A SYSTEMATIC REVIEW ABOUT CLASSIFICATION CRITERIA, APPLIED METHODS AND METHODOLOGIES FOR SELECTING SPARE PARTS SUITABLE FOR ADDITIVE MANUFACTURING

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Abstract: Additive manufacturing (AM), also known as 3D printing, refers to a family of manufacturing technologies capable of producing products by progressively adding layers of materials. AM emerged in 1981 and is in a continuous process of technological and commercial improvement, demonstrating its relevance for the technological frontier. This fact is evidenced by the growing number of scientific publications aimed at investigating and describing the benefits and opportunities arising from 3D printing for the industrial scenario. A latent opportunity, for example, is the optimization of spare parts management through AM technologies. The aim of this paper is to present a systematic review of classification criteria, methods and methodologies for selecting suitable spare parts for MA.

Keywords: Additive Manufacturing; Classification Criteria; Selection Methodologies; Spare Parts.

UMA REVISÃO SISTEMÁTICA SOBRE OS CRITÉRIOS DE CLASSIFICAÇÃO, MÉTODOS E METODOLOGIAS APLICADAS PARA SELEÇÃO DE PEÇAS SOBRESSALENTES ADEQUADAS PARA MANUFATURA ADITIVA

Summary: A manufatura aditiva (AM), também conhecida como impressão 3D, refere-se a uma família de tecnologias de fabricação capazes de produzir produtos a partir da adição progressiva de camadas de materiais. A AM surgiu em 1981 e encontra-se em um processo contínuo de aprimoramento tecnológico e comercial. Este fato se evidencia através do número crescente de publicações científicas orientadas para investigar e descrever os benefícios e oportunidades oriundos da impressão 3D para o cenário industrial. Uma oportunidade latente, por exemplo, é a otimização do gerenciamento de peças sobressalentes através das tecnologias de AM. O objetivo deste trabalho é apresentar uma revisão sistemática dos critérios de classificação, métodos e metodologias para seleção de peças sobressalentes adequadas para a AM.

Key words: Manufatura Aditiva; Critérios de Classificação; Metodologias para Seleção; Peças Sobressalentes.

1. INTRODUCTION

Additive manufacturing (AM), also known as 3D printing, refers to the family of manufacturing technologies capable of adding sequentially, i.e., layer by layer, units of standardized input materials, thereby allowing the manufacture of physical products discrete data from digital models [1, 2]. In this way, this new manufacturing method differs from conventional manufacturing technologies (CM), which employ subtractive and formative methods of materials to produce components [3]. AM technologies are employed to manufacture prototypes, models, end-use parts, that is, ready-to-use, as well as tools for mass production of long-term components [4]. For the industrial application of parts obtained by AM, it is necessary to evaluate the level of technological maturity, described by the term TRL (Technology Readiness Level), of the additive manufacturing process [5]. The TRL scale was created by NASA (US National Aeronautics and Space Administration) in the 1970s and is widely applied to assess “technological maturity through proof of technical capabilities” [5]. Furthermore, additive manufacturing processes are divided into seven categories, namely: Binder Jetting (BJ), Directed Energy Deposition (DED), Material Extrusion (ME), Material Jetting (MJ), Powder Bed Fusion (PBF), Sheet Lamination (SL) and Vat Photopolymerization (VP).

AM is in a continuous process of technological and commercial improvement. Its history begins in 1981, with the registration of the first rapid prototyping patent developed by Professor Hideo Kodama, in Japan [6]. Three years later, American physicist Charles W. Hull, founder of the multinational company 3D Systems Corporation, registered the most significant patent, called stereolithography, from the English stereolithography apparatus (SLA), as it resulted in the commercialization of AM [7], which emerged in 1987, from the SLA production process [8]. With the academic, technological and commercial advancement involving MA, in 2018, the German automotive company BMW announced its one millionth component manufactured in series from 3D printing [9]. It was reported, in 2021, that the Brazilian companies PETROBRAS, SENAI Joinville and the Federal University of Santa Catarina (UFSC) and the German company ZEISS Group joined in a research project whose object of study was a compact heat exchanger made of AISI 316L steel and manufactured by MA [10]. In addition to these examples, taking into account the Science Direct database, in the interim between 1999 and 2023, the number of publications with the term “additive manufacturing” increased by 467,330%. Therefore, over the years, AM and its benefits have been explored in academic and industrial circles, in addition to being disseminated by the media and political circles [11].

