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Original Article

Mapping and evaluating the enablers of additive manufacturing for sustainable supply chains using ISM–MICMAC and DEMATEL methodologies

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ABSTRACT

Additive Manufacturing (AM) has been attracting attention in recent years as an innovative production technology that can enhance sustainability in supply chains. Offering maximum material utilization, this technology can reduce waste generated during production. Furthermore, its ability to produce close to the point of consumption makes it environmentally significant. Unlike traditional techniques, it produces layer-by-layer only in the required areas. This enables manufacturing processes that are demand-driven, flexible, and compatible with circular economy principles. This study reveals the factors and obstacles that facilitate the integration of AM into sustainable supply chains. It also aims to assess three-dimensional sustainability impacts. The research explored the interactions between sustainability elements using the ISM (Interpretive Structural Modeling)–MICMAC (Cross-Impact Matrix Multiplication Applied to Classification) and DEMATEL (Decision-Making Trial and Evaluation Laboratory) methods. The results demonstrate that AM-induced enablers play a critical role in influencing the sustainability of supply chains. It is also emphasized that fully realizing this potential requires policy support, stakeholder collaboration, and investments in energy-efficient technologies and environmentally friendly materials. Future research is recommended to focus on the integration of AM with Industry 4.0 technologies and the establishment of legal and economic incentive mechanisms to accelerate its widespread adoption.

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INTRODUCTION

In modern manufacturing, however, economic efficiency itself has ceased to be a sufficient indicator of performance. Other dimensions, such as environmental and social sustainability of the supply chain, have taken a central place when designing and managing production systems. Herein, AM appears to be one of the most promising technologies with the potential to revolutionize not only sustainable production but also supply chain management [1].

Conventional machining methods carve the parts from large blocks, whereas AM constructs the parts layer by layer, using only the material actually needed [2]. This drastically reduces waste and allows considerable efficiency in resource usage.

Efficiency, flexibility, and the ability to realize tailor-made designs in material use are also among the key features of AM. This leads to supply chains that can be agile and responsive to demand [3]. The ability to produce close to the point of need reduces transportation requirements

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and, consequently, reduces the overall carbon footprint. In line with the guiding principles of the circular economy, AM allows for materials that are recyclable. This ensures minimum post-production waste, therefore paving ways for sustainable methods of production.

Of course, large-scale use of AM in supply chains is not without its challenges. In particular, institutional investment remains at a low level, technical know-how is lacking, and organizational culture is resistant to change-all factors slowing integration. Besides, even though AM is designed to be much less wasteful of material, its high energy consumption and limited recyclability of certain feedstock materials raise considerable concerns about environmental performance. Technology's transformative impact on traditional supply chains also brings critical risks around cost management, potential process disruptions, and scalability challenges.

The present research identifies the factors of sustainability that need to be prioritized in implementing AM so that its positive impact on sustainable development can be maximized. We analyze the environmental, economic, and social dimensions of the impact of AM, starting from the specific factors that drive this impact. Further, we identify how these factors are interconnected and influence each other. For this purpose, 15 domain experts were involved to map the causal relationship among the identified factors using ISM and MICMAC. The developed causality map makes it crystal clear which underlying driver/s will most effectively enhance the contribution of AM towards sustainability.

The second step was to measure, using linguistic scales, the strength of these causal relationships by the same group of experts. We analyzed their judgments by the DEMATEL method and hence could identify the most critical factors in sustainability and the strength of influence of each factor on others. This will thus indicate where the efforts for improvement must be made.

Ultimately, this research goes further than the simple identification of environmental benefits of AM, since it provides a wide perspective on how AM is able to redesign supply chain processes, and delivers insights that can be used to shape industrial strategies oriented toward sustainable development.

The rest of the paper is organized as follows: first, a review of the literature on the intersection of sustainability and AM, especially within supply chain contexts, is done. Next, the description of the research methods, including justification for why ISM-MICMAC and DEMATEL have been chosen, will follow. Then comes the explanation of the implementation process, including data collection, expert judgments, and analytical steps. Finally, we will present in-depth discussions based on the findings by emphasizing the key enablers of sustainability, their inter-relationships, and implications for theory and practice.

LITERATURE REVIEW

Increasing environmental concerns have motivated manufacturing firms to adopt new or innovative technologies that enable them to produce in an environmentally sustainable manner, reducing resource consumption, global warming, and waste generation [4, 5]. In this industrial scenario, fostered by Industry 4.0, AM technologies play a central and revolutionary role, offering many economic advantages along with potential sustainability [4–8]. AM is the process of producing objects from a three-dimensional model by assembling raw material layer by layer, without molds, tooling, or dies; this is in opposition to traditional methods of manufacturing [9]. Scientific literature on the adoption of AM finds completion in systematic reviews focusing specifically on three aspects of sustainability: environmental, economic, and social [4, 10, 11].

Research interest in the intersection of AM and SC has grown significantly over the past years, increasing the number of publications between 2013–2021 [10, 11]. Studies in this topic typically employ a systematic literature review methodology and conduct an extensive search in databases such as Scopus or Web of Science [4, 10, 12]. The identified literature reported that a high percentage of research was conducted in Europe - %61 and North America, while limited in developing countries like Africa [11]. The most represented academic journals on the subject are: International Journal of Production Economics, Journal of Manufacturing Technology Management, and Additive Manufacturing [10, 12]. Even though most research in this area covers the "Make" dimension inside the SCOR framework, the most covered industries are aerospace, industrial goods, consumer goods, and automotive sectors [10, 11].

From the point of view of economic sustainability, remarkable advantages of firms arise from AM technology. Unlike traditional manufacturing, it overcomes the economies of scale since, with AM, the unit cost of the product does not depend on the volume of production [4, 13]. The utilization of AM provides a potential for shorter production times and, therefore, lower production costs and energy consumption [4, 14]. The decrease in processing waste results in positive monetary value [4, 15]. Moreover, the AM-based digital warehouses decrease significantly the cost of raw material storage and inventory [10, 16, 17]. Relocation of the production site closer to the customer reduces or totally eliminates transportation and distribution costs [4, 18]. However, due to high equipment costs and low machine turnaround times associated with AM, shifting the economies of scale currently still holds many challenges [19–21].

The most important benefits of AM concern environmental sustainability. AM produces complex-shaped products with a minimum of material waste [16, 22]. It helps to improve the circular economy, which involves less waste and less CO_2 emissions [4, 23]. These technologies have many environmental benefits, such as little waste of raw materials, energy, and emissions during manufacturing [24, 25]. Designing the whole product life cycle from a sustainable point of view supports this advantage [26, 27]. Reduction of weight in particular reduces environmental impact caused during the product usage phase [28, 29]. Additionally, AM can recycle its own waste material and also waste from other manufacturing techniques that are not AM. However, ecological balance can be affected negatively by the high energy requirements of some AM processes [30–33].

Social sustainability and supply chain resilience are increasingly important issues in the AM literature. Research on the social impacts of AM is still limited [4]. There are two key issues: worker conditions and opportunities for localized production. While AM has the potential to improve workers' health by reducing exposure to harsh environments, hazardous materials remain a concern [4]. Furthermore, the potential to relocate production to technologically advanced countries creates instability in countries reliant on industrial production [4, 34]. On the contrary, although AM is expected to reduce labor intensity and create new job opportunities [35], it also offers a risk of negative employment impacts [4]. On the other hand, after global disruptions like COVID-19, AM has again come up as a solution for supply chain resilience [12, 36]. AM enhances supply chain flexibility, reduces lead times, and decreases requirements for safety stock [37–40]. However, high material costs, a lack of material standardization, and energy-intensive processes hinder widespread adoption [11, 12, 40].

Although the impacts of AM on sustainable supply chains are widely discussed in the literature, the existing studies generally remain one-dimensional analyses and fail to explore the hierarchical relationships of the technological, economic, environmental, and social enablers through a holistic system approach. While most explain the benefits of AM at a conceptual level or assess them through case studies of specific sectors, the interdependence structures, impact-degree relationships, and causal links of the drivers (enablers) that enable AM in sustainable supply chains have not yet been systematically mapped. The literature discusses AM's contribution to sustainability from an environmental or economic point of view; however, there is a remarkable gap with regard to prioritization of key enablers, measurement of impact-dependency levels, and strategic roadmap developments.

In this respect, the combined use of decision analysis methods like ISM-MICMAC and DEMATEL offers sound methodological support for an approach which is fundamentally lacking in the literature. These methods will enable us to define the roles of the enablers within a hierarchical structure, such as drivers, dependent and linked, or autonomous variables of AM, in detail, and will make it possible to quantify the causal relationships between them in amplitude. Therefore, a pertinent deficit in the literature consists of the fact that the enabling factors allowing the integration of AM into sustainable supply chains have never been modeled in a systemic way, their relational structures have never been explained, and the determination of managerial priorities has never been performed in an empirical way. It is for this reason that this study, while contributing to the theoretical literature in this subject area, develops an integrated framework for use in industrial applications, strategic decisions support being granted.

