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On the suitability of insourced Additive Manufacturing for spare parts management

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Abstract: Additive Manufacturing (AM) has recently emerged as a promising technique in spare parts manufacturing. Unlike conventional manufacturing (CM) techniques, AM can lead to a reduction in inventory levels, particularly when insourced, through manufacturing spare parts on demand. However, due to the high production costs, the economic benefits of manufacturing spare parts through AM are unclear to managers and practitioners. Recent studies aimed at assisting in this decision have two main limitations: (i) they assume that AM spare parts typically have higher failure rates than CM parts: and (ii) they do not consider the AM machinery investment costs and parts are assumed to be externally supplied. We have developed a model that overcomes these limitations, first by assessing the failure rates of AM spare parts through an interdisciplinary approach rather than making arbitrary assumptions, which enables a comparison with the failure rates through CM reported in the literature. Second, we considered that the manufacturing of AM spare parts can be insourced and thus the investment costs for AM printers are also included, while the manufacturing of CM spare parts is considered to be outsourced. The model was tested with unconstrained and constrained stock systems, and clearly demonstrates the advantages of an insourced 3D printer for on-demand printing under constrained stock systems. Neither is AM preferable under an unconstrained system, due to the high costs of purchasing the printer and of production.

Keywords: Additive Manufacturing, Spare Parts, Management, Optimization, Constrained System.

1. INTRODUCTION & BACKGROUND

The correct management of spare parts is essential in today's production context, as the availability of machinery at a minimum cost must be ensured (Dellagi *et al.*, 2020). A lack of available spare parts can lead to significant financial losses in mass production industries (Muniz *et al.*, 2021). In the classical manufacturing (CM) approach, spare parts typically have an intermittent demand that is difficult to forecast (Syntetos and Boylan, 2001) (Croston, 1972) and long procurement lead times. These features can lead to mismanagement, thus resulting in high costs. Additive manufacturing (AM) is a promising alternative for spare part management (Li *et al.*, 2017), due to two characteristics that enable on-demand printing: i) the low lead times required compared to CM (Yadollahi and Shamsaei, 2017); ii) and the ability to produce an extensive variety of metal parts using the same printer (Galati, Minetola and Rizza, 2019). On-demand printing avoids the scenario typical of CM, in which high stock levels are required to protect the systems against downtime (Sgarbossa *et al.*, 2021). AM is defined as the process of creating an object directly from a computer aided design (CAD) model with a combination of layer by layer deposition and energy delivery (Wong and Hernandez, 2012) (Gibson, Rosen and Stucker, 2015). This has mainly been applied as a prototyping technology, due to the very short and sometimes zero set-up time (Song and Zhang, 2016) required for producing complex geometries. AM has recently been applied to mass production in various fields such as the medical sector (Regis *et al.*, 2015), due to the numerous materials that can be used and various post processes, which can extend the mechanical properties of the parts at an extra cost (Liu and Shin, 2019) in specific operation conditions (Kumbhar and Mulay, 2018). However, using AM for spare parts involves several challenges that limit its application. Although manufacturing companies typically have the knowledge and ability to source CM spare parts, they lack experience with AM (Knofius, van der Heijden and Zijm, 2019b). The challenges related to a lack of in-house knowledge regarding AM technology and a lack of working expertise with AM that complicates the identification of promising cases (Attaran and Attaran, 2017). These challenges are amplified by the lack of failure data under various loading scenarios (Mellor *et al.*, 2014). In fact, the mechanical properties of AM parts are relatively unknown. However, accelerated tests (Razavi, 2019) and failure criteria (Peron *et al.*, 2017) (Peron, Torgersen and Berto, 2018) are viable approaches for predicting the mechanical properties of AM parts. The high production and equipment costs are still barriers to the widespread adoption of AM, and although these costs are expected to decrease in the

