JUSTIFICATION FRAMEWORK FOR ADOPTION OF ADDITIVE MANUFACTURING TO AUTOMOTIVE SUPPLY CHAIN: AHP APPROACH

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SUMMARY

Additive Manufacturing holds significant potential in influencing automotive sector and its supply chain however its effectiveness depends on variety of factors. This study aims to propose an analytic hierarchy process model to justify AM implementation to automotive sector for enhanced sustainability and resilience to its supply chain. This paper outlines benefits of AM over traditional manufacturing for automotive supply chain which leads to development of more sustainable and resilient supply chain. The AHP is used in this study to justify the advantages of the AM over Traditional Manufacturing for automotive supply chain. Major benefits of AM adoption have been identified through recent review of the literature on this topic and expert perspectives. AHP is used to calculate and compare the global desirability index of AMSC and TSC. Comparing AM-based supply chains to traditional manufacturing, it is found that the former have a higher global desirability index.

KEYWORDS

Additive Manufacturing, Automotive Supply Chain Management, Analytic Hierarchy Process

NOMENCLATURE

AM	Additive Manufacturing
AHP	Analytic Hierarchy Process
AMSC	Additive Manufacturing Supply Chain
TMSC	Traditional Manufacturing Supply Chain
IOT	Internet of Things

1. INTRODUCTION

Sustaining economic growth is not easy in highly competitive environment of today. However, manufacturing sector is often considered to be the best for economic development. A few nations have grown and accumulated wealth without investing in their manufacturing industries. Therefore, any economy centered on manufacturing is the greatest long-lasting source of wealth creation. In this era of global competition where companies are competing among themselves for international leadership, organizations are forced to produce low-volume customized innovative products. Therefore, a firm's success would be strongly impacted by its choice of production technologies and implementing any disruptive technology might present organizations with both strategic opportunities and risks. "National To become a global manufacturing giant, India has set a target to raise manufacturing industry's GDP contribution to 25 per cent by the year 2025 (Pulicherla et al., 2022). Over the last decade, India registered the second-highest GDP growth among the top ten countries and became the world's fifth-largest economy. India is also likely to be the fastest-growing economy for the next five years and is projected to attain the status of the third-largest economy by 2027 (Krishan & Subbiah, 2022). In the current era of global competitiveness, environmental and social commitments are becoming more prominent to organizations, and purposeful and proportional use of technology will undoubtedly aid in achieving these objectives. AM presents huge potential for automotive supply chains to be resilient enough to bounce back from any disruption. Relevant bodies now have implement AM to the automotive sector, however there is ambiguity and uncertainty in their evaluation due to many criteria and subjectivity of various decision-experts. Consequently, its assessment can be thought of a multi-criteria decision-making (MCDM) process due to uncertainty. Amidst this context following research questions related to AM's role in the automotive sector as well as its potential opportunities for sustainability and resilience automotive supply chain are as follows:

RQ1. Why is AM necessary to the automotive manufacturing sector?

RQ2. What are major advantages of adopting and implementing AM in the automotive sector and how might these benefits promote an automotive supply chain that is sustainable and resilient?

RQ3. Is the adoption of AM justified for sustainable and resilient automotive supply chain?

Following the introduction, the structure of the paper is as follows. Such as section 2 presents a review of substantial literature on AM, its integration with the automotive supply chain, and its use. Section 3 details the research methodology. The use of the AHP technique to determine the global desirability index is covered in Section 4. While Section 5 discusses the findings, Section 6 summarizes management implications and conclusions.

