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Evaluation of the importance of additive manufacturing technology in terms of sustainable production with the DEMATEL method

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ABSTRACT

It is possible to argue that Additive Manufacturing technology has positive environmental impacts when compared to traditional production. The Additive Manufacturing technology, which provides less waste of raw materials with the use of smart materials, allows the materials to be included in the production process layer by layer (i.e. in a stratified manner) and with very high precision. Based on this point of view, the importance of Additive Manufacturing technology emerges for a sustainable production approach minimizing negative environmental effects, protecting energy and natural resources, and aiming to produce products rationally. Additive Manufacturing, which focuses on innovation and creativity, should take its place in industries as part of a holistic sustainability plan. With this study, the purpose was to determine the importance of Additive Manufacturing technology for sustainable production. It is thought that the results to be reached by the study will constitute a guiding reference for the strategies that the enterprises will develop on the subject. In this context, important application areas of Additive Manufacturing technology that are considered to contribute to sustainable production were uncovered as a result of a wide literature review and expert opinions. Ten criteria, which were considered to contribute to the sustainable production of Additive Manufacturing technology, were identified and the effects and relations among these criteria were analyzed with the DEMATEL Method. Obtained results show that Additive Manufacturing technology has a very important effect on sustainable production, with its contributions such as developing sustainable solutions, enabling green production, encouraging the production of innovative products, and preventing excessive resource use.

1. Introduction

There is a need for an environmental requirement that will positively affect and improve working efficiency in manufacturing industries. A sustainable production approach that will have minimum negative effects on the environment means minimum consumption of resources without causing waste (Krishna and Srikanth, 2021). With globalization, increasing consumption also increased resource consumption considerably. The use of non-renewable resources that have low efficiency by traditional production practices has prepared the ground for the emergence of environmental, social, and economic problems (Cao et al., 2015). The sustainable production concept, which emerged to solve these problems, aims to manage natural resources effectively and plan business operations and volume according to present resources. Based on this understanding, it becomes possible to save energy and increase resource efficiency (Ghobakhloo, 2018).

Right at this point, it becomes possible to strengthen sustainable production with the adoption of contemporary practices, e.g. the technology of Additive Manufacturing instead of traditional production models (Ngo et al., 2018). It is possible to argue that Additive Manufacturing has become a transformation for the manufacturing industry in terms of sustainability. Additive Manufacturing has sustainable benefits such as minimal material consumption and high energy efficiency (Huang et

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al., 2013). Additive Manufacturing can be referred to as the most convenient, attractive, and potentially useful way of product development. Additive Manufacturing is a method of combining different materials to create objects from a 3D model (Mani et al., 2020). Additive Manufacturing technology, which is also called "3D Printing," is based on the principle of stratified material integration and creates physical elements that match digital representations of objects by using 3D modeling or computer-controlled tools (Mandolla et al., 2019). Additive Manufacturing performed production by adding and integrating materials, unlike the abrasive production methods, which are often known as turning or using a milling cutter (Ashima et al., 2021).

Additive Manufacturing technology is developing and becoming more important in terms of industrial production with the rapid development of 3D printing technologies. Additive Manufacturing technology, which is optimized with each passing day increasing its accuracy and versatility, is the most important tool in the transition from "Rapid prototyping" to "Rapid production" in industries (Zhang et al., 2021). With this technology, which has increased its popularity due to its high potential in the production of complex structures, it is possible to increase the success of engineering applications (Tian et al., 2017). Traditional production methods such as pultrusion, vacuum bagging, filament winding, compression molding, stamping, and pouch-assisted molding have important disadvantages such as multiple preparation procedures, long production cycles, and high production costs. However, Additive Manufacturing technology, which is also known as the process of adding materials in successive layers to produce objects by using 3D models, provides flexibility in design and important cost advantages in the production of personalized products (Sano et al., 2018). Materials science, laser beam technology, mechanical engineering, Computer-Assisted Design (CAD), and manufacturing engineering technology are part of it. Stereolithography (SLA), 3D Printing (3DP), Combined Deposition Modeling (FDM), and Laser Metal Deposition (LMD) are among the Additive Manufacturing technologies that have been extensively researched, developed, and commercialized (Zhu et al., 2020).

Composites, metals, ceramics, and polymers are materials used in Additive Manufacturing. Polymer materials are the most frequently used materials in Additive Manufacturing for easy availability, low cost, high mechanical properties, and compatibility with many 3D printing methods (Talib et al., 2021). Metals and alloys can be produced with Additive Manufacturing technology. This technology is used for prototyping, research, and small-scale manufacturing, especially in the aerospace, automotive, biomedical, and military industries, and complex shapes are printed (Pérez et al., 2020).

