

Impact of Industrial Symbiosis on Additive Manufacturing of Spare Parts during Supply Chain Disruptions

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Abstract: In a world increasingly impacted by supply chain disruptions and the demand for low-emission industrial districts, this study explores how additive manufacturing (AM) and industrial symbiosis (IS) can transform spare parts supply chains. Through simulation modelling, conventional and AM-supported SC configurations are compared across scenarios involving stability, disruptions, and recovery strategies. AM facilitates localised, on-demand production, improving flexibility and spare parts availability, while IS utilises waste materials to lower emissions and costs. The findings highlight that integrating AM and IS enhances supply chain resilience and sustainability, addressing global challenges and advancing circular practices within industrial ecosystems.

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1. INTRODUCTION

Supply chain (SC) disruptions, such as in the COVID-19 pandemic, have pointed toward the need for resilient SCs. Shortages are becoming way more common in globalised SC and several sectors are facing difficulties to cope with high inflation and supply interruptions. Countries struggling the most with supply chain issues and inflation include those in Europe, where manufacturers take longer due to missing spare parts. Over the past few years, manufacturing systems have increasingly requested availability through proper management and large inventories of spare parts (Peron, 2024). Since AM can produce complex geometries in small batches with efficient exploitation of raw material, it can be applied to produce spare parts (Huang et al., 2013; Khajavi et al., 2018). AM can be an effective emergency solution, as it enables companies to bypass bottlenecks by manufacturing parts on demand and closer to the point of use (Peron et al., 2022). AM contributes positively to metrics within SCs, suggesting that the strategic use of AM enhances resilience and flexibility (Singh et al., 2024). AM facilitates on-demand production, proving to be cost-effective for low-volume manufacturing (Chekurov et al., 2021), and helps minimize non-value-added activities like inventory storage and goods movement (Tuck et al., 2007). These advantages make AM a suitable solution for optimizing the spare parts SC under

certain conditions (Mecheter et al., 2022; Peron et al., 2024). Spare parts typically exhibit sporadic demand, long procurement lead times, and high downtime costs (Knofius et al., 2019; Lolli et al., 2022). The application of AM in the spare parts SC has shown several benefits (Huang et al., 2013), including the economic feasibility of small batch production, the flexibility to rapidly change part designs, and the ability to produce complex geometries. This can lead to SC simplification, reduced lead times, and lower inventory levels (Khajavi et al., 2018). Shortages of spare parts can lead to inefficiencies and ripple effects throughout the supply chain, resulting in further disruptions. This is critical in sectors where delays can cause significant financial losses, such as original equipment manufacturers (OEMs). Recent studies suggest that recycled polymers and metal scraps, which have been successfully utilised in AM for local production, can reduce the carbon footprint and enhance supply chain resilience. For instance, titanium, aluminium, and nickel alloys are widely studied for their recyclability, with applications in aerospace and high-performance parts. However, challenges include ensuring material quality and achieving the desired mechanical properties, while keeping supply chain cost low. Other metals, such as copper, stainless steel, magnesium, and rare earth elements (e.g., zirconium, neodymium), are also being recycled for innovative uses, such as components and magnets (Shah et al., 2024). In this context, industrial

symbiosis (IS) is a cooperative circular strategy where a business's surplus or waste becomes a valuable input for another. The use of waste or by-products from other industries as material inputs in AM processes can provide a cost-effective source of materials, reducing landfill waste (Ferreira et al., 2021). However, the existing literature lacks insights evaluating the impacts of IS on sourcing performance under disruptions. Despite the significant interest in risk management strategies, little is known about the opportunities and challenges stemming from IS in managing the availability of materials. Therefore, our research goal is two-fold:

- (1) How does AM impact spare parts availability during disruptions?
- (2) How can IS help improve sourcing performance for AM?

This paper is organised as follows: Section 2 delineates the background of spare part management and AM critical aspects. Section 3 describes simulation logic, input data, and analysed scenario. Lastly, Section 4 discusses the results and Section 5 summarises the major implications.