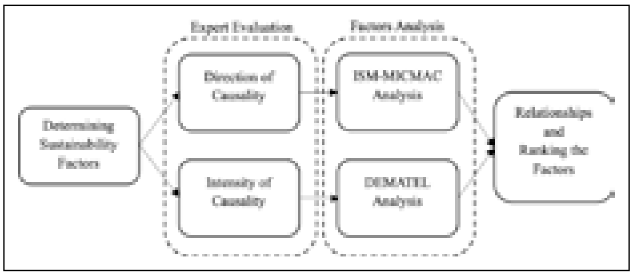

Figure 1. Proposed methodology.

MATERIALS AND METHODS

In this study, the methodological framework shown in Figure 1 was used to identify the key sustainability factors that strengthen the contribution of AM practices to sustainability, as well as to evaluate how the AM approach influences progress toward sustainable development.

In the first step of the proposed methodology, criteria for sustainability were determined by using the literature so that AM could be evaluated by experts. To determine the impact of the resulting sustainability criteria and sub-criteria on AM's sustainability, it is necessary to uncover their hidden inter-relationship effects. In this context, in the second step, expert opinions were obtained through a survey to determine the inter-relationship effects of the sub-criteria and the direction of the impact. In the third step, the obtained expert opinions were analyzed using the ISM method to determine the direction of the relationships and impacts, and the intensity of the relationships was determined using the DEMATEL method. In the final step, the criteria were ranked according to the results obtained, and it was determined which criteria should be given the most importance and developed within the framework of AM's sustainability.

Determining the Sustainability Factors

In the first step of proposed methodology, factors driven by AM and have effect of sustainability are determined. The impacts of AM within the framework of sustainability can be systematically examined under three interrelated dimensions: economic, environmental, and social sustainability. Economically, AM contributes to cost efficiency through reduced material usage, minimized inventory requirements, and streamlined production processes. From an environmental point of view, AM is highly beneficial in reducing material waste, enabling more energy-efficient processes for production, and lastly, allows the manufacture of products locally, thus reducing carbon emissions. The social perspective sees AM fostering inclusivity, increasing the ability to produce highly customized products, and facilitating the adoption of decentralized production methods that can help augment regional manufacturing capabilities. This is able to create new, high-skilled jobs in areas relating to advanced technologies. From both ecological and social standpoints, AM is more than just a novelty in manufacturing; it is also a driver of sustainable industrial change. Figure 2 summarizes the role of AM in terms of the main dimensions of sustainability.

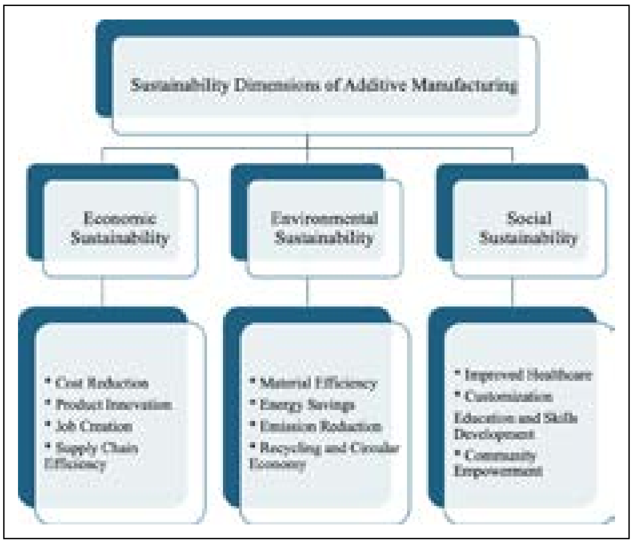

Figure 2. Sustainability dimensions of additive manufacturing.

When we look at it from a sustainable manufacturing point of view, AM brings some clear economic benefits. It changes the way traditional production works and also opens up new job opportunities [41]. Out of the three main pillars of sustainability, the economic side is where its impact can be seen the most. In this context, the key ways in which AM contributes to economic sustainability can be outlined as follows:

- Cost Reduction: AM helps cut material waste, supports demand-driven production that reduces the need for large inventories, and decreases transportation costs by making it possible to manufacture products closer to where they are needed [42].
- Product Innovation: AM makes it possible to produce complex, highly customized designs that traditional manufacturing methods cannot easily achieve. This design freedom opens the door to new markets and niche opportunities, encouraging the creation of innovative products.
- Job Creation: The widespread adoption of AM technology increases the demand for skilled professionals in fields such as design, engineering, and machine operation. This contributes to the creation of employment opportunities in advanced manufacturing sectors, supporting economic growth [42].
- Supply Chain Efficiency: AM facilitates the production of parts closer to their point of use, thereby simplifying supply chains, reducing lead times, and decreasing dependence on offshore manufacturing, ultimately enhancing operational efficiency.

AM contributes to environmental sustainability through its resource-efficient processes and potential for emission reduction [43]. The environmental sustainability benefits of AM can be examined through the following key factors:

- Material Efficiency: AM minimizes waste by using only the exact amount of material required for the product, significantly reducing material waste in comparison to traditional manufacturing processes [44].
- Energy Savings: In industries such as aerospace and automotive, the production of lightweight components using AM reduces energy consumption throughout the product's lifecycle [45].
- Emission Reduction: Localized production facilitated by AM reduces the need for long-distance transportation, which in turn lowers greenhouse gas emissions, contributing to a decrease in the overall environmental footprint [45].
- Recycling and Circular Economy: AM makes it easier to use recycled and even biodegradable materials, which helps support a circular economy where materials are used again instead of being thrown away. This approach moves manufacturing closer to a more sustainable, closed-loop model [43].

AM has a big impact on society by helping improve quality of life, making technology more accessible, and supporting sustainable developmen [46]. We can look at its social impact through a few main aspects:

- Improved Healthcare: AM makes it possible to produce custom medical devices like prosthetics and implants, which can greatly improve patient care and make important healthcare services more accessible [47, 48].
- Customization: AM allows efficient production of customized solutions for many areas, like consumer goods, architecture, and mobility, helping meet the changing and varied needs of society [49].
- Education and Skills Development: The proliferation of AM technology has spurred the development of educational and training programs that equip individuals with the necessary skills to thrive in the future workforce, preparing them for emerging industry demands [50].
- Community Empowerment: By decentralizing manufacturing processes, AM empowers local communities to independently produce goods, thereby fostering self-reliance, resilience, and economic autonomy [51].

Expert Evaluations

In the proposed methodology, expert opinions were obtained for the determination of the sustainability effectiveness of the applications. In this context, experts were asked to compare the sub-criteria in pairs in order to determine their influence on each other. A group of experts with academic and professional backgrounds in the fields of sustainable supply chain management, logistics operations, and AM was called upon to assess the impact of AM on sustainable supply chains using established criteria through pairwise comparison methods. A total of 15 experts were engaged in the pairwise comparison of the criteria.

The academic participants are scholars in sustainability, supply chain management, logistics, operations management, and AM, with a particular focus on the integration of emerging technologies within supply chains.

The majority of the professional participants belong to different industries and encompass practitioners with expertise in supply chain operation practices. The sample also encompasses individuals with experience related to practices of AM and technological integration.

Both groups exhibited a satisfactory level of expertise concerning AM, sustainability principles, and sustainable supply chain management.

Application Steps of Proposed Methods

In this stage, ISM was used to identify relationships among the variables. The facilitators were then classified into different groups using the MICMAC analysis in the form of a driver-dependency diagram. The ISM methodology presents the variables in the form of hierarchical levels of relationship. Similarly, the MICMAC method divides these variables into four classes of variables based on their driving power and dependency characteristics: autonomous (inactive) variables, dependent (affected) variables, link (both affecting and affected) variables, and independent (affected) variables. Lastly, the DEMATEL method is used to analyze facilitators of sustainability on different dimensions. This leads to a cause-and-effect diagram showing the cause-and-effect relationship of factors.

The study used both ISM–MICMAC and DEMATEL methods. Both techniques have been considered powerful tools in solving complex problems that include a lot of interdependent variables [52]. They can be used in investigations of relationships among AM-supported sustainable supply chain management facilitators. The ISM–MICMAC method provides a hierarchical structure by investigating drivers and interdependencies in the facilitators. This provides a clearer view of how these facilitators that affect the dimensions of sustainability influence and are interlinked with each other. This way, the relationships can be investigated in a systematic and transparent way [53].