Additive Manufacturing technology, which accelerates prototyping and the speed of bringing the product to market, contributes to making businesses more efficient and competitive by reducing product development costs (Nyman and Sarlin, 2014). Recent developments in technology helped reduce the cost of 3D printers, making it an affordable technology that can even produce customized products. Product customization is a challenge for manufacturers with high costs, but it is easy to print small quantities of customized products at affordable prices for Additive Manufacturing technology (Upadhyay et al., 2017). This technology, which shortens repair times and reduces labor costs, also increases quality (Alfaify et al., 2020). Additive Manufacturing, which is defined as the method of producing parts by stratified deposition of materials, has prepared the ground for producing innovative and quality products at lower costs, faster, and more efficiently (Zhu et al., 2020). This technology also offers advantages such as increased production flexibility, improved design possibilities, and reduced production time and costs (Seol et al., 2020). Additive Manufacturing has become a preferred technology in aerospace, medicine, automobile, processed food, and many other industries with these advantages (Bhushan and Caspers, 2017; Yang et al., 2018). It is estimated that the global Additive Manufacturing market will rise from $8.44 billion in 2018 to $36.61 by 2027.

A sustainable production is an approach to minimizing pollution and encouraging activities with high eco-efficiency. Sustainable production, which aims to minimize wastes and prevent environmental degradation by recycling elements (e.g. raw materials, electricity, paper, and plastic) affects the productivity and performance of enterprises closely in today's conditions of intense competition (Cao et al., 2015). It is possible to argue that Additive Manufacturing technology supports sustainable production with its characteristics. Among the many potential sustainability benefits of this technology, three come to the fore, which are improved resource efficiency, extended product life, and a re-engineered value chain. Sustainability in production has an important role in combining operational practices in design, distribution, use, product service, and governance with manufacturing practices for innovative and marketable products and service combinations contributing to sustainability (Holmström et al., 2017).

Right at this point, the low resource requirement is among the contributions of Additive Manufacturing to sustainability (Colorado et al., 2020). Additive Manufacturing also minimizes energy demand throughout the life span of the product. This technology designs products very quickly and eliminates waste by enabling efficient resource use and reuse (Machado et al., 2019).

Additive Manufacturing also lowers the level of waste by enabling efficient recycling and regeneration of manufacturing products and processes developed by using different techniques to minimize the negative effects of production on the environment (Haleem and Javaid, 2018). To ensure sustainability, especially in the aviation and automotive sectors, reverse engineering processes must be used. Additive Manufacturing, which encourages the use of renewable raw materials, provides more organized, effective, and sustainable production (Loy, 2015).

Among the most important sustainability benefits of Additive Manufacturing, there is a high recycling rate. Also, Additive Manufacturing, which encourages the use of renewable raw materials, makes it possible to reuse disposable materials such as plastic water bottles. Since printing can be made on materials such as plastic, which has significant environmental effects, these materials are reused with this technology instead of thrown into nature. Also, negative environmental effects are seen at lower levels with the more efficient use of energy resources (Savolainen and Collan, 2020).

Manufacturing by using 3D printing pollutes the environment less (Mohd Yusuf et al., 2019). The production of aerosols such as ultrafine smoke, gas, sprays, and volatile compounds creates harmful toxicants for humans, which poses significant risks. To minimize the harmful effects of these materials, it has become necessary to design and produce less toxic and low-emission 3D printing materials. It has become possible to solve the problems encountered with 3D printing, in which renewable and biodegradable polymers are used (Wang et al., 2018). Life cycle analyses show that adopting Additive Manufacturing can result in significant savings in goods production. Savings are estimated to be $113-370 billion by 2025 with savings in material inputs and use, and high recycling potential (Birtchnell and Urry, 2016).

It is considered that Additive Manufacturing will contribute to the sustainable production concept, especially because it is a technology saving energy-time and can produce effectively with small amounts of input. Based on this idea, the purpose was to determine the contributions of Additive Manufacturing technology to sustainable production and to determine the effects and relation levels of these contributions. In this regard, a wide literature review was performed and criteria that represented the areas where Additive Manufacturing technology can contribute to sustainable production were determined. These criteria, which are numerous and complex, were reduced to the final number to be included in the analyses with expert opinions. A total of 12 criteria were determined and analyzed with the DEMATEL Method. As a result of the analysis, the criteria that represented the areas where Additive Manufacturing technology contributes to sustainable production were determined and interpreted according to their effects and relationship levels.

2. Literature review

In this part of the study, the other studies in the literature on the subject were examined.

