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The impact of Additive Manufacturing on Supply Chain design: a simulation study

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Abstract

Additive Manufacturing is a production technology, which completely differs from the traditional subtractive approach. Because its different nature, its application could cause strong changes in supply chains and it could affect the relationship between the supply chain players. This paper proposes a quantitative evaluation of the Additive Manufacturing effects on the supply chain performance, considering different system configurations. A simulation model has been implemented in order to reproduce the behavior of the players and compare different scenarios. Both additive and traditional technologies have been modelled in order to compare their efficiency. Moreover, different supply chain configurations have been tested to assess the additive production feasibility combined with different supply chain structures. Results confirm that Additive Manufacturing provides good improvements in supply chain performances offering significant benefits in the decentralized solution.

Keywords: Additive Manufacturing; supply chain modelling; descrete event simulation, performance measurement

1. Introduction

Additive Manufacturing (AM) is a well-known manufacturing technology, which completely differs from the traditional manufacturing (TM) approach. AM allows creating objects adding material layer by layer rather than removing material from a block or through molding technologies. For such reason, it is totally opposite to the

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conventional subtractive technologies and its adoption requires strategic changes. In the last decades, the attention on AM was growing and many researchers have started to study its benefits as alternative production strategy compared to traditional manufacturing [1]. Environmental advantages have been widely demonstrated in literature and AM results to have a green potential compared to the subtractive methods [2]. In recent years, the impact of AM on supply chain (SC) performance has started to be investigated too [3]. In general, AM seems to offer many advantages to industries, but it also has a significant impact on supply chain processes and integration [4]. Many studies pointed on the custom design and the possibility to offer quicker response to the market with small and economical batches [5]. In fact, AM promotes rapid product innovation and modification, changing the relation with the customer and creating dynamic connections [6]. At the same time, a strong collaboration with suppliers is required since the characteristics and quality of raw material became fundamental in the printing process [7]. Moreover, producing a single body, AM limits the number of components, drastically reducing the number of suppliers [8]. The combination of such factors has also a positive effect on the inventory management with a stock level reduction in both raw material and final product [9]. Moreover, the reduction of transportation requirements due to adoption of AM could bring both economic and environmental benefits. There is also evidence that the faster production process combined with the simpler supply network reduces the supply chain lead time (SCLT). It has been estimated a SCLT reduction up to 60% switching from conventional to additive manufacturing [10].

Despite the widely discussed benefits of AM on SC performance, SC reconfiguration due to AM technique has received less attention [11]. Additive Manufacturing implicates a new manufacturing concept, involving the customer in the product design and promoting home fabrication [12]. Thus, distributed production and facility locations close to the customer become the right way to take the best advantages from such technology. For such reason, AM is considered a potential disruptive technology for supply chains and it could completely revise or even create new configurations. Some researchers have debated the disruptive implications of AM on supply chain structure with reviews or qualitative studies [13]. [14] concluded their literature analysis asserting that AM alters the way that supply chain operates, thus a new SC managerial approach should be re-examined and developed to take advantages. [15] discussed the consequences of AM implementation on different SC players based on their position on the chain and considering different points of view.

In such context, few studies have measured the impacts of AM on supply chains focusing on its disruptive effects and quantifying them [16]. [17] performed a computational study in order to study the impact of AM on the supply network structure; transport and facility costs have been analyzed and the study shows a good improvement moving the production sites closer to the customers. Different configurations have been modelled by [18] considering centralized and distributed production scenarios; a cost analysis has been conducted offering cost trade-offs and providing some guidelines on AM machines and technology development.

Starting from the considerations above, this paper aims to contribute to the current literature with a quantitative evaluation of the AM effects on the Supply chain performance considering different SC structures. A set of key performance indicators (KPI) have been identified considering logistics and supply chain processes. A discrete event simulation model has been implemented using Microsoft Excel™ in order to reproduce the behavior of the players and compare different scenarios. Both additive and traditional technologies have been modelled in order to evaluate their performance. Moreover, different supply chain configurations have been tested to assess AM feasibility combined with different SC structures.