The DEMATEL method was employed in this study to reveal the cause-and-effect relationships among facilitators after the ISM-MICMAC step. DEMATEL generates a cause-and-effect diagram representing centrality and relationship among the facilitators within the system. Among the strengths of the method is its capability to show not only direct effects but also the broader, indirect effects of these interactions. This comprehensive perspective provides useful insights in making strong and actionable strategic recommendations.

ISM Method

The ISM is an approach that finds interrelationships among factors of a complex system through expert opinion. It is also a step-by-step process of explaining the linkages of a system. These factors are then systematically grouped in a hierarchical order. The method becomes more useful when there are many variables that interact, and multi-level diagrams make visibility and understanding of these relationships easier. Basic steps in applying the ISM methodology are outlined as follows:

- Definition of the Problem and Determination of Objectives: The focus of the study and the variables to be analyzed are clearly defined. The boundaries and scope of the system under investigation are established.
- Identification of Variables (Elements): Key factors, variables, or elements relevant to the system are identified through expert input.
- Determination of Binary Relationships Between Variables: Experts assess the direct pairwise relationships between variables, typically by responding “Yes” or “No” to the question: “Does Variable A Influence Variable B?”
- Construction of the Structural Self-Interaction Matrix (SSIM): The experts’ evaluations are put into a matrix, using predefined symbols to show whether a relationship exists and its direction.
- Development of the Reachability Matrix and Conversion to a Binary Matrix: The SSIM is converted into a binary reachability matrix. This matrix shows the direct connections between the variables.
- Calculation of the Transitive Closure: Indirect links between variables are found and added by calculating the transitive closure. This way, the system shows both direct and indirect influences.
- Level Partitioning of Variables: Variables are sorted into different levels. Ones that influence others the most are placed higher, while those that depend more on others are placed lower.
- Development of the Structural Model: The hierarchical relationships among variables are graphically represented, resulting in an ISM model that visually depicts the system’s structure.
- Model Review and Validation: Experts review the completed model to check its accuracy and relevance. Any needed changes are made based on their feedback.

MICMAC Method

MICMAC is an analytical method for the study of the interactions between the variables of a system based on the influence they exert and their dependence on the others. Based on an evaluation of these two dimensions, that is, driving power and dependence, the method classifies variables into four distinct groups [54].

The first group, driving variables, are elements that strongly influence others and are themselves only minimally influenced. The second group, dependent variables, strongly influenced by other elements, themselves contribute little influence in return. The third group, called linkage variables, both strongly affect and are strongly affected by others, making them pivotal and often sensitive components of the system. Lastly, autonomous variables show low levels of both influence and dependence, indicating that they have little interaction with the system as a whole. The steps for applying the MICMAC method are described below.

- Identification of Variables: All relevant and significant variables (factors or agents) within the system under investigation are identified.
- Determination of Direct Interactions Among Variables: Utilizing expert judgments or empirical data, the direct influence exerted by each variable on others is assessed. These influences are typically quantified using a numerical scale (e.g., 0: no influence, 1: weak influence, 2: moderate influence, 3: strong influence).
- Construction of the Direct Influence Matrix: The quantified direct effects are organized into a matrix format, where each row corresponds to the influence of a specific variable on all other variables.

- Calculation of Indirect Effects: Through iterative matrix multiplication, indirect influences among variables are computed. This process yields the cumulative effects—both direct and indirect—within the system.
- Computation of Driving and Dependence Powers: For each variable, the total number of variables it influences (driving power) and the total number of variables influencing it (dependence power) are calculated.
- Classification and Clustering of Variables: Based on their driving and dependence powers, variables are classified into four categories: driving variables, dependent variables, linkage variables, and autonomous variables.
- Development of the Driver-Dependency Diagram: Variables are graphically represented according to their driving and dependence scores, providing a visual depiction of their roles and interactions within the system.
- Analysis and Interpretation: The classification and visualization facilitate the identification of system dynamics, critical leverage points, and strategic priorities for intervention or further study.

DEMATEL Method

DEMATEL represents a multi-criteria decision-making method used for analyzing and visualizing the cause-and-effect relationships between components in complex systems. This technique is designed to identify and understand the relationships and interactions that exist between influencing factors.

DEMATEL systematically identifies the causal relationships of variables according to expert opinions: their effects are then quantified and arranged in a structured matrix that considers the relationships through direct and indirect effects. The synthesized information forms a comprehensive map of the relationship between system elements.

This method classifies variables into two broad categories: cause factors and effect factors. Cause factors refer to the main driving forces that determine the value of other variables. Consequence factors are factors driven by other elements in the system and often generate secondary or indirect effects.

One of the key strengths of the method is that it can distinctly show cause-and-effect relationships in the form of a causal network. Such visualization allows identifying the most critical factors that need to be focused on strategically and intervened in. Thus, holistic analysis of system dynamics may be conducted if one considers both direct and indirect interactions. The visualization of the causal diagram is enhancing the interpretability and practical usability of the results.

In that respect, DEMATEL is a well-structured and sound method that is based on expert opinions. It unravels the entangled network of interrelations in a system and visually depicts the underlying causal structure. The steps in using the DEMATEL method are presented as follows.

- Problem Definition and Identification of Variables: Clearly define the scope of the problem and identify the key variables or factors to be analyzed within the system.
- Construction of the Direct Relationship Matrix: Collect expert judgments to evaluate the direct influence of each variable on all other variables. These influences are typically rated on a numerical scale (e.g., 0 = no influence, 1 = low influence, up to 4 = very high influence). The assessments are aggregated to form the direct relationship matrix.
- Normalization of the Direct Relationship Matrix: Normalize the matrix to ensure that all values fall within the interval [0,1]. This is usually achieved by dividing each element by the maximum row or column sum of the matrix.
- Calculation of the Total Relationship Matrix: Compute the total relationship matrix, which incorporates both direct and indirect effects among the variables, thereby capturing the overall influence within the system.
- Calculation of Prominence and Relation Values: For each variable, calculate:
  - Prominence (D + R): The sum of the corresponding row and column values in the total relationship matrix, representing the total involvement or significance of the variable within the system.
  - Relation (D - R): The difference between the row and column sums, indicating whether the variable functions primarily as a cause (positive value) or as an effect (negative value).
- Classification of Variables: Based on the prominence and relation values, classify the variables into cause-and-effect groups. Cause variables are those that drive system changes, whereas effect variables are influenced by others.
- Development of the Cause-Effect Diagram: Plot the variables on a two-dimensional graph using their prominence (D + R) and relation (D - R) values. This diagram visually represents the causal relationships and structural dynamics of the system.
- Interpretation and Decision-Making: Analyze the cause-effect diagram alongside matrix results to identify critical factors, understand the system's dynamic behavior, and support informed strategic planning and decision-making.

APPLICATION OF PROPOSED METHODOLOGY

This study analyzes the relationship and/or structure of the enablers emerging from the effects of AM technology and having impacts on supply chain sustainability. In this context, the driving forces and dependencies of these enablers brought by AM technology are examined. In this regard, the hierarchical interactions among different enablers are addressed through an ISM-based approach and MICMAC analysis and subsequently examined in detail using the DEMATEL method. The results of the study have the potential to enable decision-making mechanisms to effectively utilize the integration of AM technology, which triggers the aforementioned enablers, in ensuring supply chain sustainability. Thus, the related study may serve as a guide in improving the performance of supply chain sustainability.

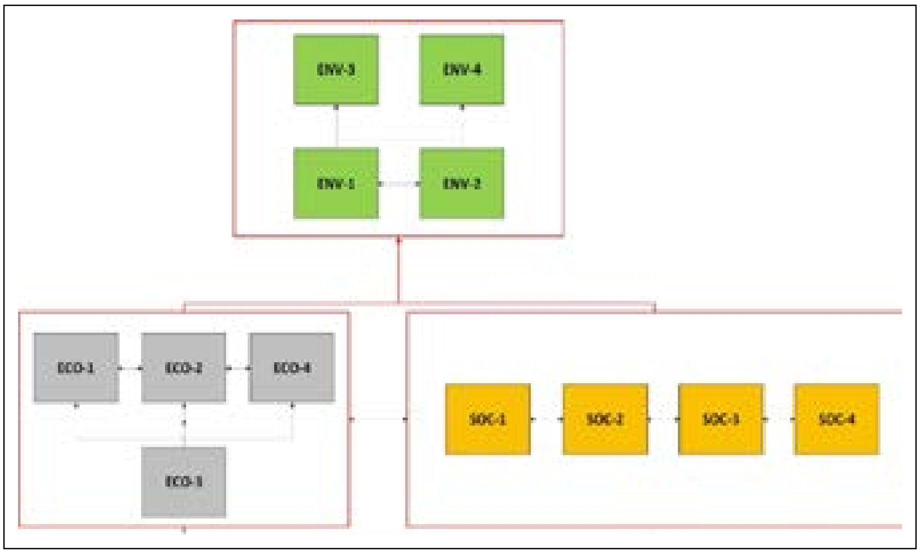

Figure 3. Hierarchical structure of supply chain sustainability sub-criteria affected by additive manufacturing identified through ISM (without inter-dimensional interactions).

