Additive manufacturing and spare parts: literature review and future perspectives

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Abstract. The use of Additive Manufacturing (AM) for spare parts management has increasingly gained interest in the last years, thanks to the possibility provided by AM technologies to print-on-demand. In such a way, the high spare parts inventory level necessary with Conventional Manufacturing (CM) techniques could be reduced due to a faster responsiveness of AM. Recently, some researchers have investigated the profitability of the transition from CM to AM for the spare parts management, and these contributions are herein reviewed, highlighting the main novelties and limitations of these studies. Based on the output of the literature review and on interviews with experts and industrial partners, future research perspectives have been reported. Four main research areas have been identified, and a multidisciplinary approach is suggested to accomplish them all.

Keywords: Spare parts, Additive Manufacturing (AM), Research perspectives

1 Introduction

In the last decades, to respond to the increasingly stringent market requirements, manufacturing companies are required to be not only more flexible, but also more efficient (1). Among the different factors influencing the efficiency of production systems, the availability of machines is the most important. To keep high the availability of production systems, besides efficient preventive maintenance programs, spare parts management is essential. Due to their long procurement lead times, in fact, the unavailability of spare parts would result in a consistent drop in the efficiency. But that is not all: due to the high downtime costs occurring when spare parts are not available in time, the unavailability of spare parts would also lead to considerable high costs. To

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avoid this, forecasting methods and inventory management approaches are thus fundamental to keep high the availability of production systems and to avoid unnecessary costs related to machines downtimes. However, a correct spare parts management represents one of the most challenging tasks for managers and practitioners since the spare parts demands are usually intermittent and difficult to predict in terms of both quantity and frequency. To avoid any risk associated with wrong forecasting methods, manufacturing companies often store more spare parts than needed. If this from one side reduces the risk to incur in machines downtime, from the other side it increases the capital allocated to the inventory (2). A solution to this problem could be a transition to Additive Manufacturing (AM) technologies.

AM is in fact a manufacturing technique that allows to manufacture even complex parts in a very limited time. Thanks to the short set-up times and no requirement for tooling, AM technology can provide on-demand spare parts ("print-on-demand" approach), thus reducing the necessity to have high inventory level to cover the inaccuracy of demand forecasting methods and to avoid high downtime cost.

However, the use of AM in spare parts inventory management might be limited by two main barriers, which are both related to the fact that AM is a recently developed manufacturing technique. The first barrier is represented by the uncertainty of the mechanical properties of AM components: the novelty of this manufacturing technique renders the amount of data on the failure behavior of AM components scarce, making uncertain the withstanding of complex loading scenarios by AM parts. The second barrier is then related to the much higher production costs of AM parts compared to conventional manufactured (CM) counterparts.

Despite these disadvantages, the transition from CM to AM for spare parts inventory management has started attracting the attention of researchers and practitioners. In the following section, these studies will be reviewed, highlighting the main strengths and limitations of each work. Based on the identified limitations and on interviews with experts and industrial partners, future research perspectives and possibilities will be highlighted in section 3, providing recommendations and advices to practitioners and researchers to further investigate the use of AM in spare parts inventory management.