In their study, Haleem and Javaid (2018) compared Additive Manufacturing and traditional production. As a result of their study, they reported that Additive Manufacturing has important benefits such as providing resource and material efficiency and reduced environmental effects. Huang et al. (2013) compared additive and traditional products in terms of sustainability and the findings pointed out that Additive Manufacturing comes to the fore with its environmentally friendly design and low resource use characteristics. Similarly, Woodson (2015) examined the effects of 3D technologies on sustainable industrial transformation and concluded that businesses must make significant investments in Additive Manufacturing technologies at the point of sustainability. Kreiger and Pearce (2013) reported that this technology is beneficial in terms of sustainability for low energy consumption and low waste emissions in their study that was conducted to determine the environmental effects of 3D writing. As a result of their study that aimed to determine new criteria for environmentally friendly production, Priarone and Ingarao (2017) reported that Additive Manufacturing provides important advantages in terms of energy consumption and CO_2 emissions.

Gebler et al. (2014) reported in their study that Additive Manufacturing technology reduces production costs by using fewer resources and has positive effects on CO_2 emissions. Jackson et al. (2018) conducted another study to calculate the energy used by Additive Manufacturing technology in metal production, processing, and deposition steps and concluded that Additive Manufacturing has very little energy consumption. Faludi et al. (2015) reported that Additive Manufacturing is a more environmentally friendly technology with its low energy use, low waste levels, and high regeneration characteristics in their study that was conducted to compare the environmental effects of Additive Manufacturing and traditional manufacturing. Tang et al. (2016) investigated the environmental effects of Additive Manufacturing and concluded that this technology has important contributions to sustainability in terms of material-energy consumption and sustainable design. Kováčová et al. (2020) reported in their study that 3D printing technology saves resources and has high recycling power. Yang et al. (2017) concluded in their study that Additive Manufacturing has strong sustainable characteristics. Also, Ullah et al. (2013) found that the Additive Manufacturing process consumes less energy and produces less CO_2. Kafara et al. (2017) concluded that Additive Manufacturing increases the efficiency of the production process minimizing the negative environmental effects of carbon fiber-reinforced polymer production. Ford and Despeisse (2016) conducted a study to measure the adoption levels of Additive Manufacturing in industries and concluded that this technology has benefits in terms of sustainable production.

2.1. The motivation of the study

As a result of an extensive literature review, it was found that Additive Manufacturing technology provides very important advantages both for enterprises, the environment, and society. Decreasing resources, increasing waste, and environmental problems have become huge problems in our present day and have increased the need for new strategies to be created in this respect. Right at this point, Additive Manufacturing technology, which contributes to the production efficiency of enterprises positively by ensuring resource efficiency, and also by minimizing the negative effects of production on the environment, comes to the forefront. Especially the effects of Additive Manufacturing on sustainable production were discussed in limited literature. Studies mostly addressed these two issues separately. Based on this point of view, the suggestion of Additive Manufacturing technology for sustainable production in the study has a great difference and importance. With the findings obtained as a result of the present study, Additive Manufacturing technology, which is an important product of today's technologies, will be suggested as an alternative for the strategies to be created at the point of ensuring sustainable production to the decision-makers.

Based on this point of view, the framework of the study was created as follows:

- What are the contributions of Additive Manufacturing technology to sustainable production?
- What are the causal relationships between these contributions?

3. Method

3.1. DEMATEL method

A method that was called "Decision Making Trial and Evaluation Laboratory (DEMATEL)" was developed at the Geneva Research Center Battelle Memorial Institute in the early 1970s. This method was originally developed to solve complex real-world problems by considering and analyzing various dimensions and factors involving many stakeholders (Duval et al., 1974; Maqbool et al., 2020).

As a kind of structural modeling method, the DEMATEL Method is used to analyze and uncover the cause-effect relations between the components of a system. The DEMATEL Method is applied to analyze the variables affecting a particular system and to use the knowledge of experts to better understand the interrelationships and interdependencies among factors. The method not only transforms the interdependencies of factors into cause-effect relations but also determines the critical components of a system with the help of effect relation diagrams (Gabus and Fontela, 1972; Chauhan et al., 2018).

To use the DEMATEL Method, the complex system must be defined first, and then the factors affecting the system (i.e. the criteria in the DEMATEL Method) must be determined. These criteria can be obtained by using literature review or expert opinions. Also, a measurement scale must be developed to express the relationships and the strong points of the relations between factors. A typical scale range for this purpose is 0 to 4, meaning "No effects," "Low effects," "Moderate effects," "High effects," and "Very high effects" (Maqbool et al., 2020; Tzeng et al., 2007).