2. LITERATURE REVIEW

2.1 ADDITIVE MANUFACTURING INTEGRATION WITH AUTOMOTIVE SUPPLY CHAIN

AM integration to automotive supply chain may have transformative impact on the way that automotive components are designed, manufactured, and delivered to customers. AM and Industry 4.0 integration with supply chain can enable greater automation and control over the manufacturing process. For example, 3D printers can be connected to the Internet of Things to collect real time printing data which can be used to optimize the printing process, reduce downtime, and improve quality (Haghnegahdar et al., 2022; Nitsche et al., 2021). Additionally, more sustainable practices may be made possible by the supply chain's integration to Industry 4.0 and AM. Due to on demand production, organizations can reduce waste and minimize the environmental impact of manufacturing operations (Ghobakhloo, 2020; Kayikci, 2018). This may reduce transportation costs and carbon emissions linked with shipping products. Overall, the integration of Industry 4.0 and AM with the automotive supply chain can enable greater flexibility, responsiveness, quality control, automation, and sustainability. Companies that can adapt and leverage these technologies are likely to gain a competitive edge globally. Present research indicates that AM can also promote closer integration between manufacturer and customer in the automotive industry, as has been shown in numerous other sectors.

2.2 ADDITIVE MANUFACTURING BENEFITS LINKED TO SUSTAINABILITY AND RESILIENCE FOR SUPPLY

With the advent of AM processes, even highly regulated industries like aircraft and military automotive are discovering ways to employ AM to produce end-use parts and streamline production processes. As a result, there are greater cost savings and a reduction in the dependence on highly fragile global supply networks. AM may improve the supply chain's status as well as specific supply chain characteristics such as agility, flexibility, and responsiveness (Naghshineh & Carvalho, 2022). Environmental sustainability related activities, such as energy efficiency and waste management, can aid in the adoption of best practices and standards throughout the supply chain. The unique benefits of AM linked to resilience and sustainability are therefore presented below.

2.3(a) Material Efficiency and Waste Reduction (MEWR)

Till now AM raw material cost is a significant part of total manufacturing cost but AM has high raw material efficiency which can dominate in cost reduction (Chiu & Lin, 2016). Parts that are additively built offer complicated optimized designs while simultaneously encouraging material efficiency (Charles et al., 2022). The information-sharing has become faster in contemporary supply chains under industry 4.0 technologies. This has enhanced sustainable operations management by integrating end-of-life (EOL) product phase planning with operations management (Stock & Seliger, 2016). End-of-life products (refurbished) are made available to customers at lower prices while OEM's intellectual property and brand reputation are safeguarded. The sustainability of products goes high with increased social environmental and economic benefits. Subsequently, recycling returned AM products helps to increase sustainability, and also it reduces the requirement for raw materials.

2.3(b) Cost Savings (CS)

AM has the benefits of low prototyping cost and minimum inventories with reduced time to market (Achillas et al., 2017; Khorram Niaki & Nonino, 2017). Additionally, the distinction between manufacturers, wholesalers, and retailers may start to become blurred as a result of localized production and simplified processes because each may be able to make products in their facilities. There are many studies which lend support to cost reduction throughout the product life cycle through short AM lead times, fewer production steps and reduced inventory cost (Ghadge et al., 2018; Thomas, 2016). This improves both environmental and economic sustainability. AM minimizes the number of linkages in the supply chain and brings manufacturing closer to customers, which reduces vulnerability to catastrophes and disruptions and improves resilience.

2.3(c) Design Flexibility and Light Weighting (DFLW)

AM sparks the interest of technology-savvy supply chain experts since it demonstrates a variety of attributes that might influence different aspects of flexibility. Freedom of geometry, the first of these attribute, illustrates the flexibility with which product designers may develop intricate AM products in order to achieve better levels of mix and new product flexibility to cope market changes. Part consolidation, the second of these AM attribute is the ability of AM to manufacture multiple discrete components as a single part (Gibson, 2017). The absence of tooling (such as jigs, moulds, or dies) is the third AM attribute important to flexibility. This feature allows for more mix flexibility, new product flexibility, and volume flexibility. Another technological benefit of AM is the ability to create lightweight components using generative design techniques. Lattice structures have already been employed to create lightweight components (Reichwein et al., 2020).

