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Reducing resupply time with additive manufacturing in spare part supply chain

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Abstract: Recently, Additive Manufacturing (AM) has started to be considered as an alternative to Conventional Manufacturing (CM) in the spare part production, due to the negligible set-up times that AM has with respect to CM and the possibility of producing small batches. However, AM production times are usually larger than those of CM, making the choice between them not as obvious as it may seem. In this paper, the impact of AM is studied in a single-echelon supply chain under the assumption of infinite production capacity of the production facility and (S-1, S) inventory policy. Results are obtained by using analytical Markov Chain models.

Keywords: Inventory control, production planning and scheduling; Design and reconfiguration of manufacturing systems; Industry 4.0

1. INTRODUCTION

Spare part management is a key issue in almost any industry, as spare parts are kept in stock to guarantee maintenance operations in the case of not operating equipment. Due to the high unpredictability of their demand, spare parts can generate high costs and/or low service levels. Nowadays, parts are needed all over the world and must be traceable for safety reasons, and stock-outs might have a high economical impact; for instance, in the airline industry, not having a spare part means leaving an aircraft-on-the-ground (AOG) (Gu et al., 2015; Simão and Powell, 2008). When stock-outs have high risk and thus a high associated cost, very high service levels are required, possibly together with low levels of inventory, to guarantee a limited amount of capital tied up in storage.

Taking as example the airline industry, benchmark studies show that many airline companies today hold up to 20% excess inventory and much of this excess inventory is for slow moving parts (Walter et al., 2004). To reduce the amount of needed inventory for airlines, large aircraft companies have worked on cutting lead times and delivery costs (Michaels, 1999). Using Additive Manufacturing (AM), parts can be produced directly at the place of consumption and in very small batches, keeping the same cost per part (Marchese et al., 2015; Tuck and Hague, 2006). In this context, AM technologies could be an opportunity for improving supply chain performances, considering the make-on-demand capability (Atzeni and Salmi, 2012). Thus, CNC paths, tooling and machine set-ups can be avoided (Chen et al., 2015). To cite a realistic case, Airbus in Hamburg–Fuhlsbüttel owns more than 120.000 parts, the 80% of which is used only few times a year but require 100% service level (Walter et al., 2004); for these parts, AM technology can be useful to have zero inventory and make-on-demand production.

While AM has already been applied in aerospace production industry to produce light weight parts (e.g., Bourell et al. (2009); Wohlers (2010)), the reconfiguration of spare part supply chains and inventory management due to the introduction of AM is still under research. For example, the location of AM facilities in supply chain configurations have been studied for the make-to-order slow moving part production, analyzing both centralized and distributed configurations (Walter et al., 2004; Tuck and Hague, 2006; Holmström et al., 2010). Distributed configurations have been proved to have lower total costs than the centralized ones and the key factors in decreasing the costs have been identified to be the higher automation, the lower acquisition price and the shorter production time of AM machines (Khajavi et al., 2014). Also, the impact of AM on safety stocks and stock-out risk has been investigated. The safety stock issue has been studied in different scenarios characterized by various demand characteristics, manufacturing lead time, logistics lead time and cycle service level; results showed that AM can change the conventional configuration of the spare parts supply chain to achieve safety inventory reduction, thus cutting inventory holding costs across the entire supply chain (Liu et al., 2014). About stock-out risk, instead, it has been shown that using AM for spare part items under an *(S-1,S)* inventory policy, and using emergency orders in stock-out situations generally improves stock-out risk of spare parts, reduces holding cost and shortens lead time. All these issues give firms conflicting incentives in changing the optimal inventory stocking level to minimize the overall inventory

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cost (Sirichakwal and Conner, 2016). AM-based supply chains, mainly studied through system dynamic models, resulted to be superior to the conventional ones also in terms of total supply chain costs and carbon emission (Li et al., 2017; Ghadge et al., 2018). The case of having a combination of traditional and additive technologies to produce parts as a dual source model, considering a lower quality for the AM parts, has also been studied and, also in this case, the introduction of AM turned out to be beneficial (Knofius et al., 2017). No study in the literature has already addressed the issue of avoiding the set-up time of conventional technologies by moving to AM, although set-up strong reduction has been shown for various AM technologies (Mashhadi et al., 2015; Rosen et al., 2015; Rüßmann et al., 2015). With no set-up, AM can decrease the resupply time and, hence, lead to lower inventories.