This section discusses the output obtained through the combined use of the ISM-MICMAC and DEMATEL methods.

ISM MICMAC Results

ISM Analysis

In the ISM analysis, firstly, the three dimensions of supply chain sustainability were considered as the main criteria. The hierarchy of these criteria was revealed, and then the sub-criteria were evaluated among themselves. In the second stage, the interactions of all sub-criteria were addressed, and a holistic hierarchical structure was presented.

The ISM analysis has revealed a clear hierarchical relationship structure among the elements of supply chain sustainability influenced by AM technology. As shown in Figure 3, the economic and social sustainability main criteria at Level 2 affect the environmental sustainability at Level 1. Looking at the sub-criteria of economic sustainability, the Job Creation (ECO-3) criterion at Level 2 influences the other economic sustainability criteria. In other words, job creation emerges as a driving factor. This criterion is the root driver of the system, having a direct impact on cost reduction (ECO-1), product innovation (ECO-2), and supply chain efficiency (ECO-4). The strong directional links from ECO-3 to these economic enablers indicate that job creation not only strengthens the economic foundation but also triggers innovation and operational performance improvements.

From the perspective of social sustainability, it is observed that all criteria are located at the same level. However, these enablers also have mutual effects on each other at the same level. The environmental sustainability enablers at Level 1 are divided into two levels among themselves. ENV-1 (Material Efficiency) and ENV-2 (Energy Savings) take on the role of influencers from the second level. In other words, Material Efficiency and Energy Savings act as triggers for the criteria ENV-3 (Emission Reduction) and ENV-4 (Recycling & Circular Economy). In addition, ENV-1 (Material Efficiency) and ENV-2 (Energy Savings) also interact with each other. The mutual interaction between ECO-1 and ECO-2 reflects the synergy between cost optimization and product innovation and strengthens their combined capacity to increase resource efficiency. At Level 1, Emission Reduction (ENV-3) and Recycling & Circular Economy (ENV-4) are located. These criteria are highly dependent enablers, receiving cumulative effects from all lower levels. This situation emphasizes their role as final sustainability outcomes in the AM-enabled supply chain context.

Overall, the integrated ISM structure shows that job creation and improvement of health services provide the strongest leverage points for developing economic and social capacity, which also increase resource efficiency. In this way, it can be seen that the goals of reducing emissions and achieving circularity become reachable as a result of coordinated improvements across all sustainability dimensions. This finding strongly shows that decision makers should give priority to the fundamental and intermediate level enablers instead of focusing only on the final environmental outcomes.

In the second stage of the ISM analysis, the interactions among all sub-criteria are considered. The results of the relevant analysis are shown in Figure 4 (Appendix 1). Taking into account the levels and interactions obtained from the ISM analysis, a complex but distinct network of interactions emerges among the economic (ECO), social (SOC), and environmental (ENV) sustainability sub-criteria. This indicates that the sub-criteria establish strong connections not only within their own dimensions but also across other sustainability dimensions. At the lowest level, Community Empowerment (SOC-4) directly influences Job Creation (ECO-3), activating the root driver of the economic dimension, while ECO-3 contributes to strengthening economic performance by feeding into Cost Reduction (ECO-1), Product Innovation (ECO-2), and indirectly Supply Chain Efficiency (ECO-4). In the middle tier, Customization (SOC-2) and

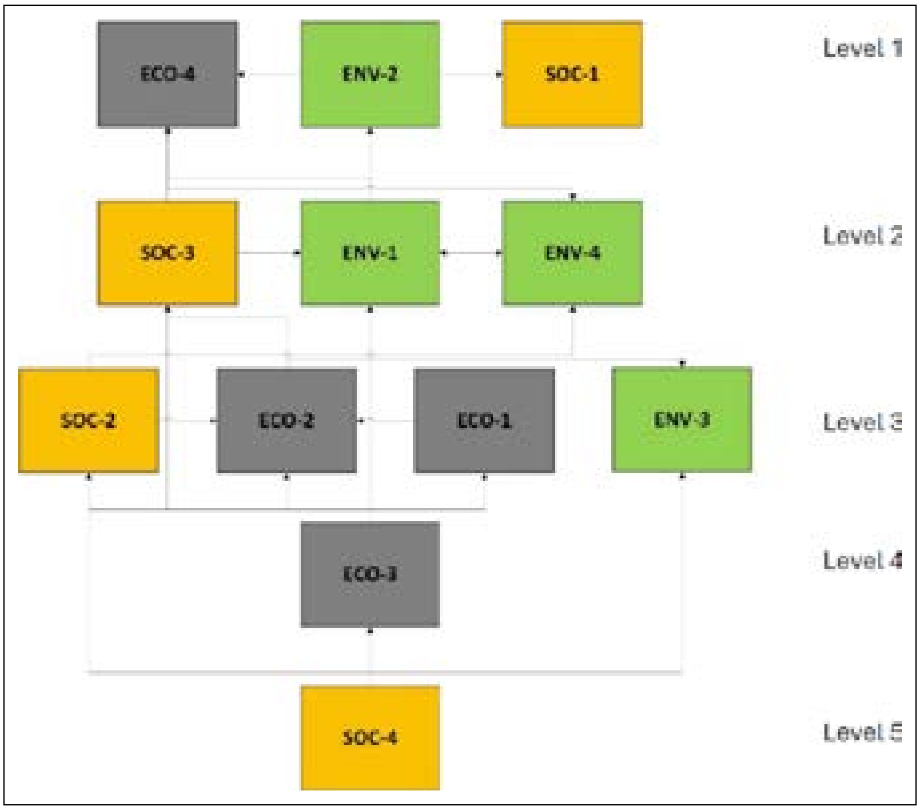

Figure 4. Hierarchical structure of supply chain sustainability sub-criteria affected by additive manufacturing identified through ISM (with inter-dimensional interactions).

Education & Skills Development (SOC-3) stand out; SOC-2 directly influences ECO-2, increasing product design flexibility capacity, while SOC-3 establishes strong connections with the environmental dimension by triggering Material Efficiency (ENV-1). Among the economic sub-criteria, ECO-1 influences ECO-2, clearly revealing the interaction between cost optimization and innovation.

The environmental sustainability criteria are dependent yet critical output areas that are fed by both economic and social factors, with ENV-1 and ENV-2 forming transition points toward environmental outcomes, interacting respectively with SOC-3 and SOC-1. At the top level, Energy Savings (ENV-2), Supply Chain Efficiency (ECO-4), and Improved Healthcare (SOC-1) are located, and they are directly or indirectly influenced by various sustainability criteria from different dimensions in the middle tier. These criteria are positioned in the affected dimension of the system.

MICMAC Analysis

When examining the MICMAC analysis results at the main criteria level, it is observed that the economic criterion has a high driving power and relatively low dependence (Fig. 5). This indicates that the economic sustainability dimension plays a fundamental driving role that influences the other dimensions. The social criterion, on the other hand, is positioned at a medium-high level in terms of both driving power and dependence and is located close to the linkage area, indicating a bidirectional relationship structure in which it both influences and is influenced by other dimensions. The environmental criterion has higher dependence and a moderate level of driving power, positioning it close to the "dependent" area, and is thus evaluated as an output dimension that is strongly influenced by the other dimensions.

At the economic sub-criteria level, Job Creation (ECO-3), with its high driving power and low dependence, is located in the driving area and is the most important trigger of the economic sustainability dimension. Product Innovation (ECO-2), Cost Reduction (ECO-1), and Supply Chain Efficiency (ECO-4) have relatively lower driving power and are positioned close to each other in the dependent area. However, they are also located close to the linkage area. This shows that they are intermediate variables that mutually influence each other and other criteria.

In the environmental sub-criteria, Material Efficiency (ENV-1) and Energy Savings (ENV-2) have high driving power and low dependence, placing in the "driving" area, so they stands out as main leverage points for improve environmental performance. Emission Reduction (ENV-3) and Recycling & Circular Economy (ENV-4) are positioned in the "dependent" area with high dependence, therefore showing that they are final environmental outcomes shaped by effects coming from other criteria.