It is recommended for researchers to perform the following steps to implement the DEMATEL Method (Tzeng et al., 2007; Sumrit and Anuntavoranich, 2013; Kumar and Dash, 2016; Guo et al., 2021);

- Step 1: Creating the direct relationship matrix (D):

$$D=\begin{bmatrix} d_{11} & d_{1j} & \cdots & d_{1s} \\ d_{i1} & d_{ij} & \cdots & d_{is} \\ \vdots & \vdots & \cdots & \vdots \\ d_{s1} & d_{sj} & \cdots & d_{ss} \end{bmatrix} \text{(i,j=1,2...,s)} \quad (1)$$

At this stage, a Direct Relationship Matrix is created based on expert opinions. Here, the factors are compared in pairs with an effect ranging between 0 and 4. K1, K2, and K3 represent decision-makers. The first stage is completed by taking the arithmetic averages of the answers given by all the decision-makers to form the Direct Relationship Matrix. 0 means no effect, and 4 shows a high effect level (Table 1).

Table 1: Pairwise comparison scale (Tzeng et al., 2007)

Numerical value	Definition
0	Ineffective
1	Low impact
2	Moderate impact
3	High impact
4	Very high impact

- Step 2: Normalization of the decision matrix:

$$n = \frac{1}{maks \sum_{j=1}^{s} dij}, \text{ (i, j=1,2,.. s)}$$

$$\widetilde{D} = n(.)D \quad (2)$$

At this stage, the direct relation matrix shown with D is normalized, and the normalized direct relation matrix shown with $\widetilde{D}$ is created.

- Step 3: Creating the total relationship matrix:

$$T = \widetilde{D}(I - \widetilde{D})^{-1} \quad (3)$$

The Total Relationship Matrix represented with T is created in this step.

- Step 4: Creating the cause and effect matrix:

$$V= \left[\sum_{j=1}^{s} t_{ij}\right]_{sx1} \quad Y = \left[\sum_{j=1}^{s} t_{ij}\right]_{1xs} \quad \propto = \frac{\sum_{i=1}^{s}\sum_{j=1}^{s}[t_{ij}]}{s} \quad (4)$$

Calculating the alpha (threshold value) is performed at this stage where vector values are also found to draw the diagram, which also shows the interaction between the system elements. The X vector represents the sum of the lines in the total relationship matrix, and the Y vector represents the sum of the columns. The horizontal axis vector (V+Y), which shows how important the criteria are, is also calculated at this stage. Similarly, the vertical axis vector (V-Y) is calculated and determined according to the threshold value. If the effect of this vector is negative, it indicates that the criterion is included in the affecting group (cause), and if it is positive, it indicates that the criterion is included in the affected group (effect). This (X+Y, V-Y) is used in the creation of the Dataset Relationship Diagram (Uludağ and Doğan, 2021).

- Step 5: Obtaining the internal dependency matrix and the diagram showing the effect relationship:

$$V_i + Y_i, V_i - Y_i$$
$$C_i = \sqrt{((V_i + Y_i)^2 + (V_i - Y_i)^2)} \quad (5)$$

At this stage, the weight coefficients of the criteria, i.e. C_i values are calculated by using the relevant formula.

- Step 6: Determination of criterion weights:

$$w_i = \frac{Y_i}{\sum_{i=1}^{s} Y_i} \quad (6)$$

In the final step, criteria weights obtained by using the formula are normalized with the relevant formula. In this way, the weight of each factor, i.e. the w_i values are calculated.

4. Implementation

4.1. Study problem

It was reported in the previous sections of the study that Additive Manufacturing technology eliminates the negative effects of traditional production technologies on the environment and society, especially by minimizing the waste of resources and time, making it possible for businesses to be more productive and perform more. In today's world, where the sustainable production approach, which is considered to eliminate the negative impacts of production on future generations, has become important, efforts are underway on what steps to be taken right at this point.

Right at this point, it becomes an important problem of the study to make suggestions to contribute to the concept of sustainable production. The starting point of the study was the idea that a sustainable production approach could become widespread by integrating new production technologies offered by technology into production processes. In this respect, the purpose was to determine the contributions of Additive Manufacturing technology to sustainable production by conducting a wide literature review. However, it was also considered that determining the cause-effect relations and importance levels between these contributions could be an important guide, especially for decision-makers in their decisions on the subject.