The aim of the paper is to study the impact of AM in a single-echelon spare part supply chain on slow moving parts. The effect of the resupply time caused by the use of different technologies (AM and Conventional Manufacturing-CM) on the inventory performance is investigated. As the resupply time is composed by the production and the set-up time, the paper focuses on how the set-up time can favor the shift from CM to AM technologies. For both AM and CM, the *(S-1,S)* inventory policy has been considered (as suggested by Sherbrooke and Feeney (1966); Sherbrooke (1968); Muckstadt and Sapra (2014); Graves (1985) for slow movers). Markov Chains have been used to model the production time and the set-up time. A numerical experiment has been carried out to understand the extent to which AM is more convenient than CM. Differently from Sirichakwal and Conner (2016), who studied the case of lost demand and emergency orders, backorders are included in the proposed model and the set-up is explicitly taken into account.

The remainder of the paper is organized as follows. Section 2 shows the supply chain model and its properties. Numerical results are discussed in Section 3. Section 4 concludes the paper with some highlights and limitations.

2. THE SUPPLY CHAIN MODEL

The supply chain considered in this paper is characterized by a single Original Equipment Manufacturer (OEM), with its own spare part inventory and its own workshop, a single echelon and a single spare part. Two cases are compared: (i) the part is produced by a CM technology; (ii) the part is produced by an AM technology. The part is a slow mover, thus its demand is assumed to be $Poisson(\lambda)$ distributed. The inventory is ruled by a $(S-1, S)$ policy. When needed, parts are resupplied by producing them with either CM or AM technology. In the following, first the system is described in details, second the minimization inventory problem is proposed, and then the resupply phase is modelled with Markov Chains.

2.1 System description

The two spare part production technologies have infinite capacity. The resupply time is a function of the production and the set-up times, which are both assumed exponentially distributed (with different rates for CM and AM). Specifically, the AM average production time ($\tau_{p,am}$) is greater than the average production time of CM ($\tau_{p,cm}$); instead, for the set-up, the average CM set-up time ($\tau_{su,cm}$) takes a significant amount of time whereas the average AM set-up is negligible ($\tau_{su,am} = 0$). Moreover, in CM, set-up occurs if and only if an arriving order does not find another already in production (i.e., if the machine is idle). Two Markov Chains are modelled to calculate the average number of parts in resupply $E[X]$ (with X being the related stochastic variable), and the mean CM (τ_{cm}) and AM (τ_{am}) resupply times.

The spare part inventory is ruled by a continuous $(S-1, S)$ policy (i.e., an order is placed immediately when a demand occurs and the order quantity is equal to the demand size) and backorders are allowed. The total cost $TC(S)$ is the sum of the holding ($CI(S)$) and the backorder ($CB(S)$) costs. Given $B(S)$ backorders, $CB(S)$ is given by $C_B B(S)$ (being C_B the unit backorder cost). The holding cost, instead, is given by $C_I(S - E[X] + B(S))$, with $S - E[X] + B(S)$ being the average on-hand inventory (target S minus parts in resupply $E[X]$ plus backorders) and C_I the unit holding cost. Given a target level S (which corresponds to the maximum available inventory), customers are satisfied with a fill rate $F(S)$, which is the fraction of demand that can be satisfied immediately by the on-hand inventory.