2 Literature review

Since the introduction of AM technologies, their potential benefits on the spare parts management were clear. Particularly, due to the short time needed for production, AM has the potential to reduce the need of safety inventory and to change the configuration of the spare parts supply chain of various industries. As often happens, the aerospace sector has paved the way. Holmstrom et al., for example, qualitatively evaluated the impact of AM on the aircraft supply chain (3). Particularly, they reported that AM could modify the conventional aircraft supply chain by being deployed either in the centralized distribution centers or in the service locations (i.e., decentralization), and they supposed the centralized deployment of AM to be the most likely approach to succeed. Liu et al., then, analyzed the two above mentioned approaches to integrate AM in the aircraft spare parts supply chain considering six different components, reporting that the reduction of the inventory level when AM was used (either in a centralized or decentralized way) ranged from 13% up to 70% (4). However, in their work, the authors focused only on the inventory level, not on the holding costs. In fact, the higher production costs of AM compared to CM could limit the convenience of AM components: despite a lower inventory level, the high AM production costs could lead to similar or even higher holding costs than in the case of using CM spare parts. Moreover, they neglected also another disadvantage of AM compared to CM, i.e. the uncertain mechanical properties, which could result in a higher inventory level than that reported if the reliability of AM components is lower than that of CM components. Therefore, AM and CM technologies should be compared under a cost perspective, not just considering the reduction of the inventory level, considering also the two main drawbacks of AM (i.e., high production costs and uncertain mechanical properties). A first attempt in this direction was done by Song and Zhang, who evaluated the opportunity of switching from CM to AM by means of cost-based optimization models (5). In their work, they considered different production costs between CM and AM (but not different mechanical properties) and they reported that the transition to AM would lead to total costs savings. However, to consider that parts produced by the two different technologies possess equal reliabilities limited somehow the validity of their findings. In fact, Westerweel et al. evaluated the profitability to switch from CM to AM spare parts considering both different production costs and reliabilities, and, based on different case studies, they reported that CM was often still preferable (6). Based on their lifecycle cost analysis where different designing costs and potential benefits associated with AM parts were also considered, they found that AM became convenient only when the net benefits provided by AM technologies were high. In such a way the negative impact of the high production costs was limited. As stated by Knofius et al., in fact, "high unit cost or low and uncertain reliabilities of printed parts often rule out the use of AM", and they suggested that AM will more likely complement CM technologies in the spare parts management, rather than replace them (7). In their work they considered a single-item inventory system and they compared three different sourcing policies, i.e. single sourcing with CM, single sourcing with AM and dual sourcing, where, depending on the situation, one may decide whether to source spare parts with AM or CM technologies. They reported dual sourcing to outperform single sourcing (either AM single sourcing or CM single sourcing), also when the Mean Time To Failure (MTTF) of AM parts was largely inferior than that of CM parts. Based on this observation, the authors suggested that AM parts could be used as emergency source to temporary fix goods operating at remote locations. This was investigated by Westerweel et al., who investigated the impact of on-site printing as emergency source in remote locations (8). They considered 14 different parts, and they reported an overall cost reduction of more than 50% due to a decreased optimal base-stock level, which decreased by 76% on average compared to the CM single sourcing policy. The same authors, then, investigated another field of applications, i.e. the use of AM technologies for preventive maintenance (9). They considered a component for a single system subjected to an age-based preventive maintenance policy and they developed two new age-based maintenance policies: one where printed spare parts were used as temporary backup options and they were removed when the CM part arrived, and one where the AM parts continued operating until their own age-based preventive maintenance threshold. These two maintenance policies were compared against each other and also to a maintenance policy where a CM part is continuously kept in stock. They reported that printing policies were convenient when holding costs and backorder costs were high. In these situations, the differences between the two printing policies where small, except when AM parts had a MTTF much longer than the lead time of the CM parts. The works from Knofius et al. and Westerweel et al. (6–9), despite having the merit to consider different failure behaviors between AM and CM parts, are limited by the fact that the different reliabilities were just estimated by the authors, without any underlying experimental data. This was overcome by Sgarbossa et al., who proposed an inventory management model for spare parts capable of choosing between traditional and additive manufacturing technologies (10). The choice between AM and CM parts was made considering different production lead times, different production costs and different reliabilities between the two technologies. Particularly, the different MTTFs for AM and CM parts were obtained thanks to a multi-disciplinary approach that used data coming from the material science field. Although this paper was limited by a reduced scenario analysis, it paved the way toward the development of a multi-disciplinary approach, where knowledges coming from different fields are required and claimed to provide reliable results that can be used by managers and practitioners.

Based on interviews with industrial partners and on the main topics, novelties and limitations of the above-mentioned papers (that are summarized in Table 1), suggestions for future research are depicted in the next section.

Table 1 Summary of the papers treated in the literature review, with a particular focus on the topic, finding, novelty and limitation

Paper	Topic	Main Finding	Novelty	Limitation
Liu et al. (4)	Impact of AM on the aircraft supply chain	Reduction of the inventory level up to 70%	First quantitative paper	Same production costs and reliabilities for AM and CM
Song and Zhang (5)	AM vs CM sourcing option (cost-based model)	Total costs savings using AM	Different production costs	Same reliabilities
Westerweel et al. (6)	Switch from CM to AM based on a lifecycle cost analysis	CM often the cheapest solution	Different production costs and reliabilities	Estimated different reliabilities, no experimental data
Knofius et al. (7)	Dual sourcing AM/CM vs single sourcing (either AM or CM)	Dual sourcing outperforms single sourcing also when the reliability of AM parts is largely inferior to that of CM parts	First study on dual sourcing AM/CM	Estimated different reliabilities, no experimental data
Westerweel et al. (8)	Use of AM as emergency source in remote locations	Overall cost reduction of more than 50% due to a decreased optimal base-stock level	First study on remote locations	AM is considered only as emergency source Estimated different reliabilities, no experimental data
Westerweel et al. (9)	Printing spare parts for preventive maintenance	Printing policies were convenient when holding costs and backorder costs were high	First study on AM for preventive maintenance	No failure of any component during the replenishment lead time Estimated different reliabilities, no experimental data
Sgarbossa et al. (10)	Spare parts inventory management model (AM or CM?)	CM often the cheapest solution except when limited storage area	First interdisciplinary study (different reliabilities obtained from experimental data)	Limited scenario analysis Single-item