4.2. Determining the contributions of additive manufacturing technology in terms of sustainable production

To determine the contributions of Additive Manufacturing technology to sustainable production, rank them according to importance levels, and determine the cause-effect relations between the determined contributions, a decision-making group of 6 people that consisted of 4 representatives from the textile, food, construction sectors, and 2 academicians working in the relevant field was formed. Ten criteria that were determined in line with the literature review and the opinions of the decision-making group were analyzed. The criteria are shown in Table 2.

Table 2: The criteria regarding the contribution of additive manufacturing technology to sustainable production

Criteria	Explanation	Sources
Innovative and sustainable design	Additive manufacturing enables more creative design with its technology requiring fewer resources with its rapid prototyping characteristics. Also, this technology supports best environmental practices.	Haleem and Javaid (2018); Savolainen and Collan (2020); Bogue (2013); Petrick and Simpson (2013); Paris et al. (2016); Wang et al. (2018); Holmström et al. (2017)
Meeting environmental targets	This technology allows businesses to achieve their environmental targets. With its low waste rate, it provides significant benefits in ensuring sustainability.	
Reducing excessive resource use	This technology, which does not require excessive use of resources, paves the way for greener production processes with its prototyping and design speed.	
Minimizing material wastes	Additive manufacturing reduces waste and eliminates material waste with its high recycling potential. It is considered that it will be used as the most effective technology in the future, especially in recycling.	
Less energy consumption	Additive Manufacturing technology uses very little energy when compared to traditional manufacturing. Especially at the point of providing energy efficiency, it is very important for sustainability.	
Material recycling	Recycling and reusing are among the important benefits of Additive manufacturing. This technology especially makes it possible to recycle and reuse plastic and metal powders.	
Producing environmentally friendly products	It is possible to produce environmentally friendly products with this technology, in which biodegradable organic resources are used. In this technology, the materials used contain minimum toxic waste and can be easily degraded in nature.	
Producing innovative products	Additive manufacturing brings great benefits in producing customized, innovative products that contain a large number of small parts. The fact that it needs less resource use has great importance in terms of sustainability.	
Enabling green production	This technology supports green production by eliminating waste and reducing energy and resource consumption. It also enables an environmentally sensitive production process with its low toxicity and emission.	
Developing sustainable solutions	Additive manufacturing develops with a sustainable solution with digital inputs. This technology offers sustainable design and prototyping by using smart materials.	

After the criteria to be used in the study were determined, a decision-maker group that consisted of 6 academicians and sector representatives was formed. At this step, the decision-makers were asked to score between 0 and 4 by comparing the criteria. The criteria used in the study were coded as follows; Innovative and sustainable design (C1), Meeting environmental targets (C2), Reducing excessive resource use (C3), Minimizing material waste (C4), Less energy consumption (C5), Material recycling (C6), Manufacturing of environmentally friendly products (C7), Manufacturing innovative products (C8), Enabling green production (C9), and Developing sustainable solutions (C10).

The findings on the DEMATEL Method are given below.

The normalization values in the second stage were found by taking the arithmetic average of the data or scores obtained in the light of the evaluations of the expert groups, and the Direct (Direct) Relationship Matrix given in Table 3 was obtained.

In line with the Normalized Direct Relationship Matrix, the normalized direct relationship matrix is extracted from the unit matrix (Table 4).

Table 3: Normalized direct relationship matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0.0000	0.0882	0.0882	0.0882	0.0882	0.0882	0.1176	0.0882	0.0882	0.0882
C2	0.0294	0.0000	0.0588	0.0294	0.0588	0.0294	0.0588	0.0294	0.0588	0.0294
C3	0.1176	0.1176	0.0000	0.0882	0.1176	0.1176	0.1176	0.0882	0.1176	0.1176
C4	0.0882	0.0882	0.1176	0.0000	0.0882	0.0882	0.0882	0.0882	0.1176	0.0882
C5	0.0882	0.1176	0.0882	0.1176	0.0000	0.0882	0.1176	0.0882	0.0882	0.0882
C6	0.0588	0.0588	0.0588	0.0882	0.0882	0.0000	0.0882	0.0882	0.0588	0.0588
C7	0.0588	0.0588	0.0882	0.0588	0.0588	0.0588	0.0000	0.0588	0.0588	0.0882
C8	0.0588	0.0294	0.0294	0.0294	0.0588	0.0588	0.0588	0.0000	0.0294	0.0294
C9	0.0588	0.0588	0.0588	0.0882	0.0588	0.0882	0.0588	0.0588	0.0000	0.0588
C10	0.0294	0.0294	0.0294	0.0294	0.0294	0.0588	0.0294	0.0588	0.0294	0.0000