2.2 The problem

The optimal S^* must be chosen to minimize the total cost, while assuring a minimum target fill rate α. The minimization problem can be mathematically modeled as follows:

$$\min_{S} \; C_I(S - E[X] + B(S)) + C_B B(S) \tag{1}$$

$$s.t. \quad F(S) > \alpha \tag{2}$$

$$S \geq 0 \tag{3}$$

The objective function (1) minimizes the sum of holding and backorder costs and constraint (2) assures the achievement of the target fill rate. For both $F(S)$ and $B(S)$, the system steady state behavior has to be considered. Let $p(x)$ be the steady state probability, i.e., the probability of having x parts in resupply, then $F(S)$ and $B(S)$ can be computed as follows:

$$B(S) = \sum_{x>S} (x - S)\, p(x), \tag{4}$$

$$F(S) = \sum_{x \leqslant S-1} p(x). \tag{5}$$

2.3 Resupply Markov Chain

The mean resupply times are obtained through two Markov Chain models, one for each technology. The following notation is used:

- $\mu_t = \frac{1}{\tau_{p,t}}$: production rate of machine t ($t = \{am, cm\}$);
- λ: arrival rate;
- $\rho_t = \frac{\lambda}{\mu_t}$ $(t = \{am, cm\})$;
- $X\{0, 1, 2, ..., \infty\}$: state space for the AM system, which corresponds to how many parts in resupply are present;

- $\mu_{su,cm} = \frac{1}{\tau_{su,cm}}$: frequency of the CM set-up;
- $X\{a, b\}$: state space of the CM system, where
  - $a \in \{0, 1\}$: indicates the production status ($a = 1$ if the machine is working and $a = 0$ if it is idle),
  - $b \in \{0, 1, 2, ..., \infty\}$: indicates the number of parts in resupply.

(i) The AM technology has no set-up and infinite capacity, thus the resupply can be represented by an $M/M/\infty$ queue (Fig. 1 shows its state transition diagram).

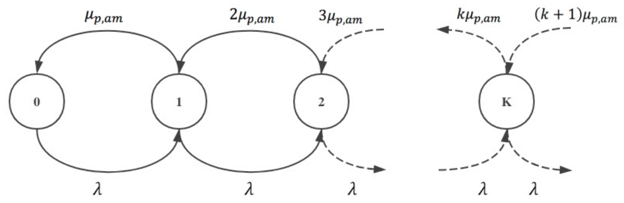

Fig. 1. State transition diagram for the AM system.

The probability of being in state x, given a Poisson demand, is:

$$p(x) = e^{-\rho_{am}} \frac{\rho_{am}^x}{x!}. \tag{6}$$

Being $E[X]$ the expected number of parts in the system (which is equal to $\frac{\lambda}{\mu_{am}} = \rho_{am}$ for a $M/M/\infty$ queue), by Little's Law, the expected average system time, which can be seen as the AM mean resupply time $\left(E[T_{am}] = \frac{E[X]}{\lambda}\right)$, is:

$$E[T_{am}] = \tau_{am} = \frac{1}{\lambda} \sum_{x=0}^{\infty} e^{-\rho_{am}} \frac{\rho_{am}^x}{x!} = \frac{\rho_{am}}{\lambda} = \tau_{p,am}. \tag{7}$$

(ii) The CM case is more complex due to the presence of set-up, which makes the Markov Chain irreducible and aperiodic as represented in Fig. 2 (general numbers in the brackets correspond to the states). The nodes at the bottom of the Markov Chain represent the states with no jobs in the queue and set-up, whereas the nodes at the top represent the states with jobs already present in the queue and, hence, no set-up.

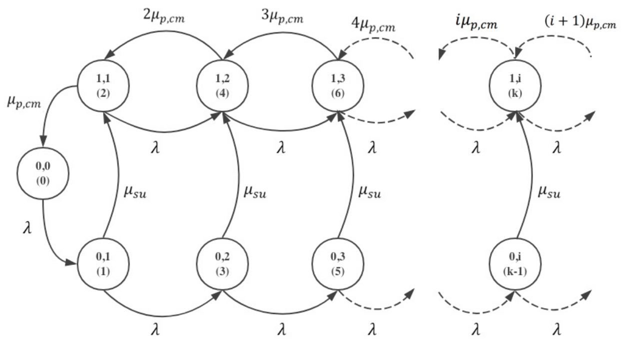

Fig. 2. State transition diagram for the CM system.

Also in this case, by using Little's Law, the expected CM resupply time can be computed as follows:

$$E[T_{cm}] = \tau_{cm} = \frac{E[X]}{\lambda} = \frac{\sum_{k=0}^{\infty} m p(k)}{\lambda}, \tag{8}$$

where m is the number of parts corresponding to state k and $p(k)$ can be numerically found by solving the equilibrium and normalization equation system derived from Fig. 2 (which is not reported in the paper for reasons of conciseness).