The benefits of AM compared to CM stand out: manufacture of small batches of customized parts, consolidation of geometric features of components, possibility of creating lighter and more efficient designs [12]. In addition, there are advantages in using AM for spare parts (SP) management, such as reducing manufacturing costs, improving supply chain responsiveness, reducing inventory and its inherent costs, in addition to minimizing transportation, energy and downtime costs among other benefits [13, 14]. Consequently, studies have been published with the aim of identifying, classifying and selecting SP eligible for MA. Therefore, the aim of this article is performing a systematic review of eligibility criteria, methods and methodologies used for selecting spare parts suitable for AM.

2. METHODOLOGY

With the intention of identifying the research problems, its guiding questions, from the English research question (RQ), were elaborated, as it is a fundamental step before starting any research. RQs are intended to explore existing uncertainties in an area of concern and address identified research needs. Therefore, it is concluded that it is pertinent to formulate the RQs suitable for the research even before starting it [15]. Thus, the guiding questions of this dissertation are the following: RQ1. What are the criteria that should be considered when identifying spare parts eligible for additive manufacturing? RQ2. How to define the most appropriate eligibility criteria for the companies' interests when deciding to adopt additive manufacturing as an alternative for managing spare parts? RQ3. How to select spare parts eligible for additive manufacturing? RQ4. What benefits can companies gain by adopting additive manufacturing as a method to produce replacement parts and optimize their management? Therefore, in order to answer the aforementioned guiding questions, a literature review was carried out using keywords corresponding to the main themes of this research, that is, Additive Manufacturing (AM), spare parts management (SPM) and a multi-criteria decision making (MCDM). In other words, the keywords chosen were those that are frequently used in the literature to search for criteria, methods and models for selecting and classifying spare parts for AM, in addition to collecting technical standards corresponding to additive manufacturing and PS management.

After carrying out the necessary search for the literature review, those reference materials more in line with the objectives of this dissertation were selected. After that, the most used criteria in the literature for classification and selection of SP eligible for AM were identified and analyzed. Subsequently, with the aim of identifying problems and suggested and/or applied solutions, methods and methodologies existing in the literature for classification and selection of appropriate SP for AM were examined. Therefore, aiming to solve the identified problems, it was decided to develop a methodology capable of classifying and selecting PS eligible for MA and intended for industrial applications.

The scientific database used in the collection of reference materials available in English was CAPES Periódicos. As for the search for literature written in Portuguese, Google Scholar and the CAPES Catalog of Theses and Dissertations were defined as the database. Appropriate search operators for publications in English and Portuguese were identified by combining keywords, including their synonyms, with Boolean modifiers, as shown in Table . The search in the literature published in English was restricted to research and review journals, peer-reviewed and published in any year. For the search carried out in Google Scholar and in the Catalog of CAPES theses and dissertations, periodicals, theses and dissertations available in Portuguese and published in any period were applied as a filter. This strategy is based on the attempt to find reference materials published in Brazil and in Portuguese, thus expanding the database for this dissertation. Therefore, one can list as a differential of this research the search for keywords relevant to MA, SPM and MCDM in different scientific databases widely recognized and used for literature review, in addition to this research being oriented to the search for materials previously published in more than one language, that is, English and Portuguese.

Table 1. Search operators used in scientific databases defined for literature search.

Publications	Search operators	Data base
in English	*(("selection" OR "classification") AND ("additive manufacturing" OR "3d printing") AND ("spare part" OR "spare parts"))*	Periodic CAPES
In Portuguese	*((“selection” OR “classification”) AND (“additive manufacturing” OR “3D printing”) AND (“spare part” OR “spare parts”))*	Academic Google CAPES Theses and Dissertations Catalog

The decision-making process regarding the reference materials used in the literature review consists of five phases, as described in Table 2.