Table 4: Subtraction of normalized direct relationship matrix from unit matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1.0000	-0.0882	-0.0882	-0.0882	-0.0882	-0.0882	-0.1176	-0.0882	-0.0882	-0.0882
C2	-0.0294	1.0000	-0.0588	-0.0294	-0.0588	-0.0294	-0.0588	-0.0294	-0.0588	-0.0294
C3	-0.1176	-0.1176	1.0000	-0.0882	-0.1176	-0.1176	-0.1176	-0.0882	-0.1176	-0.1176
C4	-0.0882	-0.0882	-0.1176	1.0000	-0.0882	-0.0882	-0.0882	-0.0882	-0.1176	-0.0882
C5	-0.0882	-0.1176	-0.0882	-0.1176	1.0000	-0.0882	-0.1176	-0.0882	-0.0882	-0.0882
C6	-0.0588	-0.0588	-0.0588	-0.0882	-0.0882	1.0000	-0.0882	-0.0882	-0.0588	-0.0588
C7	-0.0588	-0.0588	-0.0882	-0.0588	-0.0588	-0.0588	1.0000	-0.0588	-0.0588	-0.0882
C8	-0.0588	-0.0294	-0.0294	-0.0294	-0.0588	-0.0588	-0.0588	1.0000	-0.0294	-0.0294
C9	-0.0588	-0.0588	-0.0588	-0.0882	-0.0588	-0.0882	-0.0588	-0.0588	1.0000	-0.0588
C10	-0.0294	-0.0294	-0.0294	-0.0294	-0.0294	-0.0588	-0.0294	-0.0588	-0.0294	1.0000

In the next step, the related formula was applied to create the total relationship matrix and the total relationship matrix represented by T was created in this step (Table 5).

Table 5: Total relationship matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0.0000	0.0205	0.0200	0.0200	0.0205	0.0211	0.0326	0.0205	0.0205	0.0206
C2	0.0029	0.0000	0.0076	0.0030	0.0077	0.0032	0.0083	0.0031	0.0078	0.0031
C3	0.0318	0.0337	0.0000	0.0225	0.0336	0.0346	0.0364	0.0231	0.0336	0.0338
C4	0.0200	0.0212	0.0304	0.0000	0.0212	0.0218	0.0229	0.0211	0.0312	0.0212
C5	0.0202	0.0315	0.0210	0.0306	0.0000	0.0219	0.0338	0.0213	0.0214	0.0214
C6	0.0099	0.0104	0.0102	0.0175	0.0179	0.0000	0.0193	0.0180	0.0104	0.0105
C7	0.0093	0.0098	0.0165	0.0095	0.0098	0.0101	0.0000	0.0098	0.0098	0.0171
C8	0.0073	0.0031	0.0030	0.0030	0.0077	0.0079	0.0083	0.0000	0.0030	0.0031
C9	0.0093	0.0099	0.0097	0.0167	0.0099	0.0175	0.0107	0.0099	0.0000	0.0099
C10	0.0025	0.0026	0.0025	0.0026	0.0026	0.0070	0.0029	0.0069	0.0026	0.0000

Alpha (Threshold Value) is the important criterion to be considered while examining the total relationship matrix data. Alpha (i.e. the Threshold Value) is calculated to avoid weak relations from being shown on the diagram The Threshold Value of this study was calculated as (α=0.0137) and is presented in Table 6.

Table 6: Determination of values according to alpha threshold value (α=0.0137)

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	0.0000	0.0205	0.0200	0.0200	0.0205	0.0211	0.0326	0.0205	0.0205	0.0206
C2	0.0029	0.0000	0.0076	0.0030	0.0077	0.0032	0.0083	0.0031	0.0078	0.0031
C3	0.0318	0.0337	0.0000	0.0225	0.0336	0.0346	0.0364	0.0231	0.0336	0.0338
C4	0.0200	0.0212	0.0304	0.0000	0.0212	0.0218	0.0229	0.0211	0.0312	0.0212
C5	0.0202	0.0315	0.0210	0.0306	0.0000	0.0219	0.0338	0.0213	0.0214	0.0214
C6	0.0099	0.0104	0.0102	0.0175	0.0179	0.0000	0.0193	0.0180	0.0104	0.0105
C7	0.0093	0.0098	0.0165	0.0095	0.0098	0.0101	0.0000	0.0098	0.0098	0.0171
C8	0.0073	0.0031	0.0030	0.0030	0.0077	0.0079	0.0083	0.0000	0.0030	0.0031
C9	0.0093	0.0099	0.0097	0.0167	0.0099	0.0175	0.0107	0.0099	0.0000	0.0099
C10	0.0025	0.0026	0.0025	0.0026	0.0026	0.0070	0.0029	0.0069	0.0026	0.0000

It is a feature of the DEMATEL method that data below the (α=0.0137) threshold value is not taken into consideration, and values above this value are taken into account while evaluating the factor groups. In light of this information, Table 7 shows the effect of the factors between each.