2.4 Model properties

The behavior of the components of the analytical model is studied in the following. Specifically, the behavior of the resupply time and of the total cost in (1) with respect to the set-up time, the production time and the demand rate λ is shown in the following.

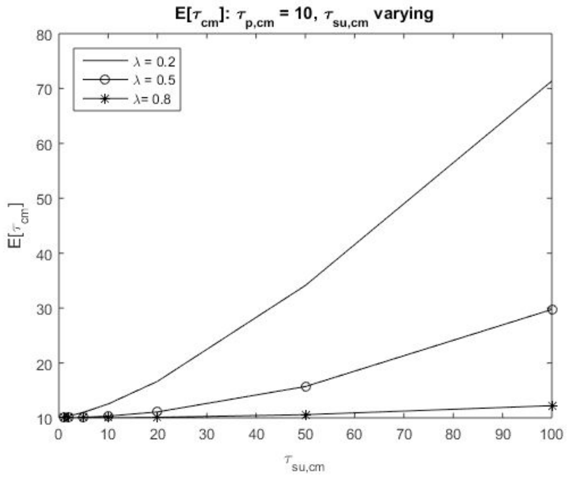

Fig. 3. CM: resupply time for different values of $\tau_{su,cm}$.

Resupply time As shown in Section 2.3, the resupply time is a function of the set-up and the production time. Specifically, the AM technology has no set-up, thus the mean resupply time is equal to the mean production time of the part (as shown in (7)). Instead, for the CM technology, set-up occurs every time the machine is idle and has to start producing again; thus, the resupply depends on both production and set-up average times, as stated in (8). Fig. 3 shows its behavior. As expected, with very low demand rates, the resupply time is largely influenced by the set-up; thus, very slow moving parts (at the end of the life-cycle), usually characterized by very low demand rate and very large set-up time and cost, are affected by large resupply time and, as a consequence, keeping overstocked inventory might be necessary to avoid set-up. On the contrary, for products with high demand rate, the set-up rarely occurs and resupply time, as a consequence, depends mostly on the production time.

Total cost The total cost, as in (1), directly depends on the backorder and inventory costs, which are influenced by the resupply time. For the AM technology, whose resupply time does not depend on set-up (i.e., $\tau_{am} = \tau_{p,am}$), Fig. 4 shows the total cost with different values of λ and τ_{am}. With smaller λ, the curves are sharper around their minimum value, which is in the very left part of the horizontal axis. Thus, the S minimizing the total cost is small, for all production time values. As expected, when the resupply time τ_{am} increases, the S minimizing the curves increases as well, meaning that higher inventories are needed (with higher related costs). When λ is large,

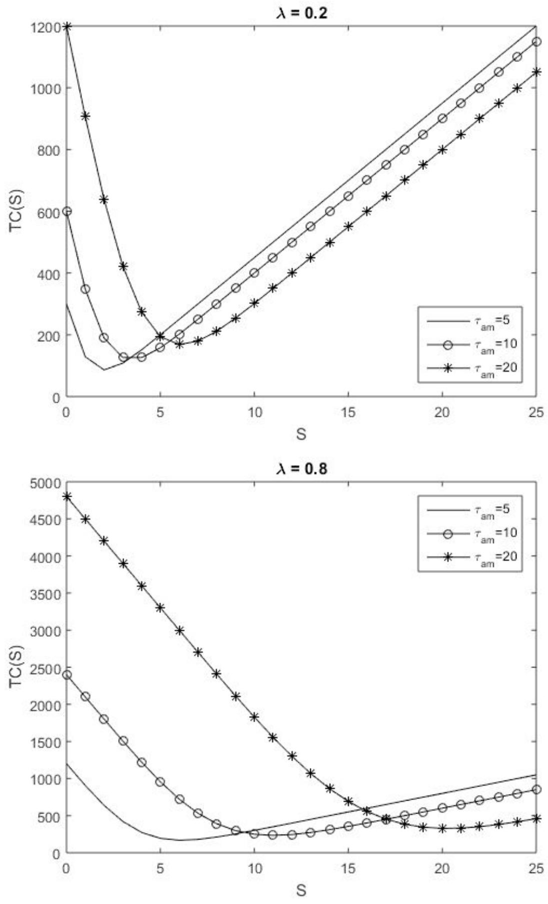

Fig. 4. AM total cost for different values of λ and τ_{am}.

