Alarjani, and E.-A. Attia, "Simulation based performance improvement: A case study on automotive industries," Int. J. Simul. Model., vol. 21, no. 3, pp. 406-416, 2022, doi: 10.2507/IJSIMM21-3-606.
[42] N. Li et al., "Progress in additive manufacturing on new materials: A review," J. Mater. Sci. Technol., vol. 35, no. 2, pp. 242–269, 2019, doi:10.1016/j.jmst.2018.09.002.
[43] T. DebRoy et al., "Additive manufacturing of metallic components–process, structure and properties," Prog. Mater. Sci., vol. 92, pp. 112–224, 2018, doi:10.1016/j.pmatsci.2017.10.001.
[44] Z. Hu and S. Mahadevan, "Uncertainty quantification and management in additive manufacturing: current status, needs, and opportunities," Int. J. Adv. Manuf. Technol., vol. 93, no. 1, pp. 2855–2874, 2017, doi:10.1007/s00170-017-0703-5.
[45] A. S. Sohal, J. Sarros, R. Schroder, and P. O'neill, "Adoption framework for advanced manufacturing Technologies", Int. J. Prod. Res., vol. 44, no. 1, pp. 5225–5246, 2006, doi:10.1080/00207540600558320.
[46] P. Kulkarni, A. Kumar, G. Chate, and P. Dandannavar, "Elements of additive manufacturing technology adoption in small-and medium-sized companies", Innov. Manage. Rev., vol. 18, no. 4, pp. 400–416, 2021, doi:10.1108/INMR-02-2020-0015.
[47] H. Bikas, P. Stavropoulos, and G. Chryssolouris, "Additive manufacturing methods and modelling approaches: a critical review," Int. J. Adv. Manuf. Technol., vol. 83, no. 1, pp. 389–405, 2016, doi:10.1007/s00170-015-7576-2.
[48] E. Atzeni and A. Salmi, "Economics of additive manufacturing for end-usable metal parts," Int. J. Adv. Manuf. Technol., vol. 62, no. 1, pp. 1147–1155, 2012, doi:10.1007/s00170-011-3878-1.
[49] F. T. Piller, C. Weller, and R. Kleer, "Business Models with Additive Manufacturing—Opportunities and Challenges from the Perspective of Economics and Management," Adv. Prod. Technol., vol. 1, no. 1, pp. 39–48, 2015, doi:10.1007/978-3-319-12304-2_4.
[50] M. Khorram Niaki and F. Nonino, "Additive manufacturing management: a review and future research agenda," Int. J. Prod. Res., vol. 55, no. 5, pp. 1419–1439, 2017, doi:10.1080/00207543.2016.1229064.
[51] M. K. Niaki and F. Nonino, The management of additive manufacturing. Birmingham, UK: Springer, 2018.
[52] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges," J. Cleaner Prod., vol. 137, pp. 1573–1587, 2016, doi:10.1016/j.jclepro.2016.04.150.
[53] K. S. Prakash, T. Nancharaih, and V. S. Rao, "Additive manufacturing techniques in manufacturing-an overview", Mater. Today Proc., vol. 5, no. 2, pp. 3873–3882, 2018, doi:10.1016/j.matpr.2017.11.642.
[54] C. Sun, Y. Wang, M. D. McMurtrey, N. D. Jerred, F. Liou, and J. Li, "Additive manufacturing for energy: A review", Appl. Energy, vol. 282, p. 116041, 2021, doi:10.1016/j.apenergy.2020.116041.
[55] T. Peng, K. Kellens, R. Tang, C. Chen, and G. Chen, "Sustainability of additive manufacturing: An overview on its energy demand and environmental impact", Addit. Manuf., vol. 21, pp. 694–704, 2018, doi: 10.1016/j.addma.2018.04.022.
[56] P. C. S. Filho et al., "A Measurement Tool for the Competitiveness of Startups' Innovation Ecosystem," J. Knowl. Econ., 2023, doi: 10.1007/s13132-023-01170-7.
[57] T. Pereira, J. V. Kennedy, and J. Potgieter, "A comparison of traditional manufacturing vs additive manufacturing, the best method for the job," Procedia Manuf., vol. 30, pp. 11–18, 2019, doi:10.1016/j.promfg.2019.02.003.
[58] N. Xu, X. Y. Hou, and N. Jia, "Optimization of multi-stage production scheduling of automated production," Int. J. Simul. Model., vol. 21, no. 1, pp. 160–171, 2022, doi: 10.2507/IJSIMM21-1-CO3.
[59] V. Jain and P. Ajmera, "Modelling the enablers of industry 4.0 in the Indian manufacturing industry," Int. J. Prod. Perform. Manage., vol. 70, no. 6, pp. 1233–1262, 2021, doi:10.1108/IJPPM-07-2019-0317.
[60] R. Novak, F. Valjak, N. Bojčetić, and M. Šercer, "Design Principle for Additive Manufacturing: Direct Metal Sintering," Tehn. Vjesn., vol. 30, no. 3, pp. 937–944, 2023, doi: 10.17559/TV-20210625150328.
[61] J. Patalas-Maliszewska and M. Topczak, "A new management approach based on Additive Manufacturing technologies and Industry 4.0 requirements," Adv. Prod. Eng. Manage., vol. 16, no. 1, pp. 125–135, 2021, doi:10.14743/apem2021.1.389.
[62] A. Neuenfeldt-Junior, M. Cheiram, M. Eckhardt, C. Scheuer, J. Siluk, and M. Francescatto, "Additive and Subtractive Rapid Prototyping Techniques: A Comparative Analysis of FDM & CNC Processes", Int. J. Ind. Eng. Manag., vol. 12, no. 4, pp. 262–273, 2021, doi: 10.24867/IJIEM-2021-4-293.
[63] A. Haleem and M. Javaid, "Additive Manufacturing Applications in Industry 4.0: A Review," J. Ind. Integr. Manage., vol. 4, no. 4, p. 1930001, 2019, doi:10.1142/S2424862219300011.
[64] V. Gerhardt, J. D. Santos, E. Rubin, A. Neuenfeldt, and J. C. Mairesse Siluk, "Stakeholders perception to characterize the start-ups success," J. Technol. Manage. Innov., vol. 16, no. 1, pp. 38–50, 2021.
[65] A. Neuenfeldt-Júnior, B. D. Oliveira, V. Alves, and J. Siluk, "Tactical economic business performance measurement