2. BACKGROUND

Spare parts have a very fragmented SC, which involves multiple stages, from production to after-sales (Pfähler et al., 2019). OEM can be interested in the AM potential for after sales operations, mainly when the large installed base makes the importance of after-sales markets much larger than markets for new equipment (Lolli et al., 2024). In this case, the companies must manage a spare part storing system and a relevant share of external suppliers, resulting in high minimum order quantities and inventory levels, also facing challenges due to the diversified products' portfolio, the wide geographic distribution of customers and the multi-level distribution network, together with customers' requirements for short downtimes (Heinen and Hoberg, 2019). In these cases, co-located AM manufacturers can act as on-demand producers in organized AM centres or facilities that concentrate low volume, customized, and high urgency production (Sasson and Johnson, 2016). The adoption of AM technology in after-sales spare parts supply chains depends on its technical feasibility and associated costs. For example, the automotive sector is a focal point in this discussion due to its intricate SC demands, characterized by the need for rapid delivery of diverse spare parts. While, according to the traditional distribution model, a mandatory path links the final customer to the local dealers that can place the orders at the regional distribution centre, which in turn is supplied by the OEMs, the distribution chain integrating AM can be organized by creating AM hubs, which are automated, centralized platforms through which orders are collected and redirected to a network of distributed AM manufacturers that often are highly specialized small and medium-sized enterprises (SMEs). This configuration reduces the SC length complexity and logistic costs, limiting the related emissions. In addition, it makes feasible the integration of reuse, recycling and reconditioning operations (Isasi-Sanchez et al., 2020). Khajavi et al. (2018) compared three configurations (centralized, AM-hub, and decentralized) and found that an AM-hub approach is the most

cost-effective, provided that AM machine capacity and hub size are properly calibrated. Digital twin can enhance this configuration by digitally storing parts and enabling their on-demand, local production (Peron, 2024). Design freedom and on-demand manufacturing lead to minimized environmental footprint and improved SC performance (Priyadarshini et al., 2023). Lakshmanan et al. (2023) indicated how AM contributes to waste minimization through light weighting, reduced scrap rates, and short lead times. Ivanov (2023) looked into recovery strategies supported by AM, among the others. These technologies enable both resilience and sustainability during the recovery process, hence offering double benefits in disruption situations. Still, some issues need to be considered in the environmental impacts of AM. AM generally requires significantly more energy than conventional manufacturing (CM) due to lower productivity and high-temperature processing requirements (Kellens et al., 2017). Nevertheless, materials used in AM and the components produced have the potential for recycling and reuse (Peng et al., 2018). AM has the potential to sustain the scale-up among multiple sectors while prolonging product lifetimes, and producing spare parts for repair, refurbishment, and upgrades. However, designers must take into account factors such as raw material procurement, usage scenarios, and end-of-life management (Graziosi et al., 2024). Yet, other studies involving different exchange approaches for AM-driven IS are required (Ferreira and Carvalho, 2024). Simulation modeling, as the methodology behind this study, has been utilized in numerous other papers, such as those by Gianesello et al. (2017); Ivanov (2019, 2023); Schmitt and Singh (2012).

3. SIMULATION MODEL

In this study, we propose and compare two spare parts SC configurations. The first configuration assumes a conventional SC in which parts are provided through outsourcing, utilising a primary supplier and a backup supplier. The backup supplier is characterised by increased distances and higher costs, whereas the primary supplier is cheaper and faster. According to Nagasawa et al. (2023), backup providers are justified in contexts where SC resilience is crucial for avoiding production loss and ensuring business continuity. The second configuration employs a multiple-sourcing strategy that involves a third party. This third entity operates in a different sector and collaborates with the OEM in an IS setting, where it supplies spare parts by recycling by-products and waste materials. The conventional SC for spare parts produces and supplies OEMs in quantities sufficient to ensure parts availability, given the erratic nature of spare parts demand. The requirement for safety stock leads to high warehousing and inventory management costs. Spare parts may be stored either at the OEM's location or by a service provider (e.g., a regional distributor), which introduces an additional layer to the distribution network. Fig. 1 shows a schematic of a conventional spare parts supply chain, with arrows indicating material flows and connections between actors via transport. The recycling policy has led to reduced costs (Neves et al., 2019). Since the supplier covers the expenses for the AM printer, we concentrate only on the final product price. Furthermore, the symbiotic partner can manufacture components using AM technology directly on-site,