The remainder of the paper is structured as follows. Section 2 describes the different configurations reproduced and defines the supply chain structures. The simulation model is presented in Section 3, which details the main logics and the input data of the model. The main results are discussed in Section 4. Finally, the last section summarizes the main findings of the study and the future research directions.

2. Supply chain configuration

The current literature has demonstrated that the technological changes and innovations could strongly influence the SC performance and structure [19]. As already discussed in the previous section, Additive Manufacturing is a new technology, which completely differs from the traditional subtractive approach. Its application could cause strong changes within supply chains and it could affect the relationships between SC players. Thanks to the simulation tool, this paper carries out a quantitative evaluation on SC performance testing different scenarios with simple and fast changes. Both Additive and Traditional manufacturing systems have been reproduced, in order to test the AM potential. Moreover, two different AM configurations have been implemented in order to study the AM feasibility in different SC environments. The Aircraft spare parts industry has been analyzed using data obtained by the literature; in particular, supply chain structure has been defined starting from the configurations proposed by [20]. The three scenarios modelled are discussed below.

Figure 1 shows the traditional manufacturing solution, characterized by a centralized supply chain. Generally, a conventional spare parts SC is composed of a single Producer, which manages and controls the whole production. He supplies few centralized storage centers, which distribute the components to smaller warehouses located close to the final user. Moreover, a single supplier has been inserted, considering just the procurement process of the main raw material. Thus, a five-echelon supply network has been modelled, composed of a Supplier (S), an Original Equipment Manufacturer (OEM), two Regional Distribution Centers (RDC), eight Local Distribution Centers (LDC) and the Final customers (FC).

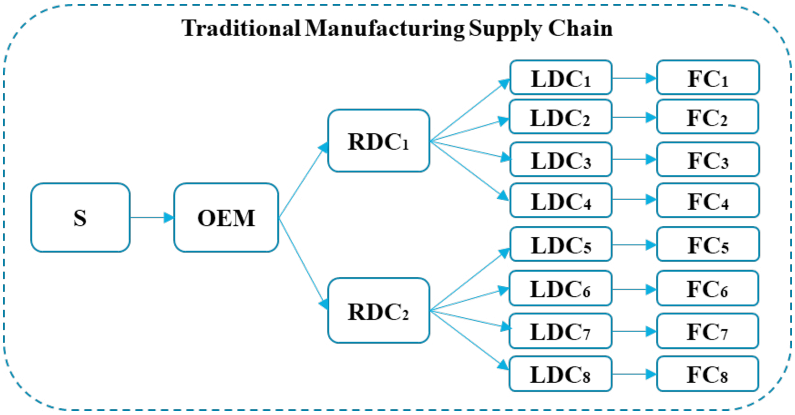

Figure 1: Traditional manufacturing structure

As already explained, two AM configurations have been tested, both represented in Figure 2. The first scenario presents an AM supply chain with centralized structure. The idea is to consider a configuration similar to the previous scenario, in order to test the suitability of the solution just changing the production technology. Thus, the regional distribution centers become both Producers and they serve the small facilities, which face the end user. In the same way, the traditional OEM becomes the powder supplier. Finally, a four-echelon supply network has been implemented, considering one Supplier (S), two Original Equipment Manufacturers (OEM), eight Local Distribution Centers (LDC) and the Final customers (FC).