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coming years (Westerweel, Basten and van Houtum, 2018), this is difficult to predict in terms of timing and order (Jiang, Kleer and Piller, 2017) (Peron and Sgarbossa, 2020). Despite these barriers, AM can be a viable option for part management, and particularly for spare parts (Knofius, van der Heijden and Zijm, 2019a). However, few studies have evaluated its application. Liu et al. (2014) investigated the reduction in safety stock brought by the introduction of AM technologies for aircraft spare parts in the two scenarios of centralized and decentralized AM production. However, the purchasing cost of a 3D printer in the centralized scenario and the lower reliability of AM compared to CM were not considered. The evolution of AM technology and post processing has recently improved reliability, and thus AM parts are comparable or more reliable than CM parts (Peron *et al.*, 2018). Song and Zhang (2016) considered an overseas equipment manufacturer and on-demand printing. They modelled the problem as a multi-class priority queue with Poisson demand and divided the spare parts into two clusters (make-to-stock and printed on demand) to determine the optimal continuous review policy. They considered the dynamics of the insourced 3D printer (i.e., the waiting time in the queue) although real failure data was not applied. In addition, they did not factor the cost of the 3D printer into their insourcing option or analysis and assumed that AM and CM parts had the same failure rates. Similarly, Knofius et al. (2017) modelled the dual sourcing problem as a continuous Markov decision process, taking a single-item perspective. In fact, they accounted for a single item installed on a base of identical systems as done in our work, but they considered outsourced AM parts with replenishment lead time exponentially distributed. Westerweel *et al.* (2020) extended the dual sourcing problem with fixed order cycles by considering two supply sources and found that on-demand printing on site leads to savings by reducing the inventory and increasing availability. The AM parts were again considered to be less reliable. Similarly, Knofius et al. (2019a, 2019b) optimized the switching period from a regular component to AM through a dynamic programming approach, which considered the reduction of printing costs over time. This novel approach addresses the high cost of AM, which remains a major drawback. Finally, Sgarbossa *et al.* (2021) modified the classic reorder model proposed by Babai, Jemai and Dallery (2011) by applying it to a periodic dual sourcing inventory system. Their innovative approach involved evaluating various AM technologies for spare part management, thus enabling them to identify the best match in terms of materials and post-processing. However, they did not consider the insourcing of the 3D printer and assessed the management of only one part at a time. In a recent study of preventive maintenance with multiple printing options (Lolli *et al.*, 2022) various AM technologies and post processing approaches were investigated and a decision support system (DSS) was developed, through which practitioners can select the optimum specific combination.

This brief literature review of the applications of AM to spare parts management has highlighted two main limitations in the research: (i) the assumption that AM spare parts are characterized by higher failure rates than CM parts; and (ii) investment costs for AM machines are not considered and AM parts are externally supplied. Thus, we address these limitations by presenting a new inventory management model that considers a spare part installed on a pool of systems that can be managed with CM or AM. All spare parts or a fraction can be managed with AM under a strictly on-demand approach, using an insourced 3D printer. We also consider both the purchasing cost and the waiting time of the parts at the printer. We propose a purely on-demand approach with AM, instead of the the classical reorder model of Babai, Jemai and Dallery (2011), in which an AM part can be kept in stock, as Sgarbossa *et al.* (2021) suggested. This assumption is based on the need to eliminate the inventory in spare parts logistics (Ivan and Yin, 2018), which is a rational choice. For example, in the automotive industry, older parts may be held due to discontinued manufacturing (Song and Zhang, 2016), and in constrained remote systems like offshore platforms, stocks cannot be held or are highly constrained (Westerweel *et al.*, 2021). Instead for the parts being managed with CM we have considered the classical reorder model of Babai, as applied in Sgarbossa *et al.* (2021) modified in order to account for the backorder costs of CM parts. We consider these to be unitary costs per part and per unit time and not only per part in the backorder, as in Sgarbossa *et al.* (2021). We regard the CM management system as having an unconstrained and a constrained storage capacity to account for remote systems, as previously described. Thus, our aim is to identify situations in which AM is profitable for spare parts management when a spare part producible both by CM and by AM is installed in a pool of identical machines (e.g., aircraft and production systems). By considering AM as insourced and by taking an on-demand approach, we overcome the main limitations in the literature. Unlike other studies, we include real AM part data, which indicates that post-processed AM parts have lower failure rates than CM parts (Kumbhar and Mulay, 2018). The data on the mechanicals properties of the parts are obtained from recently conducted real accelerated tests (i.e., from Sgarbossa *et al.*, 2021), and thus our work can be viewed as a natural extension of this study. In particular, we consider a small part that Sgarbossa *et al.* (2021) found to be more suitable for AM. For the CM option, the part is produced via Cast and Polishing (C+P) and via Selective Laser Melting and Polishing (SLM+P) for the AM option.