In the social sub-criteria, Education & Skills Development (SOC-3) with its high driving power is located in the driving power area and plays an important role in the development of social dimension. Customization (SOC-2), Improved Healthcare (SOC-1) and Community Empowerment (SOC-4) have medium level of driving power and dependence and are positioned close to the linkage area. This

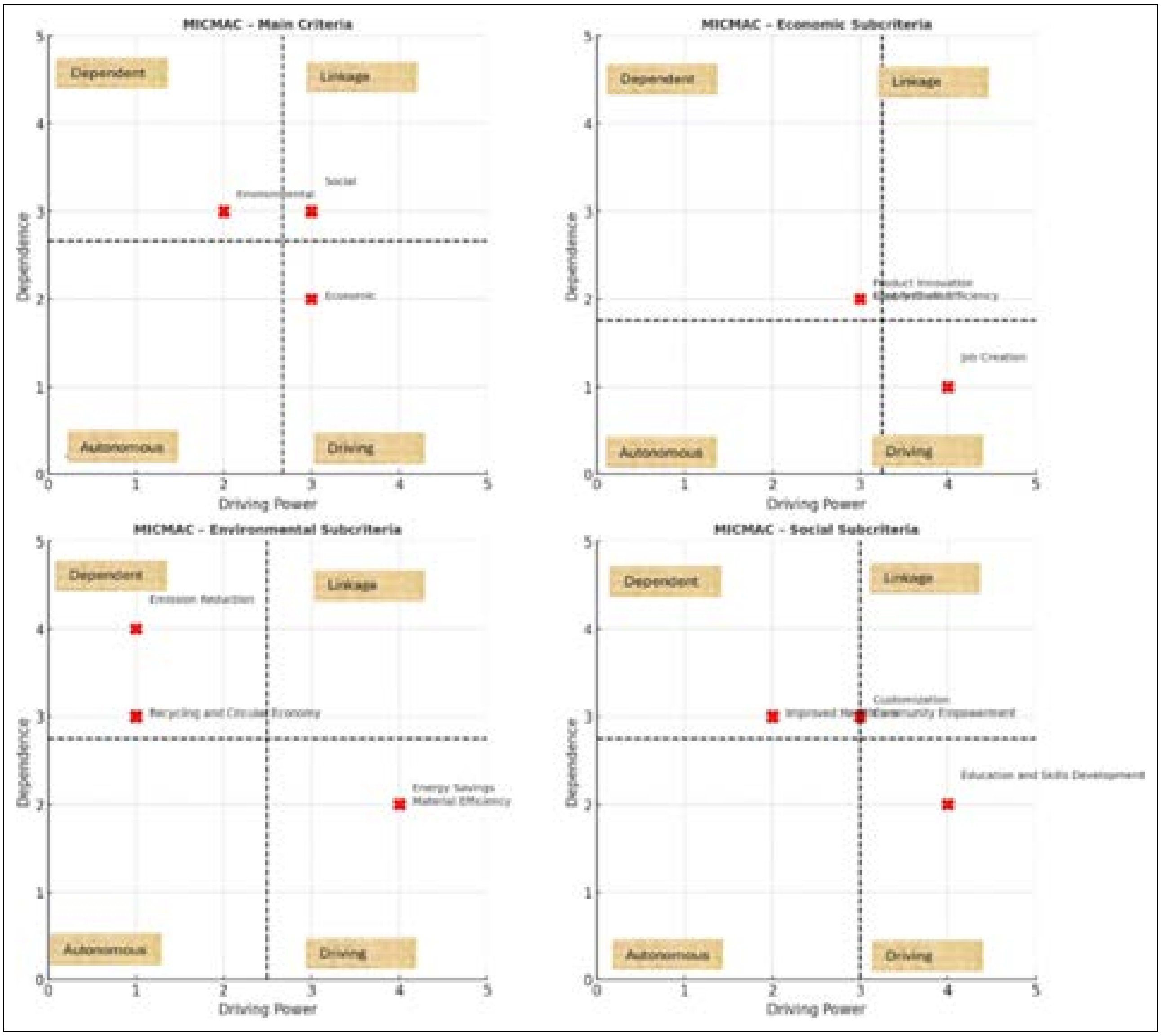

Figure 5. MICMAC analysis results of supply chain sustainability criteria affected by additive manufacturing.

situation shows that these criteria have bidirectional effect both on the social and other sustainability dimensions. When these results are evaluated in general, it is clearly seen that certain sub-criteria in the economic and social dimensions play a critical triggering role in shaping the environmental sustainability outcomes.

The final MICMAC diagram (Fig. 6) clearly reveals how all sub-criteria are positioned when evaluated within a single structure (For the final MICMAC diagram starting point, see the reachability matrix example in Appendix 2). In addition, it presents a holistic view of the interactions between the criteria. Based on Figure 6, Job Creation (ECO-3) and Community Empowerment (SOC-4) are located in the driving area. They have high driving power and relatively low dependence. In particular, Job Creation is the root trigger of economic sustainability. Community Empowerment stands out as the base factor that activates other criteria in the social dimension. These two criteria are strategic leverage dimensions that directly affect other dimensions of the system.

In the linkage area, Supply Chain Efficiency (ECO-4) and Product Innovation (ECO-2) have both high driving power and high dependence. This position shows that these criteria not only influence other sub-criteria but also are influenced by them, therefore they take an intermediate role where mutual dependencies are intense in the system. In the same way, Recycling & Circular Economy (ENV-4) is also placed here and indicate that the circular economy is fed by both economic and environmental inputs, making a significant contribution to the final outcomes.

In the dependent area, Energy Savings (ENV-2), Emission Reduction (ENV-3) and Material Efficiency (ENV-1) stand out, these criteria have high dependence and are shaped by the effects coming from other criteria. Especially Emission Reduction and Material Efficiency are strongly affected by both environmental and economic-social factors, forming the output dimension of the system. Improved Healthcare (SOC-1) and Education & Skills Development (SOC-3) also have relatively high dependence levels, and they are usually affected by triggers from social initiatives and capacity development processes.

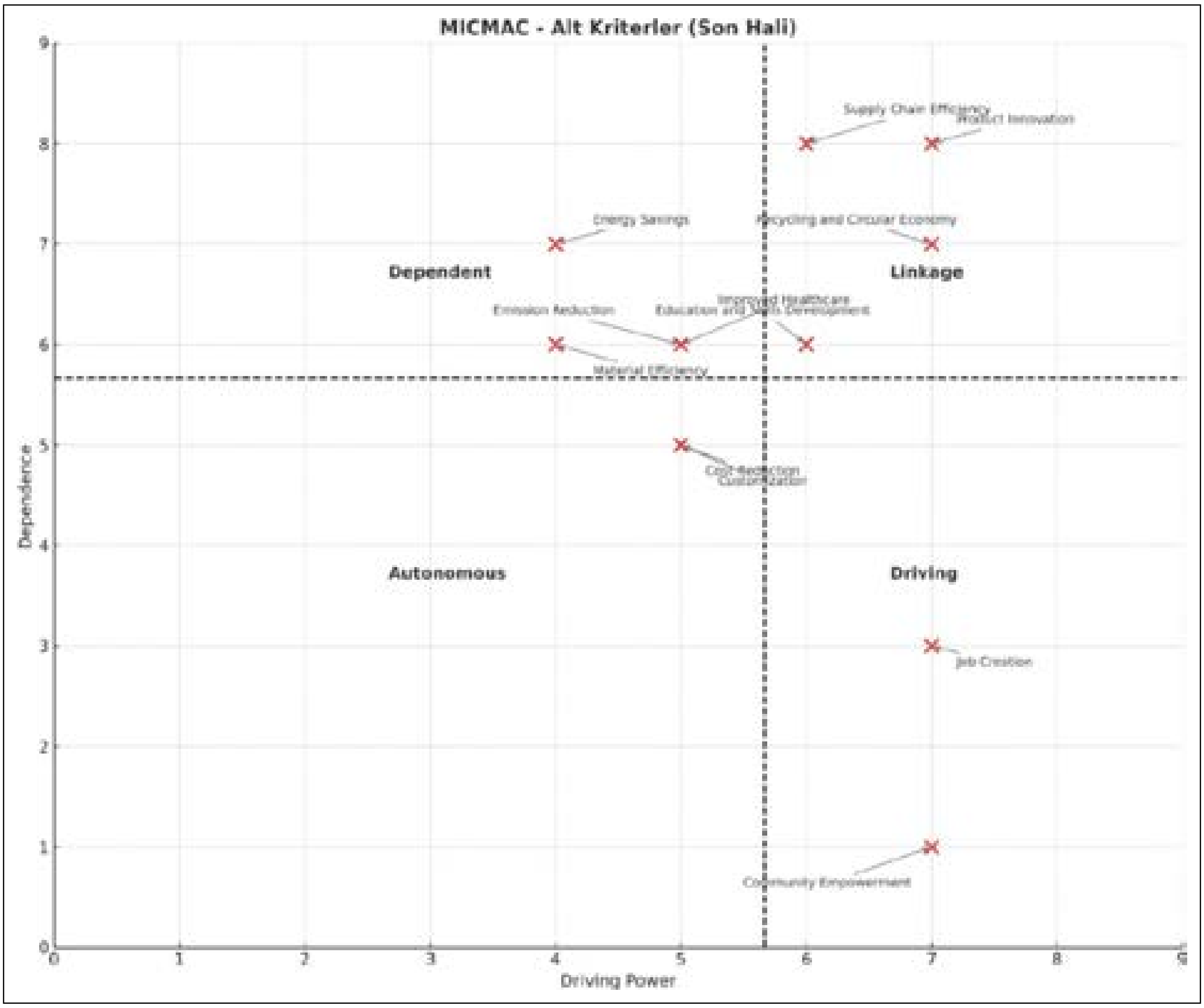

Figure 6. MICMAC analysis – sub-criteria.