2.3(d) Supply Chain Simplification (SCS)

The supply chain may be virtually viewed with the advent of Industry 4.0 technologies, and AM capabilities may further reduce lead time and complexity. Further, the supply chain and stock management may be approached differently from the perspective of the vehicle manufacturer with the help of AM. With the help of AM, it is possible to recreate a component without the use of specialized or expensive machines, turning the inventory of physical parts into a virtual warehouse where all 3D model files and manufacturing techniques are stored and ready to be used when necessary (Khajavi et al., 2018; Weller et al., 2015).

2.3(e) Resilience to Disruptions (RTD)

AM provides a more resilient supply chain by localizing production and relying on digital designs. Manufacturers can easily transfer production to multiple sites and react to changing conditions in the event of disruptions such as natural disasters or supply chain interruptions. Delic and Eyers (Delic & Eyers, 2020) performed a study of 124 European automobile manufacturing businesses to assess AM adoption and implementation, flexibility, and performance in the supply chain context. According to their research, AM adoption positively affects supply chain flexibility, which in turn improves supply chain efficiency. Additionally, theoretical implications from their research showed that SC is now capable of responding to uncertain demand because to the new AM technology, giving businesses greater capacity and competitiveness.

2.3(f) Customization and Personalization (CAP)

The supply chain for mass customization should be characterized as being customer-centric, networked, automated, transparent, and proactive. AM can produce customized products at low cost along with scope for economic and social sustainability. Studies that take into account enablers, barriers, and challenges have shown a correlation between the Supply Chain with AM and Industry 4.0 (Westerweel et al., 2021; Zheng, wang, et al., 2018). Industry 4.0 promotes higher flexibility, mass customization with increased speed and better productivity in manufacturing. This, in turn, gives lesser lead time with high-quality individualized products (Zheng, Sang, et al., 2018). Further, customization requires a shift toward just-in-time manufacturing, where components are produced as needed. This reduces the need for large warehouses and storage facilities, reducing environmental impact and enhancing supply chain resilience.

2.3(g) Faster Time-To-Market (FTTM)

Many researchers have contemplated optimizing the distributed and flexible capacity of 3D printers through AM (Achillas et al., 2017; Liu et al., 2014; Muir & Haddud, 2018). AM can be advantageous for introducing new products because it drastically cuts initial investments. Further, NPD process also helps with the ramp-up of sourcing, production, distribution, and sales activities that support the commercialization of the product. Faster time-to-market allows automotive companies to adapt quickly to evolving regulatory requirements, such as emissions standards. This proactive approach reduces the risk of non-compliance and associated penalties or market restrictions.

2.3(h) Tooling and Fixture Innovations (TAFI)

AM allows for the development of innovative jigs, fixtures, and tools which improve production efficiency and productivity (Delic, 2022). AM can generate specific elements, such as curves or other organic shapes, with simplicity and at no additional expense, increasing employee safety and comfort (Radhwan et al., 2019). Components manufactured with high precision are more likely to have longer lifespans and require fewer replacements, reducing the overall environmental impact of automotive products (Johns, 2022). Additionally, precision products have less chance of replacement which can further result in lower carbon emissions. Innovative Additively manufactured Jigs and fixtures contribute to supply chain resilience by streamlining production processes.

3. RESEARCH METHODOLOGY ANALYTICAL HIERARCHY PROCESS

The AHP method, created by Thomas Saaty (Saaty, 1980), is one of the most popular methods for making decisions involving multiple criteria. AHP determines relative weights of criteria based on pairwise comparisons. To make sure that paired comparisons are reliable and consistent, the consistency ratio is employed, which contributes to evaluating the global desirability index. Eventually, the global desirability index helps decision maker to rank and select alternative to fulfill the main goal of study. Face-to-face meetings with a structured questionnaire using a 9-point scale were used to collect the study's data. Steps of AHP methodology: An AHP methodology includes steps, which are covered in the section below.