We examine two scenarios for the on-demand printing of AM parts:

- Insourced AM: a scenario in which we include the purchasing cost of the 3D printer, and the backorder costs obtained from the printing time and the printer queue in the optimization model.
- Insourced AM and constrained storage capacity: we consider insourced AM as in the first case and also a constrained storage capacity for CM parts. This scenario represents production contexts at remote locations (e.g., oil platforms or military bases), which is an application of AM that has been explored, but that has a higher failure rate for AM parts compared to that of CM parts (Westerweel *et al.*, 2021).

The paper is structured as follows: Section 2 presents the mathematical model and its explanation; Section 3 provides the results of our experimental analysis on real data under the different scenarios; and our conclusions and further research agenda are presented in Section 4.

2. MODEL

In this section we present the notation, the hypothesis and the mathematical formulation of our inventory management model. We divide the entire set of spare parts between AM or CM, in which some or all of the parts can be produced with AM or with CM, based on the minimum total cost. The inventory for the set of parts produced via CM is then managed with the classical order-up-to level, while parts managed with AM are printed on demand when required.

2.1 Notation

Input:

- N: total number of spare parts installed.
- i: production mode (options are CM or AM)
- $MTTF_i$: mean time to failure of the spare part made with production mode i $[week]$
- λ_i: failure rate of the spare part made with production mode i $[\frac{part}{week}]$
- c_a: purchasing cost of the CM option $[\frac{€}{part}]$
- c_p: production cost of the AM option $[\frac{€}{part}]$
- c_b: unitary backorder cost per time unit $[\frac{€}{part*week}]$
- h: weekly holding rate $[\frac{1}{week}]$
- f: fixed weekly costs for the purchasing of a 3D printer, considered as depreciation $[\frac{€}{week}]$
- t_{prod}: production time of the AM option $[weeks]$
- LT: replenishment lead time of the CM option $[weeks]$
- m: number of insourced 3D printers, variable to be optimized
- T: review period $[weeks]$
- S_{max} : máximum order-up-to level for CM option in stocks constrained systems $[part]$
- y: auxiliary variable representing the number of failures of the part in $T + LT$
- CA: purchasing cost for CM parts $[\frac{€}{week}]$
- CP: production cost for AM parts $[\frac{€}{week}]$
- CB_{CM}: backorder cost for CM parts $[\frac{€}{week}]$
- CB_{AM}: backorder cost for AM parts $[\frac{€}{week}]$
- CH: inventory cost $[\frac{€}{week}]$
- CS: weekly cost for the purchasing of the printers $[\frac{€}{week}]$

Decision Variables:

- n_{AM}: number of spare parts produced on demand via AM, to be optimized. So, $N - n_{AM}$: is the number of spare parts produced with CM managed with stocks
- m: number of insourced 3D printers, variable to be optimized
- S: order-up-to level for CM option, to be optimized $[part]$

Auxiliaries Variables:

- y: number of failures of the part in $T + LT$.
- $P_{\lambda_{CM},T+LT,y}$: probability of having exactly y-failures in $T + LT$
- μ: service rate. $\mu = \frac{1}{t_{prod}}$
- ρ: utilization of the printer. $\rho = \frac{\lambda_{AM}}{\mu}$
- M: very large integer number used only to impose that no parts will be printed if the printer is not purchased (3).
- $t_{FM,n_{AM}}$: average waiting time of a backordered part if n_{AM} −parts are managed with AM.

2.2 Hypothèses

1. Failures are distributed as a Poisson process in both the production options.
2. The inventory problem regards a spare part that is installed on a pool of N identical machines where the part exhibits the same failure rate, i.e., it depends only on the production mode adopted.
3. AM option is adopted on demand only, i.e., no stock allowed.
4. The review period for the CM option is not optimized but assumed as an input variable (that can be tested with different levels).
5. If AM is chosen than only one 3D printer is allowed (i.e., $m \in (0,1)$) in order to understand the trade-off between CM and AM and to represent a practical situation for the adoption of a new technology.
6. AM can be chosen for a subset of the total spare parts installed (n_{AM}).