3 Research perspectives

The use of AM technologies in spare parts management represents a topic of increasing interest among researchers, practitioners and managers. Attracted by the reduced production lead time of AM technologies compared to CM technologies, researchers and practitioners had considered AM a breakthrough in the field of the spare parts management, but soon they had to face the limitations of AM, i.e. high production costs and uncertain reliabilities. Under a perspective of a full and effective exploitation of the advantages of AM technologies, it is thus clear that the reliabilities of AM parts need to be accurately known. Currently, the only possible way is that to carry out mechanical tests on AM parts. However, these tests are "destructive tests", meaning that the tested part cannot be used afterwards, but a new one has to be printed. This would represent a time-consuming and expensive approach if every part needs to be tested after production, especially considering that even a small change in the process parameters would risk to render useless such characterization since the mechanical properties of AM parts are highly affected by the process parameters (layer thickness, laser power, scanning speed, hatch spacing, …). In order to avoid these operations, a material science-based approach should be developed, where the mechanical properties of AM parts are estimated from the process parameters through the use of simulation and/or analytical tools. This represents already a field of study for CM parts, where interesting and promising results have been achieved, and its extension to AM parts has started being considered, but much more needs to be done.

Once the mechanical properties of AM parts are known, it is possible to reason judiciously on the possibility to switch from CM to AM in the spare parts management. This however represents a multifaceted field, where several aspects concur. First, it is necessary to understand if a part can be produced by AM, and, if so, which benefits can be achieved from a possible redesign of the part. Nowadays, AM experts need to be consulted to answer these questions, and hence the development of guidelines that managers can use for a first screening of the parts printable and of the benefits achievable is highly claimed. Recently, some researchers have started approaching this topic (11,12), but more still needs to be done, especially dealing with the understanding of the possible benefits achievable through redesign procedures. This is in fact particularly important since the profitability of AM parts compared to CM parts highly varies based on the benefits achievable with the redesign procedures, as shown by Westerweel et al. (6). Therefore, when assessing the possibility to switch from CM to AM, a lifecycle cost analysis needs to be considered. Moreover, the transition from CM to AM is also affected by the supply chain configuration. Or rather, the use of AM technologies can modify the supply chain configuration. Specifically, the use of distributed manufacturing strategies could not have been profitable when CM technologies were used, but a transition to AM might render it economic.

It can be seen how many questions are still unanswered and thus the future researches should aim to provide such answers. Particularly, based on what stated above, four main research areas have been identified:

1) Reliability characterization: the mechanical characterization of AM parts is something that is completely missing. In addition to the traditional and currently used approach of the mechanical testing, simulations and/or analytical tools able to predict the mechanical properties of a component based on the process parameters is something of extreme importance;
2) Producibility and benefits: guidelines for managers to detect the spare parts that can be printed and the benefits achievable by a redesign are fundamental initial steps
3) Lifecycle cost analysis: when assessing the possibility to switch from CM to AM technologies, a "from cradle to grave" perspective, where benefits and design costs associated to AM technologies are considered, is necessary to take full account of the potentials of AM.
4) Supply chain structure: the impact of AM technologies on the supply chain structure is still limited, especially the understanding of when a decentralized spare parts management has to be preferred over a centralized one

4 Conclusions

The use of AM technologies in spare parts management is gaining an increasing interest. Despite their undisputed potentials, particularly the "print-on-demand" approach, the use of AM technologies to produce spare parts is still very limited, to not say inexistent. To hamper the use of these techniques in the spare parts management field is their drawbacks, i.e. the high production costs and the uncertain mechanical properties, that do not make immediate for managers the understanding of the profitability from CM to AM. Some researchers have tried to address these challenges, focusing on different perspectives of the spare parts management, from the supply chain configuration to the use of AM as emergency source. However, much more has still to be done, and to guide researchers in their future work, four research areas that highly need to be investigated have been identified from the shortcomings resulting from the literature analysis and from interviews with experts and industrial partners. Particularly, the four main research areas are related to (1) the mechanical characterization of the AM parts (via mechanical testing or, preferably, through simulation and/or analytical tools), (2) guidelines to guide managers through the understanding of which parts can be printed through AM technologies and which are the possible benefits arising from a potential redesign, (3) the necessity to consider a lifecycle cost analysis when assessing the transition from CM to AM, where the potential benefits and the possible extra costs (design costs) arising when using AM are accounted, and (4) the supply chain structure, where the possible impacts of AM on the supply chain (decentralization vs centralization) are not neglected.

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