Step 1: In this step, the decision problem is logically structured in the hierarchy and a goal is finalized. To analyze criteria and options, a decision-making group is put together. Using a formative questionnaire or interview, the 9-point scale (Table 1) is used to calculate the pairwise comparison values (Saaty, 1980). To compare the criteria concerning the goal, pairwise comparison matrices are formed. Sub-criteria are compared with their linked criterion if the problem necessitates their inclusion. Thereafter, alternatives are evaluated based on the criteria, and comparison matrices are established. The pairwise comparison matrix A with n criteria is an n*n square matrix, where element a_{ij} represents the value of the i^{th} criteria over the j^{th} criteria and also element a_{ij} represents the reciprocal of $1/a_{ij}$.

Step 2: Consistency Ratio is defined by CI/RI, where CI= (λmax−n)/ (n−1), where λmax is the maximum Eigenvalue and n is the size of the matrix. Table 2 contains the random index RI. For an acceptable level of consistency, the value of CR must be less than 0.10. The method to calculate the eigenvalues:

(1) Normalize each entry of a column by dividing the total of all entries in the respective column. (2) After the column has been normalized, the importance weight (IW) is computed by taking the average of the entire normalized value of each row. (3) The maximum eigenvalue is calculated by taking the average of sum of all rows in which each element is multiplied by respective importance weight.

Step 3: A normalized pairwise comparison matrix is used to compute the eigenvector. The eigenvector value is calculated by dividing the individual values of the components by the total of the column values. The importance weights of each criterion are then estimated by row-wise averaging of eigenvector values.

Step 4: The final step is to compute the weight of the entire decision hierarchy to get the total priority in eigenvectors.

There are three main stages in proposed evaluation model to compare AM supply chain and traditional manufacturing supply chain. (1) Identifying potential benefits of AM technology to automotive sector supply chain (2) Evaluating the importance weight of criterion (potential benefits) (3) Evaluating supply chain alternatives (AMSC and TMSC) and global desirability index calculation. First stage starts with

4. PROPOSED EVALUATION MODEL FOR COMPARING AMSC AND TMSC

The identification of AM benefits to automotive supply chain as criteria followed by supply chain alternatives for their assessment, and formulation of AHP hierarchy model. In three tier AHP hierarchy model, the goal of the research was placed at the top followed by criteria at the second level and the alternatives at the third. A literature review was performed to develop the model's criteria, which were subsequently verified by a decision-making panel. In second stage, importance weights of selection criterion were determined for supply chain using AHP. The computation of AHP is based on the procedures outlined in Section 3. Using the scale shown in Table 1, pairwise comparison matrices for the criteria were made according to their contribution to improving sustainability and resilience of automotive supply chain (Table 3). In third stage, first the decision-making group consented to criterion weights after that AHP approach was used to determine alternative weights too. Following that, a global desirability index value was calculated for both supply chains.

Table 1. Nine-point scale by Thomas Saaty

Importance Intensity	Definition	Description
1	Equivalent Importance	Both activities strive to achieve aim equally
3	Weak priority of one over another	Judgements just marginally favor one over another
5	Strong importance	Judgment strongly favors one activity over another
7	Very strong importance	Very strong preference is given to one over another.
9	Extreme importance	One activity is superior to another in greatest level
2, 4, 6, 8	Values in the middle of the two adjacent judgments	In case compromise is required
Reciprocals of the above non-zero	j has the reciprocal compared to i	A reasonable assumption

Table 2. Average Random Index (RI) values

N	1	2	3	4	5	6	7	8
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

Source: Saaty (1994)

4.1 IDENTIFICATION OF CRITERIA

The decision-making group acknowledged the evaluation criteria selected from the literature review. Four experts with over ten years of experience in the automobile sector comprised the decision-making group. Their vast experience in the automotive industry made them excellent participants in this study. This study used a nine-point scale to assign relative scores to pairwise comparisons among important factors. Experts assigned scores to each comparison, resulting in a series of judgement matrices. The