instead, the curves are flatter around their minimum value, which, however, corresponds to higher values than those of small λ. Also in this case, when τ_{am} increases, larger values of S are necessary but τ_{am} is more impacting as the changes in the optimal S are larger. Thus, for very slow movers (small λ), low inventory levels are needed, the mean resupply time has a small impact but the total cost is not robust with respect to S (the total cost largely increases if a target S greater than the optimal is chosen). In the case of large demand rate ($\lambda = 0.8$), instead, S is largely influenced by the mean resupply time but the total cost is more robust (wrong chosen values of S lead to smaller increases in the total costs) than in the low demand rate case.

Fig. 5, instead, shows the total cost behavior for the CM technology. In this case, the mean production time is fixed and equal to $\tau_{p,cm} = 5$, whereas the set-up mean time varies. The behavior of the total costs is the same as that of Fig. 4, however, it is influenced by the set-up time (i.e., the set-up time plays the role played by the production time in the AM case).

Thus, there is a trade-off between AM production time and CM set-up time that must be analyzed to define if the AM technology can decrease the total cost in slow moving spare part inventories. The numerical experiment will address this trade-off.

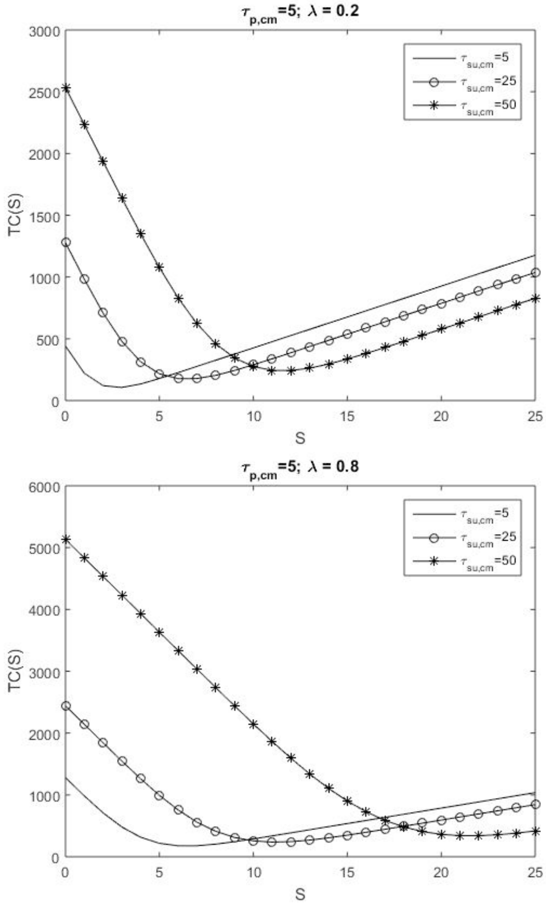

Fig. 5. CM total cost for different values of λ and $\tau_{su,cm}$, $\tau_{p,cm} = 5$.

3. NUMERICAL EXPERIMENT

A numerical experiment has been performed to compare the optimal total cost of the two technologies (TC^*_{am} and TC^*_{cm}) and evaluate the trade-off between AM production time and CM set-up time in terms of total costs.

For different input parameters, the inventory level S^* that minimizes the total cost (eq. (1)) while assuring the achievement of the target fill rate α (eq. (2)) has been determined through the use of a commercial solver, and the resulting total cost is computed.

The comparison between the two technologies is made by the difference of the total costs of the two technologies:

$$\Delta TC = TC^*_{cm} - TC^*_{am}. \qquad (9)$$

When ΔTC is positive, AM is more profitable in terms of total costs. On the contrary, when ΔTC is negative, CM is more advantageous.