In the autonomous area, there is almost no criteria, which shows that all the criteria in the system are affected by others in some way and the system is fully based on mutual dependency. This structure reveals that focusing on only one dimension in sustainability strategies is not enough, and that economic, social and environmental dimensions should be considered together. Especially focusing on high driving power criteria such as Job Creation, Community Empowerment, Product Innovation and Supply Chain Efficiency have potential to create chain and positive effects throughout the system.

The MICMAC and ISM results show a high degree of consistency. While MICMAC analyzes the driving–linkage–dependent classification of the criteria numerically, ISM places these criteria within a lower–middle–upper level hierarchy, visually supporting the identification of which criteria play a triggering role. In particular, ECO-3 and SOC-4 are identified as core factors in both analyses, criteria such as ECO-4, ECO-2, and ENV-4 appear as strategic linkage elements, and criteria like ENV-1, ENV-2, ENV-3, SOC-1, and SOC-3 are positioned as final outcomes.

DEMATEL Analysis

The findings of the DEMATEL analysis at the main criteria level indicate that the economic sustainability (ECO) criterion, with a positive D−R value, represents a strong element of the cause group, and it can be said that the social sustainability (SOC) criterion also shows influencing characteristics (Fig. 7). In addition, economic sustainability and social sustainability interact with each other. Furthermore, the environmental sustainability (ENV) criterion, with a negative D−R value, is revealed to be in the position of a result dimension with high dependence.

At the sub-criteria level, in the economic sustainability dimension, Job Creation (ECO-3) is identified as the root driver with the highest driving power and has a direct influence on Supply Chain Efficiency (ECO-4). Supply Chain Efficiency (ECO-4), with high D+R values, stands out as a linkage criterion that both influences and is influenced, while Cost Reduction (ECO-1), with a lower D−R value, is placed in the result group.

In the social sustainability dimension, Education & Skills Development (SOC-3), with a positive D−R value, is positioned in the cause group and constitutes the main

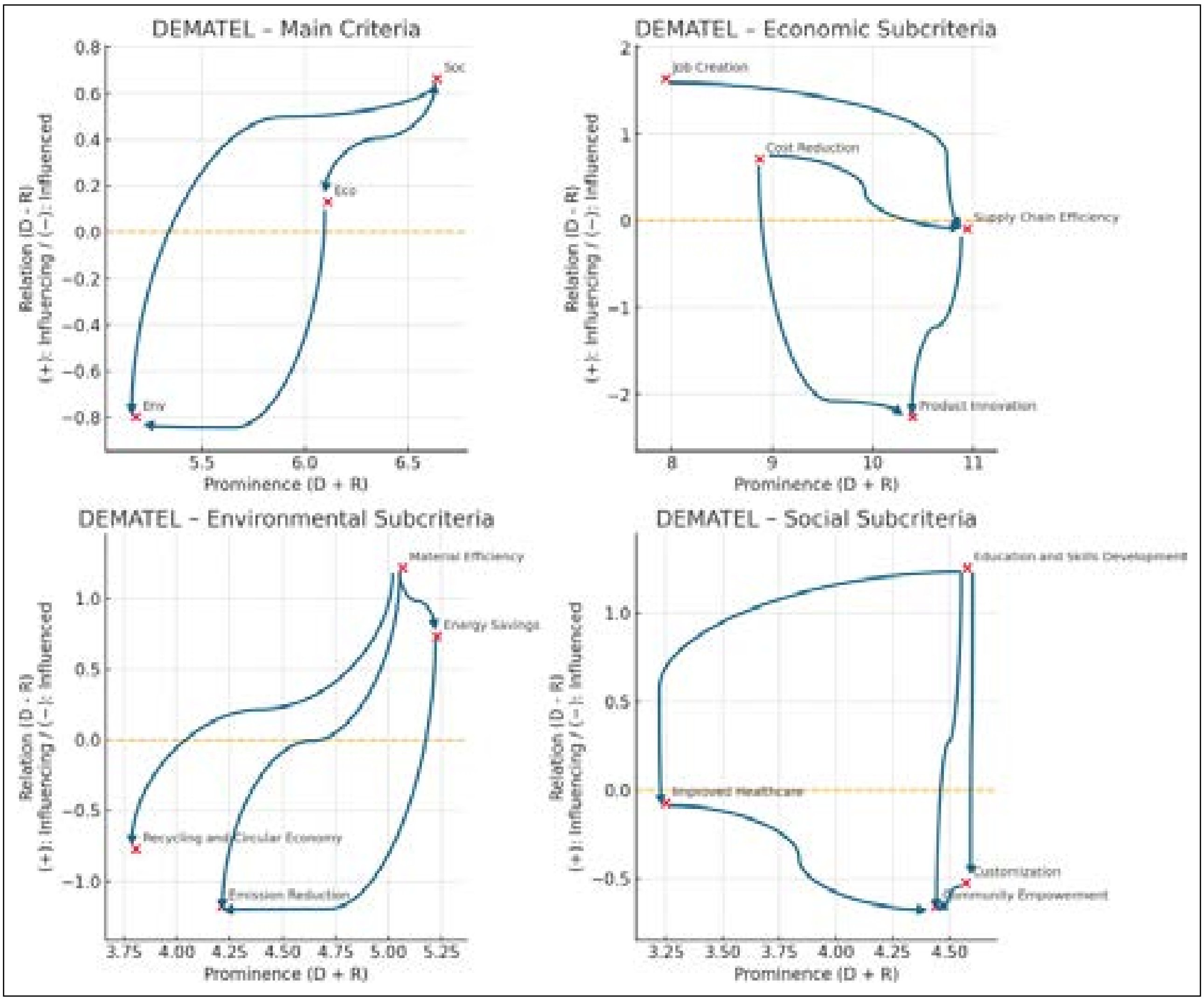

Figure 7. DEMATEL Analysis – Main Criteria and Sub-Criteria (Economic, Environmental, Social).

trigger of the social system. Customization (SOC-2), with its intermediary-oriented relationships, plays the role of a linkage criterion, while Improved Healthcare (SOC-1) and Community Empowerment (SOC-4), with negative D–R values, are included in the result group.

In the environmental sustainability dimension, Material Efficiency (ENV-1) and Energy Savings (ENV-2) are in the cause group and serve as intermediate levers for improving environmental performance. In contrast, Emission Reduction (ENV-3) and Recycling & Circular Economy (ENV-4), with negative D–R values, are located in the result group, positioned as the final outcomes of efficiency and process improvements. These results reveal that the cause–effect relationships identified by DEMATEL show a high level of consistency with the lower–middle–upper level hierarchy in the ISM analysis. In this context, strategies focusing on strong drivers such as ECO-3 and SOC-4 have the potential to create cascading and lasting effects on the top-level result criteria ENV-3, ENV-4, and SOC-1 through linkage criteria such as ECO-2, ECO-4, SOC-2, ENV-1, and ENV-2.

When examining the overall DEMATEL evaluation graph, it is evident that the interaction network of all main and sub-criteria is clearly revealed within a single integrated structure (Fig. 8 and Appendix 3, 4). According to the D–R axis, criteria with positive D–R values are in the "cause group" and represent the driving forces of the system. Among these, Job Creation and Community Empowerment stand out as root drivers with high driving power. Interestingly, Community Empowerment emerges as a triggering factor across all criteria, whereas within the social criteria set it was previously positioned as an influenced element. The criteria positioned as "linkage" have both high driving power and high dependence. At this point, Supply Chain Efficiency (ECO-4), Product Innovation (ECO-2), Recycling & Circular Economy (ENV-4), and Customization (SOC-2) are notable. These criteria represent the points where intermediary interactions are most intense in the system, being influenced by lower-level drivers while also feeding the upper-level result criteria. From a managerial perspective, these criteria can be considered as intermediate levers that play a key role in transferring cascading effects throughout the system.