Table 7: Impact status and factor weights of factors

Factors	V Vector	Y Vector	V+Y Vector	V-Y Vector	Effect Type	w	W	W %
C1	0.1961	0.1131	0.3093	0.0830	Affecting	0.320227	0.1025	10.20%
C2	0.0467	0.1131	0.1598	-0.0665	Affected	0.173063	0.0554	5.50%
C3	0.2830	0.1102	0.3932	0.1728	Affecting	0.429518	0.1374	14.00%
C4	0.2110	0.0784	0.2894	0.1326	Affecting	0.318372	0.1019	10.10%
C5	0.2231	0.0584	0.2815	0.1647	Affecting	0.326137	0.1043	10.40%
C6	0.1243	0.2344	0.3587	-0.1101	Affected	0.375187	0.1200	12.00%
C7	0.1016	0.2712	0.3728	-0.1695	Affected	0.409528	0.1310	13.00%
C8	0.0464	0.5449	0.5913	-0.4986	Affected	0.773412	0.2475	25.00%
C9	0.1035	0.7486	0.8521	-0.6452	Affected	1.068793	0.3420	34.20%
C10	0.0321	0.9624	0.9945	-0.9303	Affected	1.361806	0.4357	43.50%
					Total	3.125444	1	100.00%

According to the information given in Table 7, the main influencing factor was determined as "Reducing excessive resource use," which is the C3 coded factor that had a weight of 0.429. The second influential factor was the C5 code "Less energy consumption" factor that had a weight of 0.326, the third influential factor C1 had a weight of 0.320, the "Innovative and sustainable design" factor, and finally, the C4 coded "Material waste minimization" factor that had a weight of 0.318. Sorting according to the weights of these criteria was determined as C3>C5>C1>C4.

When the affected factors were evaluated, they are listed according to their weight values (w) from the most to the least as follows; C10 code "Developing sustainable solutions (w=1.361)," C9 code "Enabling green production (w=1.068)," C8 code "Producing innovative products (w=0.773)," C7 code "Producing environmentally friendly products (w=0.409)," C6 code "Material recycling (w=0.375)," C2 code "Meeting environmental targets (w=0.173)" factor (C10>C9>C8>C7>C6>C2).

In the process of determining the characteristics of the Additive Manufacturing technology, determining the influencing and affected factors, as well as evaluating the cause-effect relations of these factors help decision-makers. It is possible to summarize the analysis findings on the evaluation of the factors of Additive Manufacturing technology in terms of sustainable production by applying the DEMATEL Method with Fig. 1 and Fig. 2.