Table 2. Inclusion and exclusion criteria of reference materials for the literature review

Phase	Inclusion and/or exclusion criteria
1	Perform search on the defined scientific databases with the given search operators.
2	Exclude reference materials found in duplicate in scientific databases.
3	Perform evaluation of titles and keywords and exclude materials that are not relevant to the dissertation objectives.
4	Perform review of abstracts and exclude material that is not relevant.
5	Perform evaluation of full texts and exclude materials without relevance.

In order to perform the systematic review present in this article, eight publications were selected, namely: [13, 16, 17, 18, 19, 20, 21, 22].

3. RESULTS AND DISCUSSION

Table 3 summarizes the classification criteria for spare parts eligible for additive manufacturing used by the eight selected publications.

Table 3. Classification criteria for spare parts eligible for additive manufacturing

Reference	Classification Criteria and Selection Method
[16]	***Part definition**: Dimensions, mass, quantity of parts per printing cycle, type of material. ***Preliminary selection**: 1) MA machine working volume. 2) PS complexity. 3) Possibility of removing assemblies. 4) Need for post-processing. 5) Applicability of MA material already used for aerospace parts: take into account the requests or loads that the part will undergo throughout its useful life. 6) Complement of specific geometric conditions from PS to MA. 7) Improved part property by design optimization. 8) Material consumption. 9) Manufacturing time. ***Final trade-off**: 10) Possibility of changing material. 11) Comparison of material consumption between MA and machining. 12) Comparison of manufacturing time between MA and machining. 13) Comparison of manufacturing cost between MA and machining.

[13]	***Matrix for evaluating the potential for improvement with AM**: - Attributes of PS: 1) Type of material. 2) Part size. 3) Demand rate. 4) Replenishment lead time. 5) Agreed response time. 6) Usage period remaining. 7) Manufacturing/ordering costs. 8) Safety stock costs. 9) Quantity of supply options. 10) Supply risk. *** Go/No-Go Analysis**: the last 8 criteria of the Matrix for evaluating the potential for improvement with AM. ***AHP method**: 11) Safety stock costs. 12) Manufacturing/ordering costs. 13) Demand rate. 14) Probability of Survival: Spare parts with high supply risk can be obtained from AM. 15) Usage period remaining. 16) Replenishment lead time. 17) Type of plane.
[17]	***Criteria for most relevant PS classification:** 1) Probability of failure. 2) Number of suppliers. 3) Demand forecast. 4) Out-of-stock cost. 5) Availability for production. * Most appropriate technical characteristics for classification from PS to MA: 6) Dimension. 7) Weight. 8) Material specifications.
[18]	***Go/No-Go Analysis**: 0.1) Technical characteristics of the component: material, density, print volume, weight. 0.2) Technical characteristics of 3D printers: manufacturing method. ***AHP**: 1) Lead time: total time until PS available for application. 2) Restoration level: PS quality to meet aircraft combat damage repairs. 3) Cost of care: total cost up to the PS available for application.
[14]	***Filtering**: technical characteristics: 1) Material: The specific material the item is made of. 2) Dimensions: The height, width and depth of the spare part (1000 x 1000 x 1000 mm). 3) Weight: The weight of the component without packaging. 4) Tolerances (technical drawing): If the spare part can be produced according to the specifications. ***TOPSIS**: 1) Lead time. 2) Overhead cost. 3) Demand. *** Grouping:** carried out from the results found from the TOPSIS method. 8 groups were made.
[19]	1) **Manufacturing option**: manufacturing technology and post-processing treatment. *** Spare parts app features**: 2) MTTF of foundry technology. 3) Size. 4) Complexity. 5) Retention rate. 6) Unit cost of backorders. * Mechanical properties: 7) Ratio between MTTF of chosen manufacturing option and MTTF of foundry. 8) Failure rate. ***Economic and technological parameters**: 9) Lead time for the acquisition of the chosen manufacturing option. 10) Unit cost of production of the chosen manufacturing option**. *Decision variables**: 11) Deadline for revision of chosen manufacturing option. 12) Level order of chosen maintenance option. * Restrictions: 13) Maximum order level. *Costs: 14) Maintenance cost per unit of time. 15) Backorder cost per unit of time. 16) Cost of production per unit of time.
[21]	***Rating:** 1) Unit price equal to or greater than €80. 2) High consumption: based on maintenance criteria. 3) Availability of part drawings. 4) Hardness. 5) Size. 6) Diameter. 7) Mounts. ***Categorization:** 1) Structure: single piece or with assemblies. 2) Size: bulk. 3) Material: Polymer. 4) Stiffness: qualitative assessment; define whether material is rigid or flexible. 5) Printability: qualitative assessment made by a specialist. 6) Functionality: based on surface finish (roughness).
[22]	***Multicriteria ranking** (score: -1, 0, 1): 1) Maturity (spare part status): defined by the number of historical orders; if the PS is new, in use or obsolete. 2) Frequency of demand: based on maintenance records. 3)