2.3 Mathematical Model

The mathematical model is formulated as follows:

$$min\ Ctot = CA + CP + CB_{CM} + CB_{AM} + CH + CS \quad 1)$$

s.t.

$$n_{AM} \leq M \cdot m \quad 2)$$

$$0 \leq n_{AM} \leq N \quad 3)$$

$$m = \begin{cases} 0\ if\ no\ printer\ \ is\ used \\ 1\ if\ the\ printer\ is\ purchased \end{cases} \quad 4)$$

$$0 \leq S \leq S_{max} \quad 5)$$

$$n_{AM}, S\ \in N \quad 6)$$

Where the terms in 1) can be written as:

$$CA = (N - n_{AM}) \cdot c_a \cdot \lambda_{CM} \quad 7)$$

$$CP = n_{AM} \cdot c_p \cdot \lambda_{AM} \quad 8)$$

$$CB_{AM} = n_{AM} \cdot c_b \cdot t_{FM,n_{AM},m} \cdot \lambda_{AM} \quad 9)$$

$$CB_{CM} = (N - n_{AM}) \cdot \sum_{y=S}^{\infty}(y - S) \cdot P_{\lambda_{CM},T+LT,y} \cdot c_b \cdot \left(\int_0^{T+LT} \frac{\lambda_{CM}^{y} \cdot t^{y-1} \cdot e^{-\lambda_{CM} t}}{(y-1)!} \cdot (T + LT - t)\, dt\right) \quad 10)$$

$$CH = \sum_{y=0}^{S-1}(S-y)\cdot P_{\lambda_{CM},T+LT,y}\cdot h\cdot c_a\cdot\frac{y}{\lambda_{CM}}\cdot\frac{1}{(T+LT)} \tag*{11)}$$

$$CS = m\cdot f \tag*{12)}$$

$$P_{\lambda_{CM},T+LT,y} = \frac{(\lambda_{CM}(T+LT))^{y}\cdot e^{-\lambda_{CM}(T+LT)}}{y!} \tag*{13)}$$

$$t_{FM,n_{AM}} = \frac{1}{\mu}+\frac{\rho}{2\mu(1-\rho)} \tag*{14)}$$

The objective of the optimization model is to minimize the weekly total cost (1), which consists of purchasing (7) the proportion of item outsourced $(N-n_{AM})$, the production cost (8) for the insourced printed parts (n_{AM}), and the backorder cost for AM parts (9) where the waiting time is obtained by modelling the system as a M/D/m queue (14), which becomes a M/D/1 queue with our assumption of m. The total cost comprises the backorder cost for CM parts (10), which is calculated as the average waiting time of a backordered part , i.e., when the failures in $T+LT$ overcome the order-up-to level. In addition, we encounter the stocking cost for CM parts (11) and the fixed cost for the purchasing of the 3D printer if insourced (12). Note that we use the reorder model proposed by Babai, Jemai and Dallery (2011) for the CM part, as applied in Sgarbossa *et al.* (2021), but modified in the backorder cost part. Our expression for CB_{CM} is novel, and accounts for the cost of each backordered part throughout the unavailability time.

3. EXPERIMENTAL ANALYSIS

Our experimental analysis is based on real data of purchasing and production costs and on the failure rates for AM and CM, as suggested by Sgarbossa *et al.* (2021), which are representative of a small spare part.