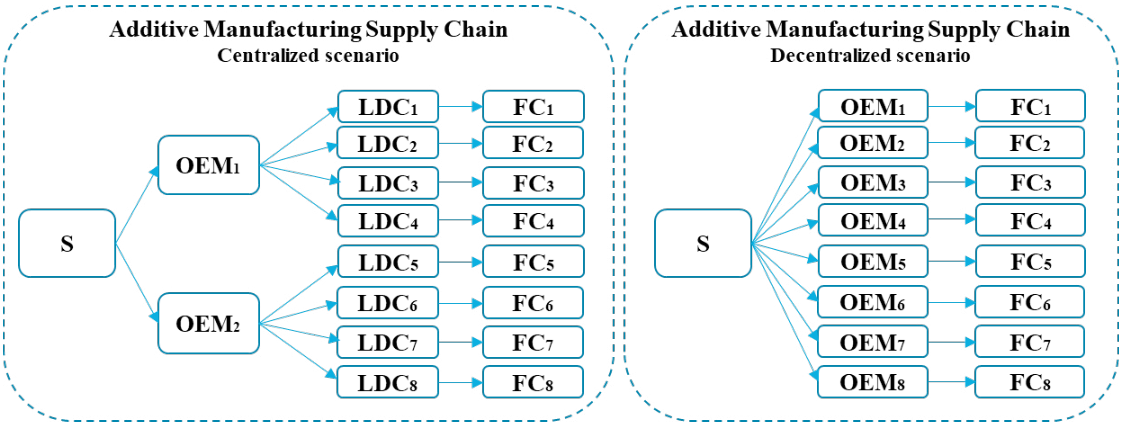

Figure 2: Additive manufacturing configuration with centralized and decentralized structure

Since AM technology well fits for small batches and promotes home fabrication, the second AM scenario adopts a highly decentralized structure. A three-echelon supply chain is considered with the local centers equipped to manage its proper production. In such case, the production stage is split and each OEM is located close to the final customer.

3. Simulation Model

A discrete event simulation model has been implemented using the computational potential of Microsoft Excel™. Three different scenarios have been modelled separately, according to their specific configuration. One year (240 days) has been simulated with a time step of 1 day. Different service levels have been tested in order to understand the supply chain efficiency varying the quality of the service provided; 11 different k values have been considered, starting from 65% up to 95% with step of 3%. Therefore, 3 (SC structures) x 11 (service level scenario) = 33 different configurations have been analysed. Moreover, since the final customer demand is described as a normal distribution with (μ, 25%* μ), 25 replications per configuration have been launched. For each service level, the simulation model provides the results for the three supply chain configurations. Following, the nomenclature used to describe the model is introduced.

Nomenclature

N	simulation duration [days]
T	Periodic review interval [days]
OUTL	Order Up To Level [units]
SS	Safety Stock [units]
LT	Procurement lead time [days]
O	Quantity ordered [units]
I	Inventory position [units]
Iso	Stock out quantity [units]
$\overline{RM}$	Average quantity of raw materials in stock [kg/day]
$\overline{FP}$	Average quantity of final product in stock [units/day]
$\bar{T}_{RM}$	Average time of raw materials in stock [days]
$\bar{T}_{FP}$	Average time of final product in stock [days]
D	Demand of the downstream player/s [units]
μ_d, σ_d	Mean and standard deviation demand of the downstream player/s [units/day]
k	Service level [dimensionless]
w_{RM}	Total amount of raw material transported [kg/year]
w_{FP}	Total amount of final product transported [kg/ year]
Co	Unitary order cost [€/order]
C_{RM}	Unitary cost of holding stock for raw material [€/kg]
C_{FP}	Unitary cost of holding stock for final product [€/unit]
C_T	Transportation cost [€/kg]
P	Machine Productivity [units/day]
Qnom	Nominal production quantity [units]
Qmin	Minimum production quantity [units]
Qmax	Maximum production quantity [units]
Q	Production quantity – first check [units]
Qf	Final production quantity – second check [units]
t	Simulation day
m	Simulation month
y	Simulation year

3.1. Input Data

As already explained, the supply chain structure and the related logistics data (final customer demand, lead time and travel distance between actors) were recovered by the literature [20]. The final customer demand seen by each location facility is shown in Table 1

Table 1. Final customer demand, mean value (units/day)

FC1	FC2	FC3	FC4	FC5	FC6	FC7	FC8
8	8	7	7	8	8	7	8

Table 2 reports the input data used to compute the KPIs and compare the three configurations.