Table 3. Pairwise comparison judgment matrix and criterion importance weight

	MEWR	CS	DFLW	SCS	RTD	CAP	FTTM	TAFI	IW
MEWR	1	2	1/7	1/7	1	1/5	4	2	0.08
CS	1/2	1	1/4	1/2	1/2	¼	3	3	0.08
DFLW	7	4	1	1	3	3	4	3	0.25
SCS	7	2	1	1	4	3	4	5	0.26
RTD	1	2	1/3	1/4	1	1/3	4	2	0.09
CAP	5	4	1/3	1/3	3	1	5	3	0.17
FTTM	1/4	1/3	1/4	1/4	1/4	1/5	1	½	0.03
TAFI	1/2	1/3	1/3	1/5	1/2	1/3	2	1	0.05

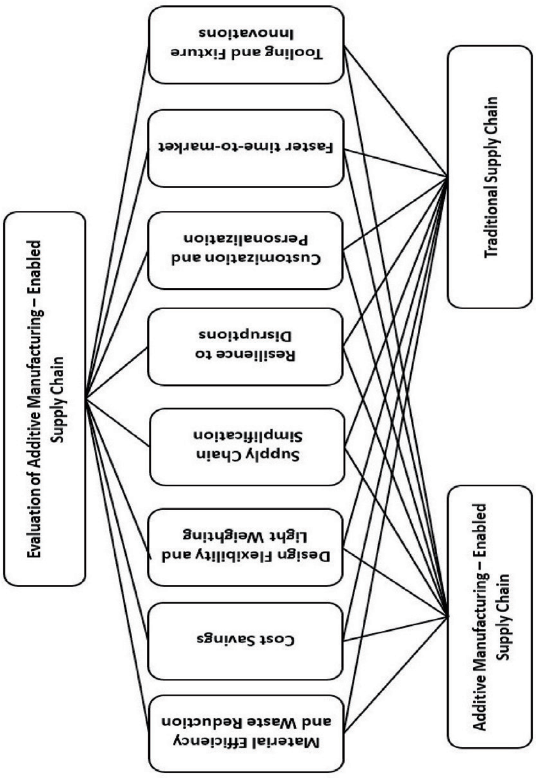

Figure 1. Proposed evaluation model for the comparison between AMSC and TMSC

following eight criteria were considered for the final analysis: Material Efficiency and Waste.

Reduction, Cost Savings, Design Flexibility and Light weighting, Supply Chain Simplification, Resilience to Disruptions, Customization and Personalization, Faster time-to-market, Tooling and Fixture Innovations.

4.2 CRITERIA WEIGHT CALCULATION

The decision hierarchical model depicted in Fig. 1 was made using the goal at top, criteria (potential benefits) at second and alternatives (supply chains) at third level. AHP is used to calculate importance weight. For the pairwise comparison matrix, the consistency ratio was discovered to be 0.08. Because of this, importance weights were seen to be consistent for later study.

4.3 ALTERNATIVES EVALUATION AND DESIRABILITY INDEX COMPUTATION

Using the scale shown in Table 1, evaluation matrices were made to compare alternatives against each of the eight criteria. Tables 4, 5, 6, 7, 8, 9, 10 and 11 include the evaluation matrices. After the assessment matrices were created, the procedures described in Section 3 were used to determine the local weight and of each criterion versus each alternative. AHP-derived importance weights for each criterion were multiplied by the local weights of the individual criteria to calculate global weights of criteria of both supply chains. The results are displayed in Table 12. For example, the local weights of cost savings for AMSC and TMSC were calculated 0.87 and 0.13, individually, whereas cost saving importance weight was determined 0.08. As a result, the global weights of the TMSC and the AMSC chain are 0.08*0.13 = 0.01 and 0.08*0.87 = 0.07, respectively. To get global desirability index of each supply chain, global weights of all criterion were added individually. TMSC has a value of 0.16, compared to the AMSC value of 0.84 (Table 13). The higher value of the AMSC demonstrates that it is justified for use in real-world scenarios.