In each experiment, the following economic parameters have been set:

- unit inventory cost: $C_I = 50 \ (\frac{\$}{u})$;
- unit backorder cost: $C_B = 800 \ (\frac{\$}{u})$;
- target fill rate: $\alpha = 99\%$.

The values have been set to reflect the behavior of industries characterized by high cost per parts (implying the high inventory cost), and by the need of a high availability of spare parts (leading to the high target fill rate), such as the airline industry. Moreover, the high value of the backorder cost reflects a strong financial impact of the unavailability of a part.

The time parameters, instead, have been chosen as factors of the experiment and have been set as follows.

- $\lambda = \{0.05; 0.08; 0.1\}$ $(\frac{u}{t})$
- $\tau_{p,am} = [0.5; 5.5]$ $(\frac{t}{u})$;
- $\tau_{su,cm} = [0; 10]$ (t);
- $r = \frac{\tau_{p,cm}}{\tau_{p,am}} = [0.1; 0.95]$ (t) $\rightarrow$ $\tau_{p,cm} = r \cdot \tau_{p,am}$ $(\frac{t}{u})$.

The results for $\lambda = 0.08$ are presented in figures 6-8, as it characterizes the demand of a very slow moving product (or a product at the end of its life cycle). The green area represents the situations with $\Delta TC > 0$ (hence, where AM is more profitable), while the red area the situations with $\Delta TC < 0$ (hence, where CM is more profitable). In all the figures, factor r indicates the ratio $\frac{\tau_{p,cm}}{\tau_{p,am}}$, i.e., the ratio between mean CM and mean AM production times.

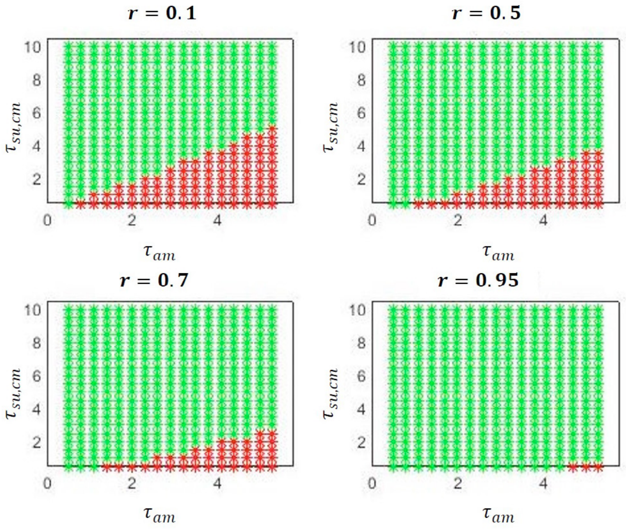

Fig. 6. ΔTC with $\lambda = 0.08$ and r fixed.

As expected, when r is fixed, (Fig. 6) CM is more convenient for small $\tau_{su,cm}$ and high $\tau_{p,am}$. Thus, when increasing $\tau_{p,am}$, CM becomes more profitable; on the contrary when $\tau_{su,cm}$ increases, AM is the best solution. This is reasonable because an increase of $\tau_{p,am}$ penalizes AM technology, as additive production becomes slower than the conventional one, whereas an increase of $\tau_{su,cm}$ supports the choice of AM. In this condition of fixed ratio between production times, increasing r, hence having a smaller difference between $\tau_{p,am}$ and $\tau_{p,cm}$, makes AM more and more profitable.

Fig. 7 shows that, when fixing CM set-up time, AM becomes more profitable when CM mean production time increases and r increases. Moreover, the larger CM set-up time, the smaller is the number of situations in which CM is the most profitable technology. In fact, if CM set-up time is large enough, avoiding it by using AM allows resupply time and backorder cost reduction.

Finally, fixing the mean AM production time $\tau_{p,am}$ (Fig. 8), AM is more profitable than CM when CM set-up time increases with respect to r. Increasing the mean AM production time, the area in which CM is more profitable increases.