Table 1. Input Data

Data	Value	Data	Value
N	90	c_p	150 $[\frac{€}{part}]$
$MTTF_{CM}$	26 $[week]$	c_b	2000$[\frac{€}{part*week}]$
λ_{CM}	0.0385 $[\frac{part}{weeks}]$	h	0.0058 $[\frac{1}{week}]$
λ_{AM}	0.0055 $[\frac{part}{weeks}]$	f	769.88 $[\frac{€}{week}]$
c_a	30 $[\frac{€}{part}]$	t_{prod}	0.1 $[week]$

The part is assumed to be produced via Cast and Polishing (C+P) for the CM option and via Selective Laser Melting and Polishing (SLM+P) for the AM option. The ratio between their $MTTF$ $(\frac{MTTF_{AM}}{MTTF_{CM}})$ is 6.93 and is derived from the accelerated tests in the literature, as described in Sgarbossa *et al.* (2021). The production cost for the part via AM is impacted by the size of the part (that influences the materials used) and by its complexity. For a full explanation of the economical and technological parameters of the part we refer to Section 3.3 of Sgarbossa *et al.* (2021). For the 3D printer, we consider a purchasing cost of 200,000 €, which is amortized in 5 years, and with 52 working weeks we obtain the weekly cost. The data presented in Table 1 and the model described in Section 3 are applied, with levels for both the CM part lead time and review periods (i.e., 12 and 24 weeks). We first analyse a scenario of unconstrained storage capacity with insourced AM, i.e., $S_{max}=\infty$. The results are reported in Table 2. To solve the optimization problem, we use a genetic algorithm implemented in MATLAB with a maximum of 3,000 generations allowed. Since our model regards an integer based optimization the genetic alghoritm is based on the work of Deep *et al.*,(2009) and comprehend a paraemter free penalty approach to handle constraint and a truncation procedure to manage the integer restriction on the optimization variables.

Table 2. Results with $LT=12, T=12$ and $S_{max}=\infty.$

	n_{AM}	m	S	$Ctot$
$T=12$ $LT=12$ $S_{max}=\infty.$	0	0	4	143.60
$T=24$ $LT=24$ $S_{max}=\infty.$	0	0	6	160
$T=12$ $LT=12$ and $T=24$ $LT=24$	90	1	-	947.41

Table 2 indicates that under the assumption of unconstrained storage capacity, the optimal solution with both the levels of T and LT is to manage the spare parts solely with CM. The order-up-to levels are equal to 4 and 6 in the lower and higher levels for T and LT, respectively. AM is never selected because the purchasing cost of the 3D printer would be almost five times that of managing the entire set of spare parts via CM. Table 2 indicates the cost for managing all of the set of spare parts with AM with constrained n_{AM} equal to N. This interesting result clearly shows that insourcing a 3D printer for managing on-demand 90 small spare parts is not profitable under an unconstrained storage capacity. By forcing AM, i.e., $n_{AM}=N$, we derive a total weekly cost of 947.41 for both the levels of T and LT, as printing on demand is not affected by any variations in the review period or lead time (this is not a negligible feature under lead time uncertainty), and the purchasing cost for the printer constitutes 81% of the total cost. We therefore conduct a sensitivity analysis to investigate the level of storage capacity constraint required to make printing on demand with an insourced 3D printer preferable. As both T and LT are equal to 12, printing on demand becomes economically advantageous from $S_{max}=2$, while with the higher order-up-to levels stocking CM parts is still the best option, as shown in Figure 1. Note that with $S_{max}=2$, the management of spare parts via CM is almost 3 times more expensive than with on-demand printing, while with $S_{max}=1$ it is 10 times more expensive. This interesting finding indicates that with a classical order-up-to level management of spare parts produced via CM, the total cost exponentially increases while the upper bound of the storage capacity increases, i.e., binding more S_{max}, even if the total order-up-to level with $S_{max}=2$ equals 180, which is not a negligible value. As visible from Figure 2 a similar situation occurs with the higher levels of T and LT because the management of spare parts via CM is cheaper up to a maximum order-up-to level allowed of 4, while with an S_{max} equal to 3 or 2 printing on demand is convenient

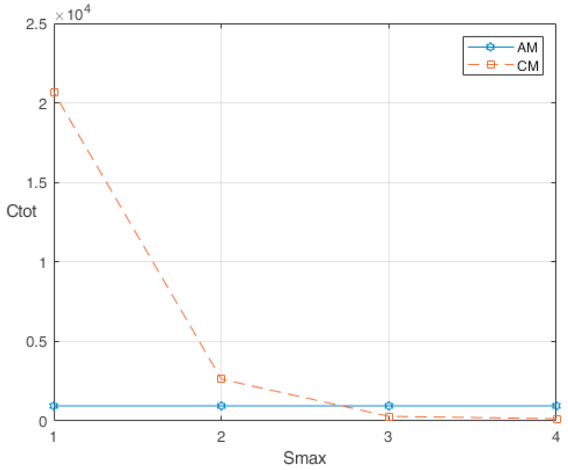

Figure 1. Sensitivity analysis with constrained storage capacity ($T = 12,\ LT = 12$).