4.4 FINDINGS AND DISCUSSION

The adoption AMSC over TMSC is justified by AHP hierarchy model by examining eight factors. In the Indian context, the defined AHP model presented in Figure 1 is utilized to justify AMSC over TSC. MEWR, CS, DFLW, SCS, RTD, CAP, FTTP, and TFI are the most significant advantages found. The global weights of the various benefits were found to be much greater in the supply chain that is enabled by AM than in the traditional supply chain. When TMSC and AMSC are compared, the global desirability index value shows that the AMSC offers higher sustainability and resilience at present. Out of the significant benefits of using AM, the highest global weight is of Design Flexibility and Light weighting productivity improvement (0.22). Designers have more freedom with

Table 4. Alternative analysis of material efficiency and waste reduction

	AMSC	TSC	IW
AMSC	1	6	0.86
TSC	1/6	1	0.14

Table 5. Alternative analysis of cost savings

	AMSC	TSC	IW
AMSC	1	7	0.87
TSC	1/7	1	0.13

Table 6. Alternative analysis of design flexibility and light weighting

	AMSC	TSC	IW
AMSC	1	6	0.86
TSC	1/6	1	0.14

Table 7. Alternative analysis of supply chain simplification

	AMSC	TSC	IW
AMSC	1	4	0.80
TSC	1/4	1	0.20

Table 8. Alternative analysis of resilience to disruptions

	AMSC	TSC	IW
AMSC	1	3	0.75
TSC	1/3	1	0.25

Table 9. Alternative analysis of customization and personalization

	AMSC	TSC	IW
AMSC	1	8	0.89
TSC	1/8	1	0.11

Table 10. Alternative analysis of faster time-to-market

	AMSC	TSC	IW
AMSC	1	2	0.86
TSC	1/2	1	0.14

Table 11. Alternative analysis of tooling and fixture innovations

	AMSC	TSC	IW
AMSC	1	3	0.75
TSC	1/3	1	0.25

AM to produce intricate geometries that are challenging or impossible to produce with conventional production techniques. This can lead to lightweight and optimized parts, which improve overall vehicle performance and fuel efficiency. Further, AM permits for the strategic placement of materials, leading to lightweight parts without compromising on strength and durability. This can contribute to overall vehicle weight reduction and improved fuel efficiency. The second highest global priority value is Supply Chain Simplification (0.21). The automotive supply chain can use AM to cut down on the requirement for substantial inventory management and storage. Parts can be printed on demand, eliminating the need for maintaining large stockpiles of components. The third highest global priority value is Customization and Personalization (0.15). AM allows automotive manufacturers to offer greater product customization options to customers. The fourth highest global priority value is Resilience to Disruptions and cost savings (0.07) jointly. With localized production and digital design files, AM provides greater resilience to supply chain disruptions, allowing for quicker adaptation to changing circumstances. AM eliminates the need for costly tooling and fixtures, making it more cost-effective for producing small batches or custom parts. The fifth highest global priority is Material Efficiency and Waste Reduction (0.06). AM is an additive process and adds material only where needed. This reduces material waste significantly, leading to improved material efficiency. The next benefit of using AM is Tooling and Fixture Innovations (0.04). AM offers the possibility to create innovative jigs, fixtures, and tooling to improve efficiency and productivity in the manufacturing process. The next benefit of using AM is faster time-to-market (0.03). AM enables rapid prototyping, allowing automotive manufacturers to quickly create and test new designs. Table 10 presents the AMSC and TMSC global desirability indexes. AMSC has a global desirability index of 0.84, whereas TMSC has 0.16. AMSC has a substantially higher global desirability index than TSC.