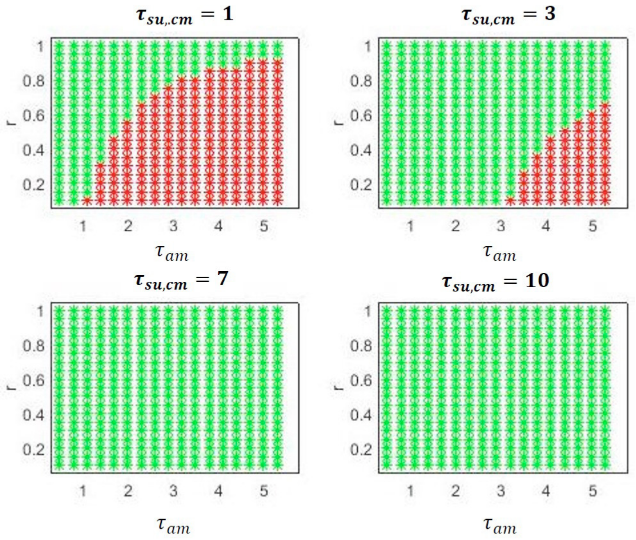

Fig. 7. ΔTC with $\lambda = 0.08$ and $\tau_{su,cm}$ fixed.

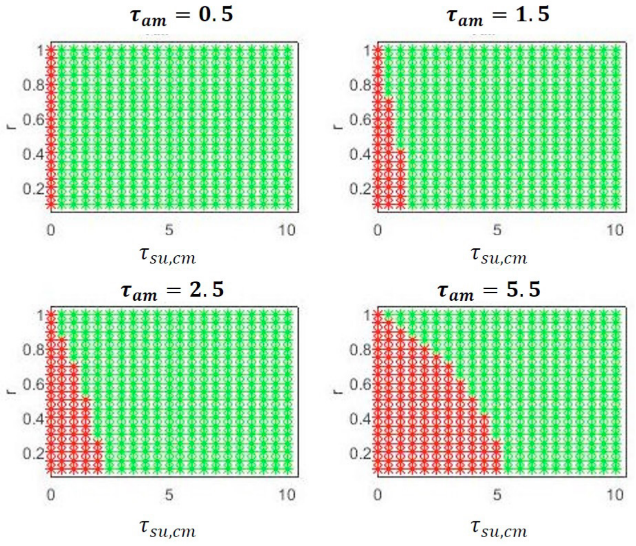

Fig. 8. ΔTC with $\lambda = 0.08$ and $\tau_{p,am}$ fixed.

The results for λ different from 0.08 lead to similar insights, however, they are not reported in the paper for reasons of conciseness.

4. CONCLUSION

The paper addresses slow moving spare parts industries characterized by very expensive and infrequently requested parts, with very high required service levels. In these situations, companies usually opt for warehouse centralization and supply of small batches. However, the fewer the ordered parts, the higher the ordering cost due to production time and complexity. Industries such those in the airline sector and companies producing parts at the end of the life cycle are good representative of this context.

From the obtained results, AM has been shown to outperform CM when CM set-up times are long (with respect to the production times). In fact, the longer the CM set-up time is, the larger the CM resupply time is with respect to the AM one. On the contrary, if the AM production time is large, then the CM set-up will have less influence, making CM more advantageous. Furthermore, it is possible to notice that, generally, the optimal AM stock levels are lower than those of CM. For products characterized by long set-up times (e.g., a spare part at the end of the life cycle with a substitute present in the market, or an aircraft spare part whose failure make the aircraft on the ground), AM can lead to considerable savings when considering the total number of spare parts for a company and their costs. However, the magnitude of the saving is strictly related to the duration of production times. Furthermore, introducing AM in multi-echelon supply chains might reduce the inventories in all echelons, by producing the part in the plant where the AM machine is and then sending it to the place where it is needed.

Although the insights of the paper on the benefit of introducing AM in spare part supply chains, the considered models have some limitations. First of all, further research must consider capacitated machines in both AM and CM systems and their production costs. Also, as AM might have less variable processing times than CM, phase-type distribution might be introduced. As set-up is necessary, especially for the CM technology, the $(S-1, S)$ policy might be generalized into a (s, S) policy, which is currently under investigation. Moreover, real industrial applications should be included.

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