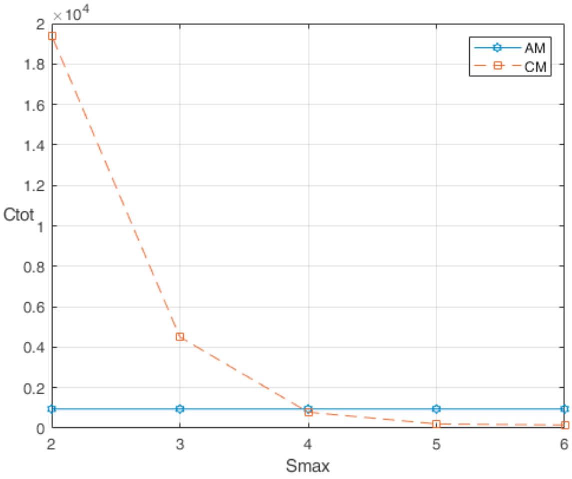

Figure 2. Sensitivity analysis with constrained storage capacity ($T = 24,\ LT = 24$).

As visible from Figure 2 a similar situation occurs with the higher levels of T and LT because the management of spare parts via CM is cheaper up to a maximum order-up-to level allowed of 4, while with an S_{max} equal to 3 or 2 printing on demand is convenient. Indeed, decreasing the maximum storage capacity allowed with the higher levels of T and LT leads to increase exponentially the cost for managing spare parts via CM, as being almost six times more expensive than printing on demand with $S_{max} = 3$. Thus, our experimental analysis clearly shows how under an unconstrained storage capacity the classical CM management of spare parts is preferable due to the high purchasing cost of the 3D printer combined with high production cost of AM. At the same time for constrained storage capacity AM is undoubtedly beneficial given the exponential increasing cost for CM management while increasing the storage capacity.

4. CONCLUSION

In this paper, we present an inventory model that optimizes the shift from CM under a classical order-up-to level inventory management to AM for on-demand printing. Our model is based on that proposed by Sgarbossa *et al.* (2021), which we have modified to account for a backorder proportional to the backorder time, the cost of the 3D printer if it is insourced and a set of identical spare parts. We applied our model to real data that include the failure rates and production costs for CM and AM along with the purchasing cost for the 3D printer, by considering the procurement of a small spare part. We selected the part based on the data from Sgarbossa *et al.* (2021). The results of our experimental analysis reveal that printing on demand with an insourced printer is not preferable if the storage capacity is unconstrained, due to the high production costs and the high purchasing cost of the 3D printer. Given the actual costs, AM is only preferable with an outsourced make-to-stock system, as analysed by Sgarbossa *et al.* (2021). We also conducted a sensitivity analysis to test various maximum stock levels by varying both the reordering and lead times. We found that the cost of the management of spare parts via CM increases exponentially decreasing the maximum allowed storage capacity, making printing on demand with an insourced 3D printer advantageous. This cost via CM under a constrained storage capacity can be up to 3 times higher than that via AM. In conclusion, we confirm that printing on demand with an insourced printer is preferable when storage capacity is constrained, such as in remote locations (e.g., oil platforms or military bases), and from a purely cost-based perspective AM is profitable when there is no constrained storage capacity.

Thus, further potential research directions include:

- Investigating the advantages of a make-to-stock policy with internally printed AM parts.
- Extending current models with dual sourcing options (e.g., Song and Zhang, 2016) by considering the insourcing of a 3D printer and selecting the parts that are suitable to be printed.
- Creating a decision support system to assist managers select either on-demand printing and printing-to-stock or the classical CM management of spare parts.

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