Table 2. Model input data.

Parameter	Input data		Measurement unit
	Traditional manufacturing	Additive Manufacturing	
Weight of raw material	3.99	1.88	kg/item
Weight of final product	1.9	1.73	kg/item
Machine Productivity	26	4	item/day
Order cost	100		€/order
Cost of holding stock - Raw material	0.069	0.66	€/kg
Cost of holding stock - Final product	1.5		€/unit

Finally, transportation cost (C_T) depends on the distance travelled. For distance lower than 700 km, the unitary cost is 0.16 €/kg, otherwise it is fixed at 0.35 €/kg.

3.2. Supply chain Modelling

The different SC players have been modelled considering their role in the network. In particular, specific Inventory policies and Production rules have been implemented in the simulation model in order to reproduce the behavior of each player. Following, a detailed description.

The Distribution Centers (both Regional and Local) handle the product distribution and sale, thus the model reproduces their inventory policy management. In both cases, an Economic Order Interval (EOI) policy has been modelled. Such reorder policy is based on periodic reviews and variable order quantities. In fact, at fixed periodic interval (T), the inventory level is checked and an order is placed considering the current inventory position. The quantity ordered allows raising the current stock to the order-up-to level (OUTL) which is the level of stock that should allow to satisfy the customer demand since the next order. The following equations have been inserted in the model:

$$T = \sqrt{\frac{2Co}{C_{FP} * \mu_d}} \tag{1}$$

$$OUTL = \overline{\mu_d} * (T + LT) + SS \tag{2}$$

Where,

$$SS = k\sigma_d\sqrt{LT + T} \tag{3}$$

The order placed at time T is calculated as:

$$O_t = OUTL - I_t \tag{4}$$

Where, the inventory position at each time t is computed considering the stock quantity at t-1, the order placed at t-LT and received at t and the demand satisfied at t:

$$I_t = I_{t-1} + O_{t-LT} - D_t \quad (5)$$

The model considers the back orders, thus if the upstream player is not able to provide the right quantity, he sends the available amount and the remaining quantity will be shipped with a late delivery. In the same way, if possible, the DCs provide the product to the following SC players in time; otherwise, they plan late deliveries.

Conversely, the Original Equipment Manufacturer handles the production stage. The manufacturer is able to manage a flexible plant productivity: in fact, a nominal quantity (*Qnom*) is fixed considering the machine productivity and the annual demand expected, but the model allows modifying the daily production amount increasing (*Qmax*) or decreasing (*Qmin*) the nominal quantity. The logics of the model provide for a double check: first, the daily production quantity (Q_t) is defined considering the demand received the previous month and the three production levels. Then, a daily check defines the daily final production (Qf_t) considering the current stock level. Figure 3 shows the OEM decisional process implemented in the simulation model.