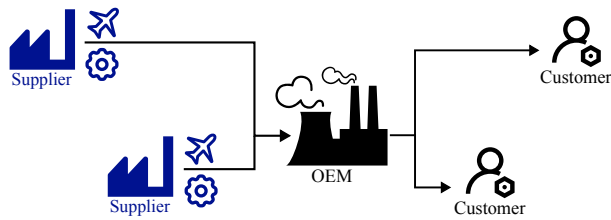


Fig. 1. Conventional spare parts SC

near the OEM's location, reducing transportation time and increasing SC flexibility. This significantly reduces delivery time and enhances responsiveness to the market (Ferreira et al., 2021). The IS supplier provides smaller quantities of parts due to its limited output capacity, which depends on the availability of waste materials at its facility. Although the partner's production capacity is limited compared to traditional suppliers, this solution is particularly advantageous for handling urgent demands or unexpected situations. Furthermore, advancements in AM technology are improving its speed and cost efficiency, making this technology increasingly competitive in the long term (Zhou et al., 2024). A schematic representation of the SC with IS is shown in Fig. 2.

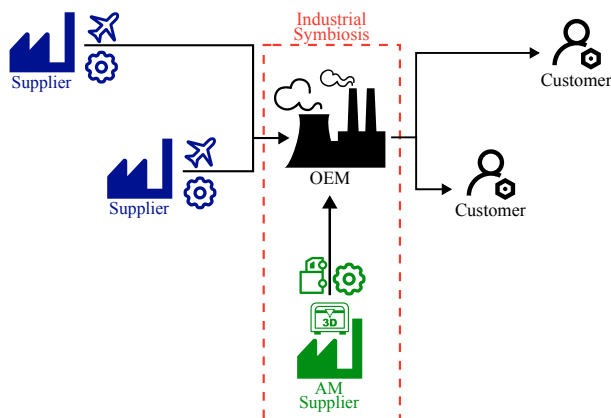


Fig. 2. Distributed IS-based spare parts SC

A car production SC, consisting of 100 customer locations, one factory, and two suppliers for brake caliper brackets (BCB), was analysed. The study used the anyLogistix PLE software, with data on car demand and inventory control sourced from Giancesello et al. (2017). The factory, located in Emilia Romagna, Italy, produces cars and requires BCB as spare parts. Since each car requires 4 brake calipers, we assumed a failure rate of 4%, resulting in a demand of 133 units per week. The failure rate, denoted as λ , indicates a mean time to failure ($MTTF$) of 0.0075 weeks/unit, where $MTTF$ is derived from the formula $1/\lambda$. In this context, the metric is used to analyse the mechanical properties and reliability of components produced using AM and CM technologies (e.g., Sgarbossa et al. (2021)). To enhance clarity, the relevant model data is summarised below. The procurement and shipment costs for each BCB vary: the main supplier incurs a cost of 104 €/shipment, the backup supplier incurs 108 €/shipment, and the IS supplier incurs 103 €/shipment. The shipping policy follows a Less-Than-Truckload (LTL) and First-In, First-Out (FIFO) approach. Vehicle capacity and speed differ by mode of transport: trucks can handle up to 40 m^3 with a velocity of 80 km/h, while aeroplanes can carry up