Criteria with very low negative D–R values are placed in the "result group" and are defined as outcomes shaped by the effects coming from other criteria. In this group, Energy

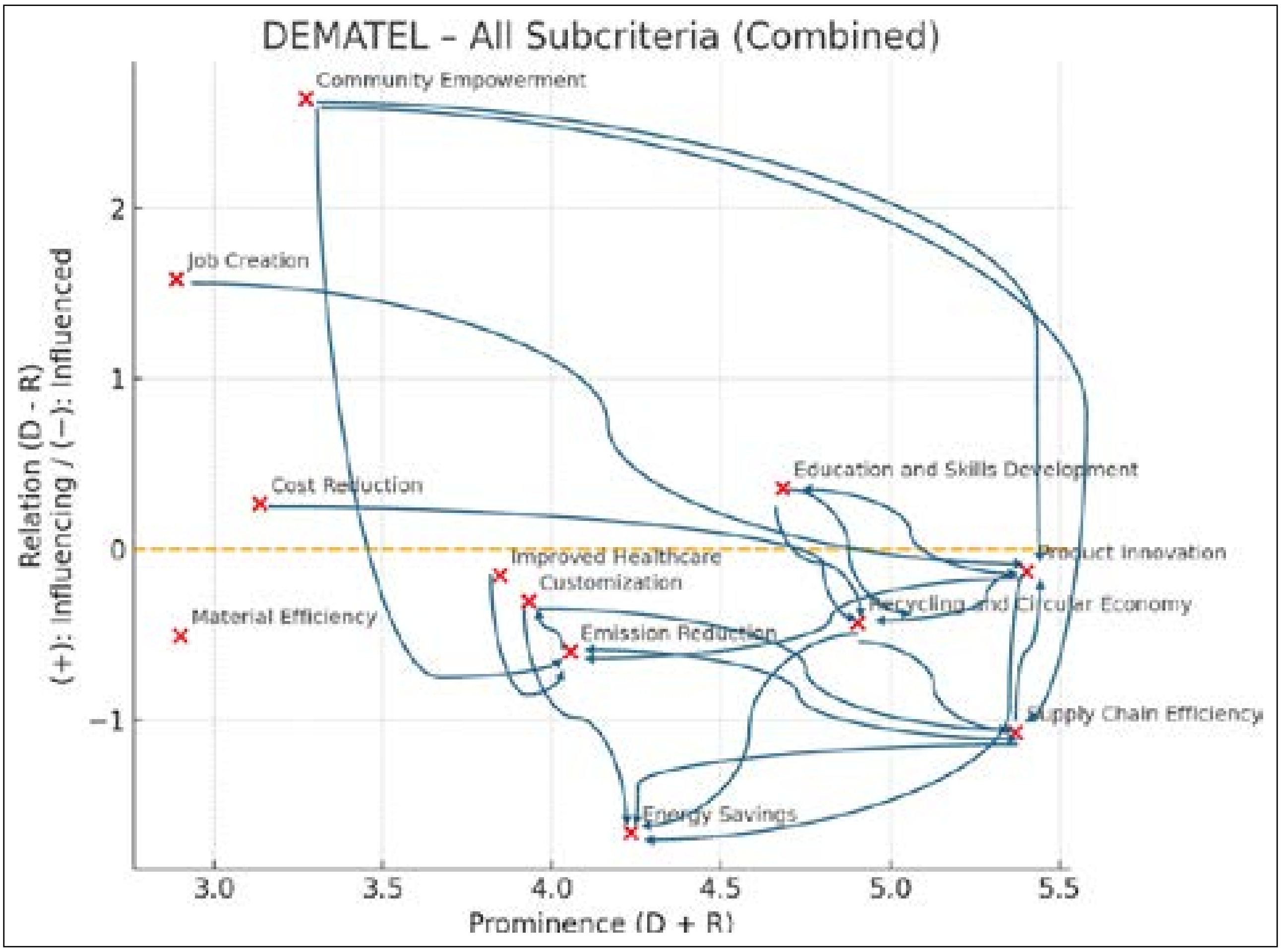

Figure 8. DEMATEL analysis – all sub-criteria (combined).

Savings and Material Efficiency stand out. Rather than triggering these criteria directly, strengthening the cause and linkage group criteria that influence them would be more effective in achieving long-term and lasting improvements. In particular, Material Efficiency is not observed to be in interaction within the overall evaluation system.

When evaluated in terms of importance level (D+R), linkage criteria such as Product Innovation and Supply Chain Efficiency have the highest centrality values and are the strategic transition points of the network. Strengthening these criteria accelerates the flow of information, resources and benefits between multiple dimensions, creating synergy across the system. Therefore, in the priority investment and improvement plans, considering together both the driver criteria with high driving power and the linkage criteria with high centrality values will make possible to increase the system performance in a holistic way.

DISCUSSIONS AND MANAGERIAL IMPLICATIONS

When the integrated ISM–MICMAC–DEMATEL results are considered together, it becomes evident that AM transforms supply chain sustainability through a layered and sequential mechanism operating across direct technical efficiencies (material/energy), economic building blocks (employment, innovation, process efficiency), and social capacity (community empowerment, education/skills, healthcare). The findings do not merely indicate where each criterion is positioned; they also reveal the channels of influence transmission: (i) Root drivers (e.g., ECO-3, and in certain contexts SOC-4/SOC-3) trigger economic and social capacity; (ii) Linkage nodes (e.g., ECO-2, ECO-4, SOC-2, and in some contexts ENV-4) propagate this trigger across operations and design; (iii) Dependent/output criteria (ENV-3, and depending on context SOC-1 and some environmental indicators) make this cumulative effect visible as environmental and societal performance. This sequencing strongly suggests that AM investments should not be approached as "isolated technology acquisitions" but rather as system-level flow design [46, 55].

The first critical managerial framing is the matter of prioritization and sequencing. The results indicate that instead of "jumping directly to the most visible environmental gains," organizations should strengthen foundational drivers (capacity expansions related to employment such as ECO-3; and depending on the context SOC-4/SOC-3 for community and skills capital), integrate these into organizational processes through linkage nodes (ECO-2 product innovation, ECO-4 process/supply chain efficiency, SOC-2 customization), and finally scale up environmental outcomes (ENV-3 emissions, ENV-4 circularity). In managerial terms, this is the driver-linkage-outcome roadmap. Without following this sequence, AM-based gains in energy/material efficiency (ENV-1/ENV-2) risk being short-lived or failing to localize because the economic and social infrastructure that sustains them remains underdeveloped [56, 57].

The second framing is the leverage–centrality tension. Some criteria may have high driving power but only moderate centrality. Conversely, some linkage criteria (e.g., supply chain efficiency and product innovation) possess very high centrality, acting as key transition hubs in the network. The strategic approach involves managing both types of nodes simultaneously: driver nodes indicate the initiation points, whereas linkage nodes determine the pathways and mechanisms through which the flow is maintained within the organization. Without this integration, isolated investments either remain local (drivers exist but spread is weak) or become fragile (linkages are strong but lack input from drivers).

The third framing concerns governance and capability architecture. To make AM's impact on sustainability visible and repeatable, capabilities in (i) design–engineering (product modularity, repairability, recyclability), (ii) operations–supply (on-demand production, digital inventory, localized spare parts), and (iii) people–community (skill transformation, workforce planning, SME supplier development) must be developed in parallel. The findings show that especially community empowerment and skills development exert indirect but lasting impacts on both economic and environmental lines, making HR/L&D programs as strategically important as technical investments. In other words, AM should be treated not merely as a "production technology" but as an organizational transformation platform [10, 58].

The fourth framing addresses the risk–resilience–outcome balance. By nature, linkage nodes that both influence and are influenced are also carriers of systemic risks. For instance, if supply chain efficiency and product innovation are simultaneously highly central, disruptions in these nodes can cascade across the entire system. Therefore, managerial advice includes embedding resilience-enhancing measures (such as operational redundancy, standardization–modularization, supplier base diversification, critical spare capacity, and cyber-physical traceability) into the program. This ensures that the gains generated by drivers are transferred to top-level outcomes without dissipation [59].

The fifth framing is measurement and feedback architecture. The findings imply that environmental outcomes (emissions, circularity) form cumulatively and with delays. Thus, indicator sets must be designed in multiple layers: early-warning KPIs for drivers (employment quality, skill acquisition, innovation cycle time), flow and centrality KPIs for linkage nodes (supply cycle time, scrap/rework ratio, value per revision), and impact KPIs for outcomes (such as recycled content ratio, life-cycle cost). Linking these three layers through A/B testing and causal tracing makes it possible to demonstrate the effect of specific investments on specific outcomes with evidence.

The sixth framing is scaling and contextual adaptation. ISM–MICMAC–DEMATEL provides a flexible roadmap for which node to pull in which context [53, 60, 61]: in capital-constrained environments, start with the 2–3 nodes with the highest leverage-to-centrality ratio; in regulation/incentive-driven sectors, early-stage emphasis can be placed on policy-aligned nodes like ENV-4 circularity; in regions with acute skilled labor shortages, a human-centric scaling focused on SOC-3/SOC-4 can yield faster returns. In short, the same topology can be orchestrated differently—the key is preserving the driver–linkage–outcome sequence.