5. CONCLUSIONS

Implementing AM in the emerging customized market which require rapid response in farming all the processes and managerial components is a strategic challenge. To justify the expenditure in this advanced Industry 4.0 technology, a comparison of the AMSC with the TMSC is required. These results significantly advance our knowledge of the adoption of AM and its advantages for supply chains, both of which were not well-defined in earlier studies. Presently organizations are moving towards AM mainly for low-volume and high-value manufacturing. Due to the disjointed dealing with AM adoption in automotive supply chain, we used a holistic approach and evaluated the potential advantages of AM utilizing AHP to the AMSC and TMSC for automobile. The findings convey that AMSC has considerably greater potential to improve supply chain sustainability and resilience than the traditional supply chain. AMSC has been found to have a higher desirability index than a TMSC. Out of eight identified important benefits of using AM, the highest desirability index goes to design flexibility and light weighing, followed by supply chain simplification. To advance agility and resilience in the

Table 12. AMSC and TSC local weight and global weight for each criteria

Attribute	Attribute Weight	Local Weight		Global Weight	
		AMSC	TSC	AMSC	TSC
Material Efficiency and Waste Reduction	0.08	0.86	0.14	0.06	0.01
Cost Savings	0.08	0.87	0.13	0.07	0.01
Design Flexibility and Light weighting	0.25	0.86	0.14	0.22	0.04
Supply Chain Simplification	0.26	0.8	0.2	0.21	0.05
Resilience to Disruptions	0.09	0.75	0.25	0.07	0.02
Customization and Personalization	0.17	0.89	0.11	0.15	0.02
Faster time-to-market	0.03	0.86	0.14	0.03	0.00
Tooling and Fixture Innovations	0.05	0.75	0.25	0.04	0.01
Total Global Weight				0.84	0.16

Table 13. AMSC and TSC global desirability indexes

1	Global Desirability Index of AM Enabled Supply Chain	0.84
2	Global Desirability Index of Traditional Supply Chain	0.16

supply chain, the automotive sector should be motivated to use AM Technology.

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7. REFERENCES

1. Achillas, C., Tzetzis, D., & Raimondo, M. O. (2017). Alternative production strategies based on the comparison of additive and traditional manufacturing technologies. *International Journal of Production Research*, *55*(12), 3497–3509.
2. Charles, A., Hofer, A., Elkaseer, A., & Scholz, S. G. (2022). Additive Manufacturing in the Automotive Industry and the Potential for Driving the Green and Electric Transition. In *Smart Innovation, Systems and Technologies: Vol. 262 SIST*. https://doi.org/10.1007/978-981-16-6128-0_32
3. Chiu, M.-C., & Lin, Y.-H. (2016). Simulation based method considering design for additive manufacturing and supply chain: an empirical study of lamp industry. *Industrial Management & Data Systems*.
4. Delic, M. (2022). BARRIERS TO ADDITIVE MANUFACTURING ADOPTION WITHIN AUTOMOTIVE INDUSTRIES. *Economic and Social Development: Book of Proceedings*, 159–180.
5. Delic, M., & Eyers, D. R. (2020). The effect of additive manufacturing adoption on supply chain flexibility and performance: An empirical analysis from the automotive industry. *International Journal of Production Economics*, *228*, 107689.
6. Ghadge, A., Karantoni, G., Chaudhuri, A., & Srinivasan, A. (2018). Impact of additive manufacturing on aircraft supply chain performance. *Journal of Manufacturing Technology Management*.
7. Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production*, *252*, 119869.
8. Gibson, I. (2017). The changing face of additive manufacturing. *Journal of Manufacturing Technology Management*.
9. Haghnegahdar, L., Joshi, S. S., & Dahotre, N. B. (2022). From IoT-based cloud manufacturing approach to intelligent additive manufacturing: Industrial Internet of Things—An overview. *The International Journal of Advanced Manufacturing Technology*, 1–18.
10. Johns, J. (2022). Digital technological upgrading in manufacturing global value chains: The impact of additive manufacturing. *Global Networks*, *22*(4), 649–665.
11. Kayikci, Y. (2018). Sustainability impact of digitization in logistics. *Procedia Manufacturing*, *21*, 782–789.
12. Khajavi, S. H., Holmström, J., & Partanen, J. (2018). Additive manufacturing in the spare parts supply chain: Hub configuration and technology maturity. *Rapid Prototyping Journal*.
13. Khorram Niaki, M., & Nonino, F. (2017). Additive manufacturing management: a review and future research agenda. *International Journal of Production Research*, *55*(5), 1419–1439.
14. Krishan, S., & Subbiah, V. (2022). *Measuring AatmaNirbharta*.
15. Liu, P., Huang, S. H., Mokasdar, A., Zhou, H., & Hou, L. (2014). The impact of additive manufacturing in the aircraft spare parts supply