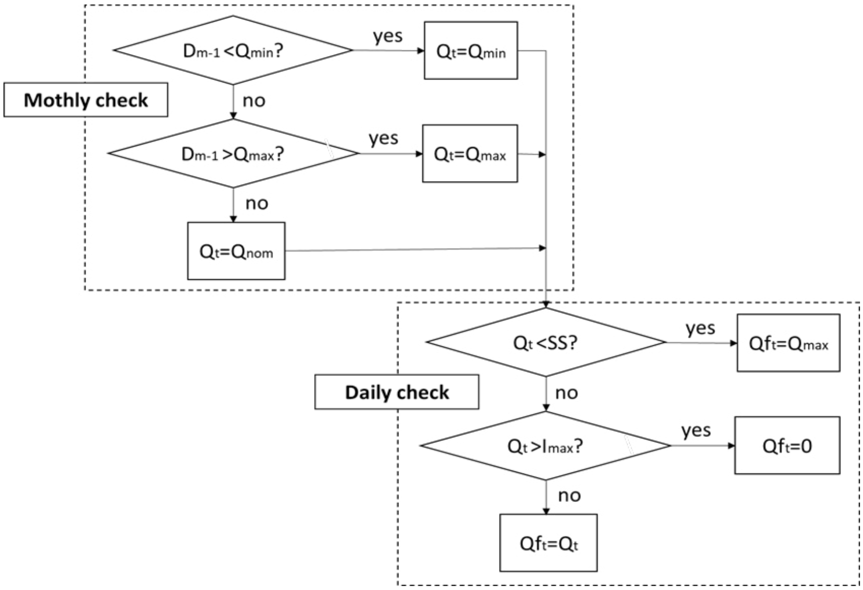

Figure 3: OEM decisional process

As already explained, just one raw material supplier has been considered. A simple procurement logic has been implemented, considering one delivery a week with the right amount required for the whole production and a suitable safety stock depending on the service level set.

3.3. Key Performance Indicators

Some suitable KPIs have been identified in order to assess and compare the performance of the three scenarios. Both economic and strategic parameters have been considered. Moreover, both the OEM and the whole supply chain efficiency have been evaluated. The KPIs computed are listed below:

1. Capacity utilization (U); it reflects the machine saturation at the OEM plant; if more than one producer exist, an average value is calculated:

   $U = D_y/(Q_{max}*N)$ [%] (6)

2. Number of machines (M); it depends on the machine productivity and the quantity which has to be produced; the total amount is computed considering all the OEMs:

   $M = \mu_d/P$ [number] (7)

3. Customer satisfaction (CS); it considers the sum of the total stock out amount at the players who face the final user, and the annual total final demand.

$$CS= 1- (Iso_y/ D_y) \quad [\%] \quad (8)$$

4. Supply Chain Lead Time (SCLT); it represents the time needed by the supply chain to transform raw material into final product and to deliver it to the final customer. It considers the total procurement lead time between echelons and the average time in stock of both raw material and final product. All the parameters depend on the SC characteristics and the number of actors.

$$SCLT = \bar{T}_{RM} + LT + \bar{T}_{FP} \quad [days] \quad (9)$$

5. Total Holding Cost (C_h); it reflects the cost of storing both raw material and final product; two contributions are computed starting from the average physical inventory and the unit cost of holding stock. A total amount is computed considering all the players of the network

$$C_h = (\overline{RM} \cdot C_{RM} \cdot N) + (\overline{FP} \cdot C_{FP} \cdot N) \quad [€/year] \quad (10)$$

6. Total Transport Cost (C_t); it reflects the cost of moving both raw material and final product; it is calculated adding up several contributions and considering all the deliveries of the year.

$$C_t = (w_{RM} \cdot C_T) + (w_{FP} \cdot C_T) \quad [€/year] \quad (11)$$

4. Results and Discussion

For each configuration, all the KPIs described in the previous section have been calculated; the average values resulting from the 25 replications are presented.

In general, supply chain parameters promote the adoption of additive manufacturing. Figure 4 compares SCLT trends; it is clear that such indicator prefers a decentralized solution respect to the other alternatives. Moreover, because of its high flexibility, AM decentralized network is not affected by the service level. In fact, the average stock and the related average time in stock slightly grows increasing the service level, contrary to the other two alternatives.