to 400 m^3 and travel at 800 km/h. This sourcing model supports dynamic inventory sourcing policies. Based on Giancesello et al. (2017) automotive case study, we assumed the same demand distribution and reorder policy. Car demand follows a normal distribution with an average of 834 units and a standard deviation of 0.2. The demand for BCB is adjusted by the failure rate. Using a 7-day order interval, reorder policies are set within a Min-Max framework. For cars, the range is 2000 to 4000 units, with a reorder point of 834 units and an initial inventory of 2834 units. Regarding the Bill of Materials (BOM), each car requires 0.16 spare brake calliper brackets, based on that each car can require 4 brake calliper and the percentage of spare parts assumed. The model's time horizon spans one year, during which assembly, production, logistics, and related environmental impacts are evaluated. Vehicle transport costs are estimated at 0.3 €/($km * m^3$) (Ivanov, 2019), while for air transport we estimated a cost of around three times as much as done in Giancesello et al. (2017). Various environmental factors that contribute to CO₂eq emissions were evaluated: outbound shipment emissions, assembly facilities emissions, and vehicle type CO₂eq. For each transport type the CO₂eq factors are modelled as follows: medium trucks emit 28 gCO₂eq/($km * m^3$), containers emit 55 gCO₂eq/($km * m^3$), and air transport emits 187 gCO₂eq/($km * m^3$), as reported by Ivanov (2023). Assembly facilities also contribute to the carbon footprint, generating 60 m^3 of CO₂eq per day (Ivanov, 2023). Outbound shipment emissions vary by supplier type. For each shipment, the CO₂eq emissions are set at 80 gCO₂eq/(m^3) for both the backup and IS suppliers, while the principal supplier achieves lower emissions of 60 gCO₂eq/(m^3) due to economies of scale. We developed four distinct scenarios to evaluate SC resilience and sustainability under varying conditions. Table 1 summarizes the number of disruptions simulated in the different scenarios and the number of suppliers activated during them. The first scenario (S1) represents a standard manufacturing SC operating under normal conditions, with no disruptions, where the principal supplier provides BCB. The second scenario (S2) introduces a disruption that prevents the principal supplier from fulfilling orders, exposing vulnerabilities in the SC and highlighting the potential for significant declines in service levels without alternative sources. To mitigate this risk, the third scenario (S3) examines the use of a backup supplier as a contingency measure, which is activated during disruptions. While this backup option supports continuity, it may still lead to a slight reduction in service level and potentially increase transportation emissions due to extended lead times. In the final scenario (S4), an IS supplier is implemented additionally as a proactive recovery strategy. This approach not only ensures the availability of BCB but also promotes sustainability by incorporating recycled materials, thereby reducing CO₂eq emissions. In particular, this study examines two disruptions: the first starting on February 1 and the second on May 1, each lasting 50 days, as described in Schmitt and Singh (2012). These disruptions occurred twice within a single year. During the first disruption, 80% of the resources were sourced from the backup site and 20% from the IS site. In the second disruption, 90% of the resources came from the backup site and 10% from the IS site.

Table 1. Simulation scenarios

Scenario	Models	Number of disruptions	Suppliers during disruptions
S1	Normal Conditions	No disruptions	None
S2	Disruption of Main Supplier	Two Disruptions	None
S3	Use of Backup Supplier	Two Disruptions	Backup supplier
S4	Integration of IS Supplier	Two Disruptions	Backup and IS supplier

4. RESULTS

The results of this study offer valuable insights into the impact of IS and AM on SC resilience and sustainability, particularly in the context of supply disruptions. The initial experiment, S1, assesses the performance of a conventional supplier operating in a stable environment, achieving a full service level of 1, which indicates perfect reliability in meeting demand. The operations resulted in total emissions of 2,817.4 tonnes of CO₂eq. The overall cost amounted to 109,099,180.7 €, with transportation expenses accounting for a substantial 22,771,575.1 €. S2 case analyses the disruption of the principal supplier, which was forced to close due to pandemic restrictions. As outlined in Schmitt and Singh (2012), the disruption is characterised by interarrival time and duration. In this case, the service level, initially at 1, declined to a minimum of 0.70 and 0.78 during the disruptions, averaging 0.88 over the year (Fig. 3). There were 1,968 late products across 246 late orders, but ultimately, all received demand was shipped to customers because the supplier fulfilled the back-ordered products after the disruption. Total emissions amounted to 2,800.5 tonnes of CO₂eq, reflecting reduced emissions during the disruption periods when production and logistics activities were paused. Nevertheless, transportation costs remained high at 22,771,575.15 €, contributing to a total cost of 109,099,180.74 €.