	Criticality: represented by the cost of losing sales. 4) Value of PS: manufacturing or acquisition cost. 5) Lead time uncertainty: represented by the lead time standard deviation. ***Operational pre-selection**: low potential (-1), non-evident potential (0) and high potential for MA (1): decision based on the sum of intermediate results found in the multicriteria classification**.** ***Technological pre-selection**: evaluate the manufacturability and select the most suitable additive manufacturing process/technology (depends on the know-how of MA specialists): 6) Material. 7) Geometry. 8) Available manufacturing technologies. 9) Technical and quality requirements. 10) Potential for reengineering. ***Definition of strategy**: estimation of costs and environmental impacts is highly dependent on technology: 11) LCC (Life Cycle Cost). 12) LCA (Life Cycle Assessment).
[20]	*** Pre-selection of specific PS considered strategic**: 0.1) Print volume (piece size). 0.2) Type of material. *** AHP and Segmentation**: **** Impact on business**: 1) Delivery time (service time). 2) Unit cost. 3) Annual demand. 4) Annual budget allocated for critical spare parts. 5) Critical for the equipment. 6) Number of Suppliers. 7) Out-of-stock cost. ****Technical compatibility**: 8) Product complexity. 9) Surface Finishing. 10) Dimensional Accuracy. 11) Reliability.

Summary, about the methodologies, [16] developed a methodology for identifying suitable candidate parts for redesign and manufacturing based on AM technologies considering the entire PS life cycle. [13] discussed the discrepancies between the value of AM for the logistics sector and its practical application, in addition to developing a method to simplify the identification of economically valuable and technologically viable business cases through AM. [17] generated a database so that companies can use it in order to develop methodologies capable of identifying the most suitable spare parts for AM. [18] presented a model for selecting spare parts for aeronautical components in the context of repairing combat damage to aircraft. [14] developed a process to identify PS eligible for MA from a portfolio of approximately 64,000 spare parts available. [19] addressed a statistical comparison between the inventory management of PS manufactured by MC and by MA. [20] presented a systematic approach to assist in the selection of spare parts that are technically compatible with AM from the point of view of business competitiveness. [21] identified the applicability of AM for PS in the automotive industry, specifically around preventive maintenance. [22] with the aim of contributing to the large-scale adoption of additive manufacturing, developed a method to support decision-making. This was designed to identify PS suitable for MA, in addition to providing support for defining new and optimized inventory management strategies.

4. CONCLUSION

A latent scientific commitment to methodologies aimed at managing PS through AM in the industrial context is noticeable. Even so, there are gaps in knowledge to be explored, which are the basis for the justifications for the present research project, such as the lack of methodologies, nationally and internationally, consolidated or standardized, thus allowing the opportunity for the generation of new methodologies, best suited to the needs of each company. In addition, of those methodologies that are available in academia, few are inclusive, that is, they allow the participation of people with insufficient technical knowledge in AM to make decisions involved in the management of PS using 3D printing. In addition, in order to better meet the needs of stakeholders, it is necessary to have a clear alignment between the eligibility criteria of SP for MA and the strategic objectives of the company when it wants to adopt additive manufacturing as an alternative for managing spare parts.

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