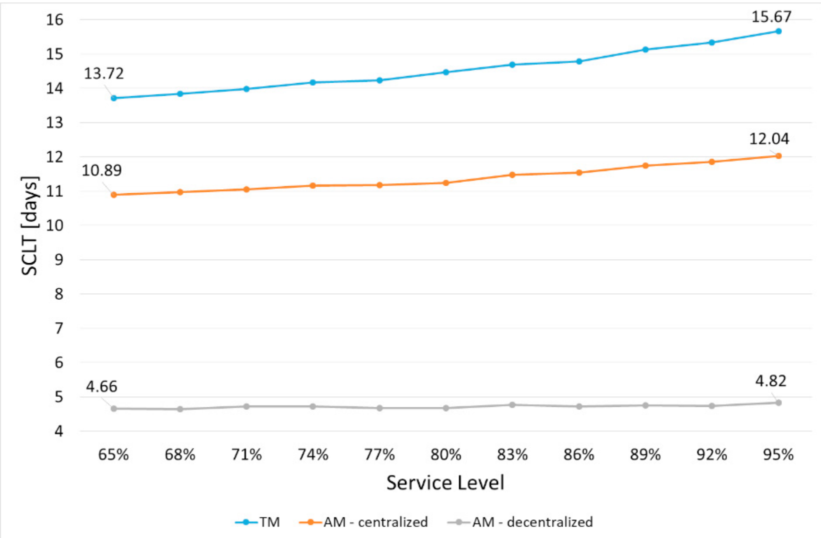

Figure 4: Simulation results: Supply Chain Lead Time (days)

For the same reason, the Total Holding Cost has a similar trend; the AM decentralized scenario shows a small increase (4%) moving the service level from 65% to 95%, while the centralized configurations present higher values (16% for Centralized AM and 26% for TM). Moreover, the centralized structure implicates higher average stock and higher annual holding costs, as shown in Figure 5. On the contrary, the Transport cost seems to be not affected by the service level. In fact, even though a higher amount is maintained at stock, the average customer demand remains constant and thus, the number and type of deliveries do not change. The different values between the three configurations depend on the structure of the network and the number of echelons of the supply chain.

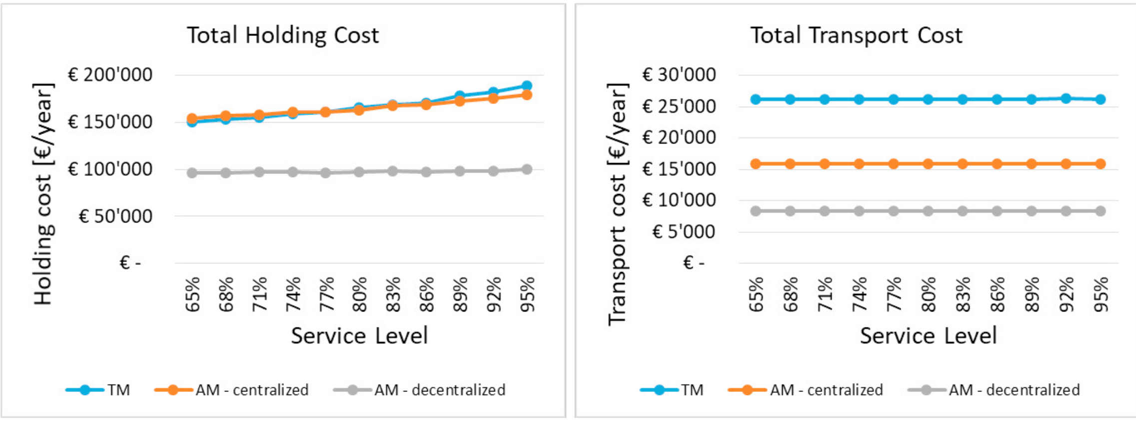

Figure 5: Simulation results: Total Holding Cost (€/year) and Total Transport Cost (€/year)

In all cases, the model shows a high customer satisfaction; such result is probably due to the proper inventory and production policies set in the model. Anyway, regardless of the service level, Additive Manufacturing reports a better result, as shown in Figure 6. In fact, the AM decentralized scenario always provides the best performance, the AM centralized structure shows a very good result with a light increase according to the service level increase, and TM presents a significant growth even though it never reaches the best performance.