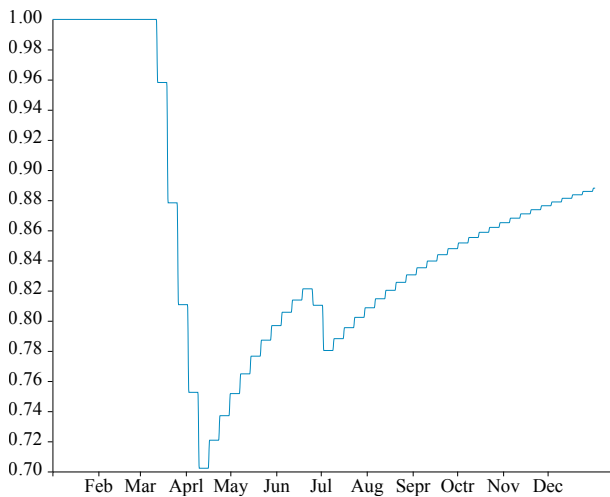


Fig. 3. S2 Service Level

The backup supplier is engaged during disruptions when the principal supplier is unavailable in S3. It is assumed that there is no delay between the onset of the disruption and the activation of the contingency plan. The overall cost is higher than in previous scenarios due to the increased expenses associated with utilising the backup supplier during emergencies. Transportation costs are also higher due to the significant distance between the backup supplier and the OEM. Furthermore, CO₂eq emissions

are elevated compared to previous cases, as the extended transportation distances result in greater environmental impact. The results of S3 reveal a perfect service level of 1, ensuring full reliability in meeting demand. Total emissions reached 2,828.8 tonnes of CO₂eq. The overall cost amounted to 109,167,475.09 €, with transportation expenses contributing significantly at 22,832,186.37 €. The integration of a new IS supplier (S4), which utilises waste materials to produce BCB, has improved SC resilience while reducing environmental impact. This approach ensures a perfect service level of 1 and lowers total emissions to 2,773.8 tonnes of CO₂eq. The overall cost decreased to 108,871,849.66 €, with transportation expenses reduced to 22,538,097.50 €. The IS supplier’s proximity to factories and clients, combined with AM, has minimised costs and emissions during disruptions, demonstrating its effectiveness as a sustainable and reliable contingency solution. Fig. 4 highlights the dual benefits of integrating IS and AM in SCs, demonstrating improvements in sustainability. Scenario 4 effectively reduces emissions and costs during disruptions while maintaining a service level of 1.

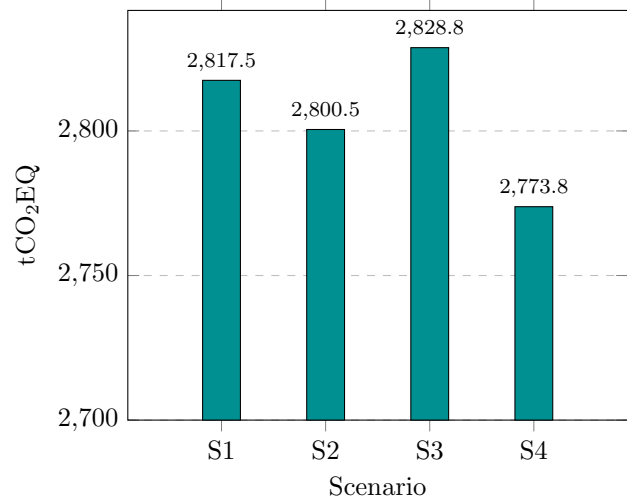


Fig. 4. Environmental impacts

The table 2 summarizes the various service levels (SL) and the products that were delivered late.

Table 2. Simulation results

Scenario	SL	Late products	Late orders
S1	1	0	0
S2	0.88	1,968	246
S3	1	0	0
S4	1	0	0

The second chart (Fig. 5) focuses on economic impact, showing that Scenario 4 also incurs the lowest overall cost (€108.8 million), primarily due to the proximity of the IS supplier to factories and clients. Conversely, Scenario 3 has the highest costs (€109.1 million) as a result

of elevated transportation expenses and reliance on the backup supplier.