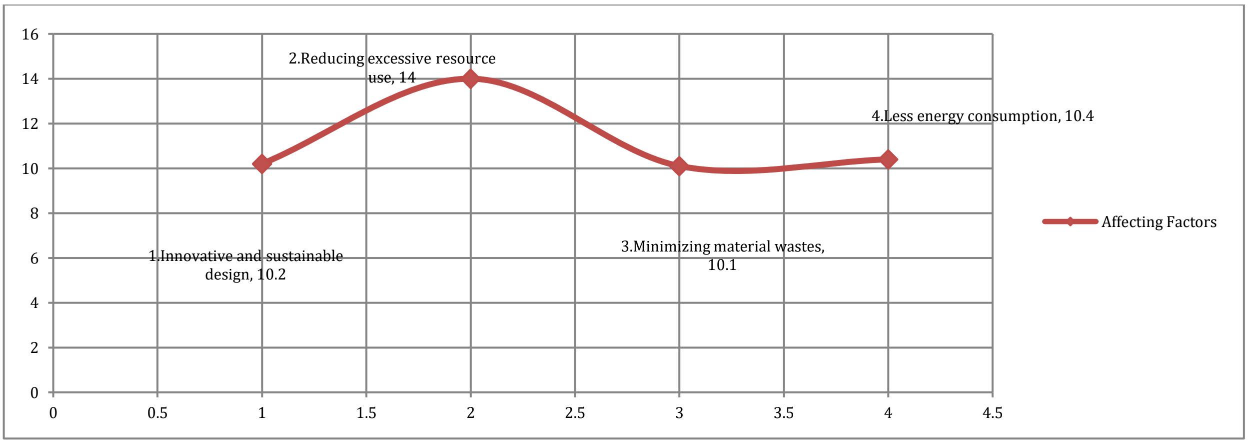

Fig. 1: Affecting factors

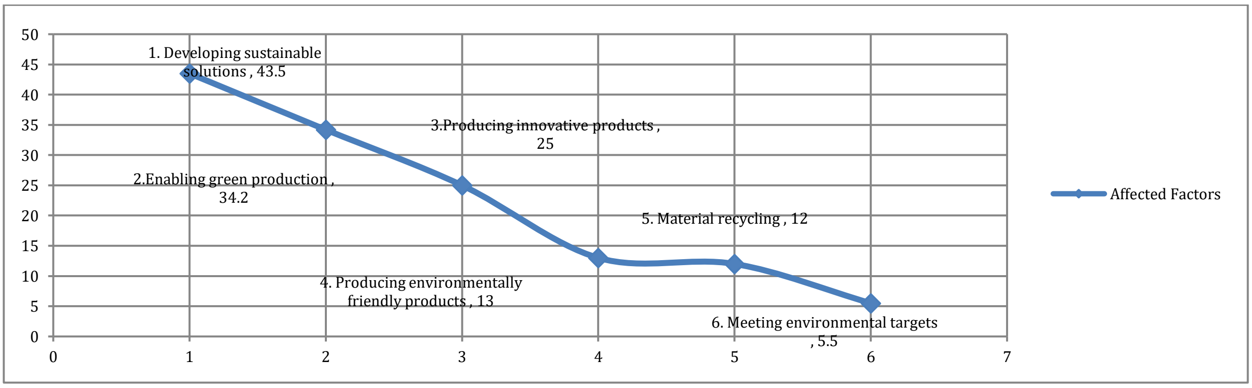

Fig. 2: Affected factors

5. Conclusion

In the present study, the characteristics of Additive Manufacturing technology in terms of sustainable production were evaluated with the DEMATEL Method. In this respect, the criteria that represent the contributions of Additive Manufacturing technology to the understanding of sustainable production were determined as a result of a wide literature review. These criteria were finalized after receiving expert opinions and 10 criteria were included in the analysis. This study aimed to analyze the criteria of Additive Manufacturing technology, which is considered to affect sustainable production, and to uncover the interrelations among these criteria. With the findings obtained in the study, the weight and effects of the Additive Manufacturing criteria on sustainable production were uncovered and a guiding basis was formed for the strategies to be developed on the subject.

In the scope of the present study, it is possible to argue that the criterion that had the highest effect on sustainable production was "Developing sustainable solutions." This was followed by "Meeting the environmental targets," "Enabling green production" and "Producing innovative products." Although "Minimizing material wastes" was the criterion that had the lowest effect on sustainable production, it was followed by "Innovative and sustainable design," "Less energy consumption," and "Material recycling."

As a result of the DEMATEL Method, C1, C3, C4, and C5 criteria for Additive Manufacturing have higher effects on other criteria, but they have higher priority. These criteria are included in the "affecting category." On the other hand, C2, C7, C6, C8, C9, and C10 were determined as the criteria that are included in the "affected category." These criteria are more affected than other criteria and have lower priority.

The findings obtained as a result of the present study show similarities with other studies in the literature. In this regard, den Boer et al. (2020) highlighted the importance of the benefits of Additive Manufacturing, especially low resource requirements and energy consumption, and reduced environmental effects. Also, Bogue (2013) reported that Additive Manufacturing technology is an environmentally friendly technology with its low energy need, efficient resource use, and low emission levels. Paris et al. (2016) reported that Additive Manufacturing is an important technology in terms of sustainability with its environmental design, high recycling rates, and low resource requirements. Ford and Despeisse (2016) qualitatively investigated the importance of additive manufacturing in terms of sustainability. The findings show that this new technology is important especially in product and process design, at the point of high efficiency, high waste utilization rate, and low resource requirement. Machado et al. (2019) qualitatively examined additive manufacturing from the perspective of sustainability and concluded that additive manufacturing technology provides performance increase, especially by providing energy savings and resource efficiency.

As a result of the present study, in which the importance of Additive Manufacturing technology in sustainable production was evaluated by using the determined criteria, businesses can develop more successful strategies and benefit from Additive Manufacturing technology efficiently by considering the Additive Manufacturing practices that have the highest and lowest effects on establishing sustainable production.

The study was limited to the analyzed results and expert opinions. The results may vary if the criteria and the number of experts are increased. It is recommended for further studies that the study should be handled with sub-criteria depending on the main criteria and different Multi-Criteria Decision Making Methods.

Compliance with ethical standards

Conflict of interest

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

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