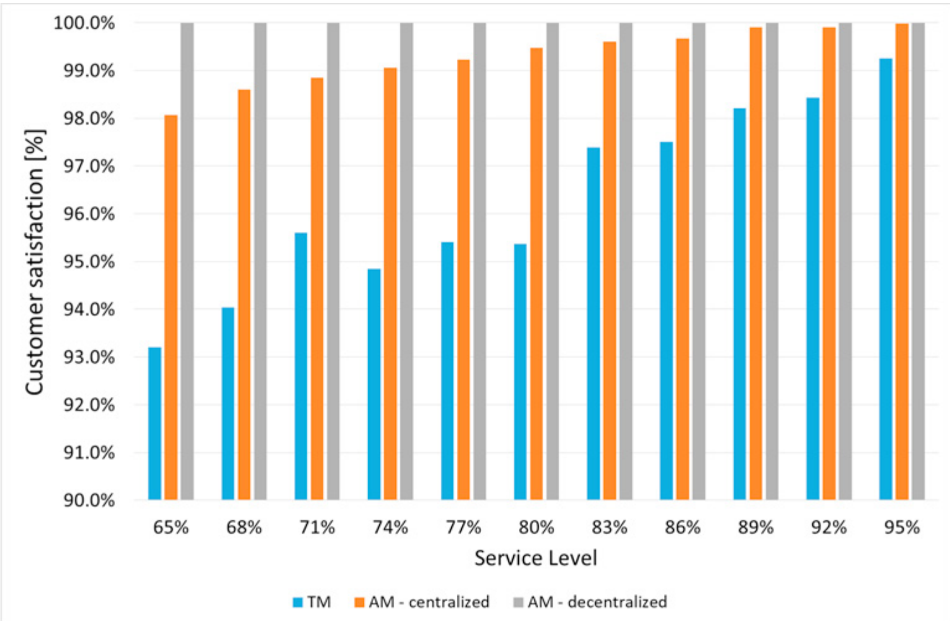

Figure 6: Simulation results: Customer satisfaction (%)

On the other hand, the TM solution is able to exploit its centralized production strategy with a higher capacity utilization and a number of machines, which is clearly smaller than the Additive solution, as reported in Table 3. Moreover, the two AM configurations present similar values; such outcome is mainly due to the AM machine productivity, which strongly differs from the subtractive technology. Moreover, the AM centralized configuration allows saving one machine compared to the decentralized scenario; in fact, a lower customer demand faced by OEM_1 respect to OEM_2 leads to the possibility to manage the production with 7 machines instead of 8.

Table 3. Simulation results: Capacity utilization and Number of machines

KPI	Traditional manufacturing	Additive Manufacturing Centralized structure	Additive Manufacturing Decentralized structure
Capacity utilization (U)	88%	78%	76%
Number of machines (M)	2	15	16

5. Conclusions

This paper has proposed a quantitative study for the SC performance evaluation, combining different SC structures with Additive and Traditional manufacturing technologies. A discrete event simulation model has been developed in order to reproduce the behavior of the players and test the sustainability of different supply chain configurations. The outcomes show some strong findings related to the AM adoption. In particular, AM allows to design a shorter SC, offering a great support for the supply chain performance and providing strong savings in the supply chain lead time. Moreover, the AM decentralized network offers the best solution in terms of holding stock, and in general, on supply chain costs. In addition, the combination of additive technology and decentralization confirms to be the most flexible solution, with a high performance on customer satisfaction.

Nevertheless, the production strategy and the machine productivity influence the competitiveness of the additive manufacturing technology. In fact, the significant number of machines affects the KPIs linked to the production stage and such aspect could limit the economic feasibility of the AM technology.

Finally, some limitations of the work are mentioned. Firstly, investment costs for changes on supply chain design are not considered: a feasibility study should be conducted in order to evaluate the financial feasibility of the choice. Secondly, in order to test the global suitability of each solution, both supply chain and production costs should be computed. Moreover, as future developments, a sensitive analysis could be conducted, in order to identify the input conditions that lead to the AM success. In particular, different customer demand with different mean and standard deviation could be tested and evaluated.

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