These framings taken together detail the managerial roadmap: (1) Establish the drivers, employment/capacity, community/skills; (2) institutionalize the linkage nodes, innovation, supply efficiency, customization; process-design integration; (3) scale the environmental outcomes, emissions, and circularity; (4) secure continuity of flows through resilience measures; (5) close the causal feedback loop through multi-layered measurement; and finally, (6) Periodically recalibrate orchestration according to context. More than anything else, this turns AM investments from a one-off technology project into a lasting transformation program anchored around organizational capability architecture and sustainable value creation.

Effective implementation of an AM management roadmap requires that additive manufacturing investments be considered an organizational transformation process rather than a technological innovation. In this respect, it is important that continuous training and skill renewal programs be designed in order to develop a qualified workforce, while establishing digital infrastructure, process standardization, and data integrity systems that will increase the efficiency of supply chains. The integration of AM technologies into existing production structures should be tested for the scalability of processes through pilot applications and with the support of a digital twin-supported design-production cycle. However, this transformation should not be limited to internal sources but should also be supported by external incentive mechanisms such as publicly supported R&D grants, green production credits, tax incentives, and sustainable innovation funds. Businesses should develop performance-based incentive systems in their organizations that will facilitate the encouragement of employee participation in innovative practices and process improvements. Finally, to ensure the lasting social impact of AM, there is a need for cooperation in joint development projects with local suppliers and SMEs, thus turning economic, social, and environmental sustainability into a self-reinforcing whole.

CONCLUSION

The paper presents a critical review of how AM technology influences supply chain sustainability based on the integrated approaches of ISM, MICMAC, and DEMATEL methods. In integrating the methods, the research reveals not just the hierarchical position of the criteria but also the causal and dependency relationships that define how economic, social, and environmental enablers interact. The results identify that the impact of AM on sustainability is not some simple direct outcome; rather, it is a result of a multi-layered and sequenced mechanism wherein root drivers, such as job creation and community empowerment, start off transformative processes transmitted through linkage criteria like product innovation and supply chain efficiency to dependent outcomes like emission reduction and circular economy achievements. This systemic perspective provides important guidance for managers to design interventions that target both the source and transmission channels of sustainability impacts and thus assure long-term and scalable improvements. Further, the focus on driving power and centrality together underlines the need to balance investment between fundamental triggers and high-centrality connectors in order to maximize system-wide synergy.

From a practical standpoint, the results recommend that organizations approach investments in AM as a strategic transformation program rather than an isolated technology acquisition. This calls for strengthening the foundational economic and social capabilities necessary to make those gains strong and scalable and also for embedding measures of resilience at key network points. The multi-layered measurement and feedback framework proposed here provides decision-makers with the tools to track causal linkages and validate, with empirical evidence, the impact of their strategies.

The findings of this study contribute uniquely to the literature by showing how additive manufacturing transforms sustainable supply chain performance through direct environmental impacts and a dynamic systemic mechanism that connects economic and social capacity. In this respect, the study develops a holistic methodological framework that integrates AM's sustainability impacts with hierarchical, causal, and centrality-based analyses, enabling decision-makers to link technology investments to multi-layered sustainability outcomes.

Despite the contributions made, the following shortcomings are associated with this study. First, this analysis is based on the evaluation of experts and could therefore be subjective; larger and more diverse respondent groups might enhance its reliability. Second, the findings are context-specific to the AM-enabled supply chain and may thus need adaptation prior to being generalized to other technological or industrial contexts. Third, although the combined approach using ISM–MICMAC–DEMATEL offers powerful structural insights, it lacks information about dynamic temporal changes; integrating system dynamics or longitudinal data would be an exciting future research avenue. Finally, other exogenous factors that may alter these identified interaction patterns, such as changed policies, market volatility, and disruption to global supplies, have not been explicitly modeled.

Data Availability Statement

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

Author's Contributions

Cihat Öztürk: Conception, Design, Supervision, Data Collection and Processing, Analysis and Interpretation, Writer, Critical Review.

Nurullah Güleç: Conception, Design, Literature Review, Analysis and Interpretation, Writer.

Conflict of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Statement on the Use of Artificial Intelligence

The authors acknowledge the use of ChatGPT for ensuring language clarity and correcting grammatical mistakes.

Ethics

There are no ethical issues with the publication of this manuscript.

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Appendix 1. ISM levels

Levels	Criteria
Level-1	Eco-4, Env-2, Soc-1
Level-2	Env-1, Env-4, Soc-3
Level-3	Eco-1, Eco-2, Env-3, Soc-2
Level-4	Eco-3
Level-5	Soc-4

Appendix 2. MICMAC reachability matrix

	Eco-1	Eco-2	Eco-3	Eco-4	Env-1	Env-2	Env-3	Env-4	Soc-1	Soc-2	Soc-3	Soc-4
Eco-1	1	1	0	0	0	1	0	1	1	0	0	0
Eco-2	0	1	0	1	0	1	1	1	1	0	1	0
Eco-3	1	1	1	1	1	0	0	0	1	1	0	0
Eco-4	0	1	1	1	0	1	1	0	0	1	0	0
Env-1	0	0	0	1	1	1	0	1	0	0	0	0
Env-2	0	0	0	1	0	1	0	1	1	0	0	0
Env-3	0	0	0	1	1	0	1	0	0	1	1	0
Env-4	1	0	0	1	1	1	1	1	0	0	1	0
Soc-1	1	1	0	0	0	0	1	0	1	0	0	1
Soc-2	0	1	0	0	0	1	0	1	0	1	1	0
Soc-3	0	1	0	1	1	0	0	1	0	1	1	0
Soc-4	1	1	1	0	1	0	1	0	1	0	1	0

Appendix 3. MICMAC reachability matrix

	ECO-1	ECO-2	ECO-3	ECO-4	ENV-1	ENV-2	ENV-3	ENV-4	SOC-1	SOC-2	SOC-3	SOC-4
ECO-1	0.0897	0.2153	0.0211	0.1605	0.0670	0.2816	0.1325	0.2709	0.2564	0.0723	0.1080	0.0270
ECO-2	0.1041	0.1975	0.0423	0.3596	0.1304	0.3463	0.3277	0.3338	0.2696	0.1814	0.3153	0.0283
ECO-3	0.1847	0.2807	0.0340	0.2799	0.2229	0.2124	0.1550	0.1801	0.2730	0.2585	0.1273	0.0287
ECO-4	0.0632	0.3020	0.1290	0.2059	0.0934	0.3256	0.2786	0.1705	0.1308	0.2860	0.1500	0.0138
ENV-1	0.0427	0.0830	0.0293	0.2685	0.0434	0.2571	0.0856	0.1782	0.0657	0.0738	0.0632	0.0069
ENV-2	0.0671	0.1106	0.0302	0.2537	0.0498	0.1064	0.1122	0.1734	0.2096	0.0778	0.0730	0.0220
ENV-3	0.0380	0.1512	0.0337	0.3104	0.1773	0.1668	0.0994	0.1499	0.0621	0.2805	0.2511	0.0065
ENV-4	0.2101	0.1704	0.0402	0.3643	0.1982	0.2973	0.2282	0.1787	0.1145	0.1558	0.2665	0.0120
SOC-1	0.2218	0.2855	0.0354	0.1599	0.0901	0.1508	0.2809	0.1430	0.1218	0.1036	0.1352	0.1180
SOC-2	0.0686	0.2682	0.0223	0.1950	0.0859	0.3031	0.1234	0.3035	0.1056	0.1014	0.2266	0.0111
SOC-3	0.0807	0.3329	0.0427	0.3878	0.2492	0.2572	0.1711	0.3574	0.1138	0.3416	0.1731	0.0120
SOC-4	0.2620	0.3691	0.1912	0.2751	0.2946	0.2423	0.3315	0.2282	0.2761	0.1835	0.2740	0.0290

Appendix 4. DEMATEL cause-effect table

	D	R	D+R	D-R
ECO-1	1.702371	1.432726	3.135098	0.269645
ECO-2	2.63635	2.766288	5.402638	-0.12994
ECO-3	2.237225	0.651322	2.888547	1.585903
ECO-4	2.148693	3.22067	5.369363	-1.07198
ENV-1	1.197558	1.702355	2.899913	-0.5048
ENV-2	1.285912	2.947032	4.232945	-1.66112
ENV-3	1.726873	2.326079	4.052952	-0.59921
ENV-4	2.236284	2.667541	4.903826	-0.43126
SOC-1	1.846048	1.999203	3.845251	-0.15316
SOC-2	1.814728	2.116155	3.930883	-0.30143
SOC-3	2.51935	2.163246	4.682596	0.356104
SOC-4	2.956616	0.31539	3.272006	2.641226