system for urban public transport.", Int. J. Bus. Perform. Supply Chain Modell., vol. 13, no. 4, pp. 405–422, 2022.

[66] C. R. Silva Júnior, J. C. M. Siluk, A. Neuenfeldt Júnior, M. Francescatto, and C. Michelin, "A competitiveness measurement system of Brazilian start-ups," Int. J. Prod. Perform. Manage., vol. 72, no. 10, pp. 2919–2948, 2023, doi: 10.1108/IJPPM-02-2022-0098.

[67] A. Neuenfeldt-Júnior and B. de Oliveira, "An agent-based approach to simulate the containership stowage problem," Soft. Comput., vol. 26, no. 22, pp. 12583–12597, 2022, doi: 10.1007/s00500-022-07222-5.

[68] C. R. Silva Júnior, J. C. M. Siluk, A. Neuenfeldt Júnior, C. B. Rosa, and C. D. F. Michelin, "Overview of the factors that influence the competitiveness of startups: a systematized literature review," Gestão & Produção (Ufscar. Impresso), vol. 29, p. 1-23, 2022.

[69] V. J. Gerhardt, J. C. M. Siluk, C. De Freitas Michelin, A. L. Neuenfeldt Junior, and C. P. Da Veiga, "Impact of Market Development Indicators on Company Performance," IEEE Eng. Manage. Rev., vol. 50, pp. 65-84, 2022.

[70] J. C. Alecio, A. Neuenfeldt Junior, and J. C. M. Siluk, "The cooperation between suppliers and an agro-industrial slaughterhouse: a measurement tool," Produção (São Paulo), vol. 31, pp. 1-14, 2021.

[71] J. C. M. Siluk et al., "A performance measurement decision support system method applied for technology-based firms' suppliers," J. Decis. Syst., vol. 26, no. 1, pp. 93–109, 2017, doi: 10.1080/12460125.2016.1204213.

[72] T. Saaty, "The analytic hierarchy process (AHP)," J. Oper. Res. Soc., vol. 41, pp. 1073-1076, 1987, doi: 10.1016/0270-0255(87)90473-8.

[73] P. Kumar, P. S. Brar, D. Singh, and J. Bhamu, "Fuzzy AHP approach for barriers to implement LSS in the context of Industry 4.0," Int. J. Product. Perform. Manage., vol. 72, no. 9, pp. 2559-2583, 2022, doi: 10.1108/IJPPM-12-2021-0715.

[74] C. Ramirez, A. Neuenfeldt Junior, J. C. M. Siluk, and L. Ataide, "A literature overview about warehouse management," Int. J. Logistics Syst. Manage., vol. 42, pp. 153-175, 2022.