chain: supply chain operation reference (scor) model based analysis. *Production Planning & Control*, *25*(13–14), 1169–1181.

16. Muir, M., & Haddud, A. (2018). Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain. *Journal of Manufacturing Technology Management*. https://doi.org/ 10.1108/ JMTM-01-2017-0004

17. Naghshineh, B., & Carvalho, H. (2022). The implications of additive manufacturing technology adoption for supply chain resilience: A systematic search and review. *International Journal of Production Economics*, *247*, 108387.

18. Nitsche, B., Straube, F., & Wirth, M. (2021). Application areas and antecedents of automation in logistics and supply chain management: a conceptual framework. *Supply Chain Forum*, *22*(3), 223–239. https://doi.org/10.1080/16258312.2021.1934106

19. Pulicherla, K. K., Adapa, V., Ghosh, M., & Ingle, P. (2022). Current efforts on sustainable green growth in the manufacturing sector to complement "make in India" for making "self-reliant India." *Environmental Research*, *206*, 112263.

20. Radhwan, H., Effendi, M. S. M., Farizuan Rosli, M., Shayfull, Z., & Nadia, K. N. (2019). Design and Analysis of Jigs and Fixtures for Manufacturing Process. *IOP Conference Series: Materials Science and Engineering*, *551*(1). https://doi.org/10.1088/1757-899X/551/1/012028

21. Reichwein, J., Vogel, S., Schork, S., & Kirchner, E. (2020). On the applicability of agile development methods to design for additive manufacturing. *Procedia CIRP*, *91*, 653–658.

22. Saaty, T. L. (1980). The Analytic Hierarchy Process Mcgraw Hill, New York. *Agricultural Economics Review*, *70*, 34.

23. Stock, T., & Seliger, G. (2016). Opportunities of Sustainable Manufacturing in Industry 4.0. *Procedia CIRP*, *40*(Icc), 536–541. https://doi.org/10.1016/j.procir.2016.01.129

24. Thomas, D. (2016). Costs, benefits, and adoption of additive manufacturing: a supply chain perspective. *The International Journal of Advanced Manufacturing*, *85*(5), 1857–1876.

25. Weller, C., Kleer, R., & Piller, F. T. (2015). Economic implications of 3D printing: Market structure models in light of additive manufacturing revisited. *International Journal of Production Economics*, *164*, 43–56.

26. Westerweel, B., Basten, R., den Boer, J., & van Houtum, G. (2021). Printing spare parts at remote locations: Fulfilling the promise of additive manufacturing. *Production and Operations Management*, *30*(6), 1615–1632.

27. Zheng, P., Sang, Z., Zhong, R. Y., & Liu, Y. (2018). Smart manufacturing systems for Industry 4.0: a conceptual framework, scenarios and future perspectives Pai. *Frontiers of Mechanical Engineering*, *13*(2), 137–150. https://doi.org/10.1007/s11465-018-0499-5

28. Zheng, P., wang, H., Sang, Z., Zhong, R., Liu, Y., Liu, C., Mubarok, K., Yu, S., & Xu, X. (2018). Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. *Frontiers of Mechanical Engineering*. https://doi.org/10.1007/s11465-018-0499-5