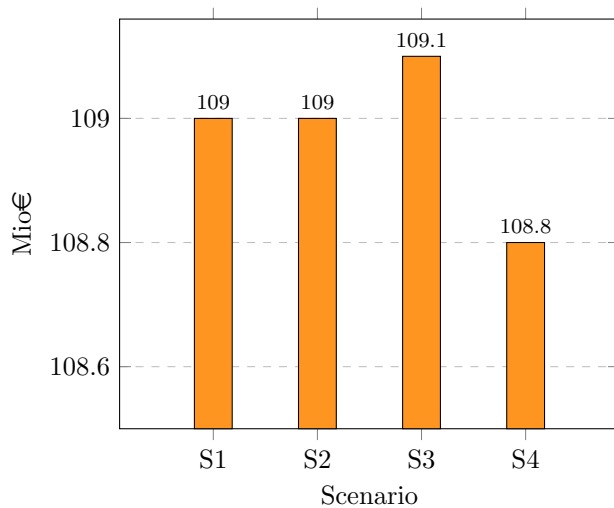


Fig. 5. Economic impacts

5. DISCUSSION AND CONCLUSIONS

The findings of this study highlight the potential of integrating IS and AM into spare parts SCs, particularly in disruption scenarios. Scenario analysis reveals significant trade-offs between cost, environmental impact, and service level. In the business-as-usual SC setup (S1), a stable environment ensures 1 service reliability but incurs high emissions (2,817.4 tonnes of CO₂eq) and overall costs (€109.1 million). When disruptions occur (S2), a lack of a strong contingency strategy leads to diminished service levels, dropping to 0.7. This results in 1,968 late deliveries and high transportation costs (€22.8 million). Although there is a slight reduction in emissions due to the temporary halt in operations, the overall impact remains significant. The use of a backup supplier (S3) ensures uninterrupted service, maintaining a satisfactory service level. However, higher overall costs (€109.2 million) and increased emissions (2,828.8 tonnes of CO₂eq) highlight the inefficiencies associated with reliance on long-distance transportation. While this solution demonstrates resilience, it presents notable sustainability challenges, particularly within a globalised SC. In response to RQ1, AM in S4 helps reduce backlogs and ensures the availability of BCB, as shown in table 2. In response to RQ2, the IS-based configuration (S4) offers the most balanced solution. By leveraging waste materials and AM technologies, this scenario reduces both costs (€108.9 million) and emissions (2,773.8 tonnes of CO₂eq) while resolving service inefficiencies. The proximity of the IS supplier to the OEM significantly contributes to lower transportation costs (€22.5 million) and reinforces the sustainability of the SC. Although this study underscores the benefits of incorporating IS and AM into spare parts SCs, several limitations should be acknowledged. First, the analysis assumes static demand and failure rates, which may not capture real-world variability. Dynamic fluctuations in demand patterns or external factors, such as changes in the availability of raw materials for IS, could affect the outcomes. Additionally, this experiment does not account for

limits in the production capacity of both the principal and backup suppliers, which should be included in a real case study. Moreover, further in-depth studies on the sensitivity of the configuration in relation to multiple factors, such as the number and capacity of the printer (technological factors), should be explored more comprehensively, along with the partner's capabilities. Another limitation is the comparison of only two alternative configurations of spare parts supply chains. Additionally, the generalizability of the findings is limited by the specific nature of the data assumed as inputs. Secondly, as customer satisfaction costs were not considered in the simulation, future research should investigate their potential impact. Third, the study primarily focuses on transportation and production costs, excluding potential setup or transition costs for adopting AM and IS. Furthermore, while AM demonstrates promise in reducing lead times and emissions, its higher energy consumption and material-specific constraints were not fully quantified. Lastly, decentralised AM models with shared investment costs and usage have not been considered. Despite these limitations, the study provides valuable insights into how IS and AM can enhance SC resilience and sustainability. AM enables on-demand production close to the point of need, significantly improving spare parts availability during disruptions. IS contributes to sustainable and cost-effective sourcing by facilitating the circular use of materials for AM processes. Future research should explore the scalability of IS-based AM systems across diverse industries, focusing on integrating various waste streams into spare parts production. Moreover, the symbiotic supplier can be included in the simulation along with its production and inventory policies in order to assess its by-product potential, as well as its printer and recycling costs. Additionally, the optimization of the hubs' location should be considered. Further investigation is also needed to assess the impact of technological advancements in AM, such as energy-efficient machinery and innovative material formulations, to improve environmental and economic performance. Additionally, studies incorporating dynamic demand scenarios, energy-specific impacts, and regional differences in sustainability practices would refine the model and expand its applicability in real-world contexts.

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