[75] B. Leal, J. Siluk, A. N. Júnior, G. Zen, and J. R. G. Dos Santos, "A performance measurement approach to risk valuation in startups' technology marketing," Int. J. Bus. Excel., vol. 31, no. 4, pp. 521–541, 2023, doi: 10.1504/IJBEX.2023.135518.

[76] B. Liu, C. Jiang, G. Li, and X. Huang, "Topology optimization of structures considering local material uncertainties in additive manufacturing," Comput. Methods Appl. Mech. Eng., vol. 360, p. 112786, 2020, doi: 10.1016/j.cma.2019.112786.

[77] C. Dordlofva and P. Törlind, "Evaluating design uncertainties in additive manufacturing using design artefacts: examples from space industry," Des. Sci., vol. 6, p. e12, 2020, doi:10.1017/dsj.2020.11.

[78] S. S. Babu, L. Love, R. Dehoff, W. Peter, T. R. Watkins, and S. Pannala, "Additive manufacturing of materials: Opportunities and challenges," MRS Bull., vol. 40, no. 12, pp. 1154-1161, 2015, doi: 10.1557/mrs.2015.234.

[79] I. L. De Camargo, C. A. Fortulan, and H. A. Colorado, "A review on the ceramic additive manufacturing technologies and availability of equipment and materials," Cerâmica, vol. 68, pp. 329-347, 2022, doi: 10.1590/0366-69132022683873331.

[80] T. W. Simpson, C. B. Williams, and M. Hripko, "Preparing industry for additive manufacturing and its applications: Summary & recommendations from a National Science Foundation workshop," Addit. Manuf., vol. 13, pp. 166-178, 2017, doi: 10.1016/j.addma.2016.08.002.

[81] S. H. Ghaffar, J. Corker, and M. Fan, "Additive manufacturing technology and its implementation in construction as an eco-innovative solution," Autom. Constr., vol. 93, pp. 1-11, 2018,

[82] R. Martens, S. K. Fan, and R. J. Dwyer, "Successful approaches for implementing additive manufacturing," World J. Entrep. Manage. Sustain. Dev., vol. 16, no. 2, pp. 131-148, 2020, doi: 10.1108/WJEMSD-12-2019-0100.

[83] A. B. Badiru, V. V. Valencia, and D. Liu, Additive manufacturing handbook: product development for the defense industry. CRC Press, 2017.

[84] M. Zaidi and S. M. Hasan, "Supply Chain Risk Prioritization Using AHP and Framework Development: A Perspective of the Automotive Industry", Int. J. Ind. Eng. Manag., vol. 13, no. 4, pp. 283–293, 2022, doi: 10.24867/IJIEM-2022-4-319.

[85] L. F. C. S. Durão, M. O. Guimarães, M. S. Salerno, and E. Zancul, "Uncertainty Management in Advanced Manufacturing Implementation: The Case for Learning Factories," Procedia Manuf., vol. 31, pp. 213–218, 2019, doi: 10.1016/j.promfg.2019.03.034.

[86] D. Rejeski, F. Zhao, and Y. Huang, "Research needs and recommendations on environmental implications of additive manufacturing," Addit Manuf, vol. 19, pp. 21–28, 2018, doi: 10.1016/j.addma.2017.10.019.

[87] D. Böckin and A.-M. Tillman, "Environmental assessment of additive manufacturing in the automotive industry," J. Clean. Prod., vol. 226, pp. 977–987, 2019, doi: 10.1016/j.jclepro.2019.04.086.

[88] P. Manco, M. Caterino, M. Rinaldi, and M. Fera, "Additive manufacturing in green supply chains: A parametric model for life cycle assessment and cost," Sustain. Prod. Consum., vol. 36, pp. 463–478, 2023, doi: 10.1016/j.spc.2023.01.015.

[89] I. C. Baierle, J. C. M. Siluk, V. J. Gerhardt, C. de F. Michelin, Á. L. N. Junior, and E. O. B. Nara, "Worldwide Innovation and Technology Environments: Research and Future Trends Involving Open Innovation," J. Open Innov. Technol. Mark. Complex., vol. 7, no. 4, p. 229, 2021, doi: 10.3390/joitmc7040229.

[90] A. Neuenfeldt Júnior and L. Rebouças Guimarães, "A Greedy Randomized Adaptive Search Procedure Application To Solve the Travelling Salesman Problem", Int. J. Ind. Eng. Manag., vol. 10, no. 3, pp. 238–242, 2019, doi: 10.24867/IJIEM-2019-3-243.