Corrigendum: Development of ecosystem for effective supply chains in 3D printing industry – an ISM approach (2021 IOP Conf. Ser.: Mater Sci Eng. 1136 012049)

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Description of corrigendum:

Page 13:
In the Methodology section, Figure 5. Captioned as “ISM Digraph” appears as follows:

![ISM Digraph](image-url)
The above diagram should be as follows:

- Meeting Variable Customer Demands on a Sustainable Basis (F - 12)
- Agile marketing strategies for growth of sales (F-4)
- Sourcing of skilled talent (F-1)
- Association with the conventional industry (F - 2)
- Optimization of investment and costs (F-3)
- Development of Universal Standards (F-14)
- Compliance with Standards (F - 15)
- Building Resilient and Flexible Supply Chains (F - 13)
- Convincing clients about the optimum cost of 3DP items (F-5)
- Deploying adequate financial resources (F-10)
- Safeguarding patents & copyright (F-9)
- Suitable infrastructure for cyber security (F-7)
- Procuring Technological Resources (F-11)
- Interaction with academia for research and development (F-6)

Fig 5. ISM Digraph
Development of ecosystem for effective supply chains in 3D printing industry – an ISM approach

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Abstract. 3D printing (3DP) is an important technology to manufacture the objects of intricate designs that are otherwise not possible for traditional manufacturing. This technology has witnessed growth in research papers in the last decade that shows the increasing interest of researchers and users in this technology. Many researchers have predicted and written about the unimaginable new supply chain configurations after the large-scale adoption of 3D printing. A supply chain is a lifeline for any business because it drives the business by satisfying customers' demands economically. This study was undertaken to explore the factors that are critical for developing a supply chain ecosystem for the 3DP industry. The study used the literature of the relevant research papers, conference articles, additive manufacturing business reports, and supply chain management (SCM) research papers & articles on 3D printing technology. This study highlights factors that are critical for the supply chain ecosystem for the 3DP industry. Interpretive Structural Modelling (ISM) methodology identified interactive association among those factors. Impact Matrix Cross-Reference Multiplication Applied to a Classification (MICMAC analysis) has classified those factors into four categories for better understanding and strategy making. The stakeholders in the 3D printing industry can draw insights from the output of this study. Researchers can do further research on these factors for the benefit of sustainable supply chains in the 3DP industry.

Keywords: Supply Chain, Supply Chain Management, Additive Manufacturing, 3D Printing

1. Introduction

Materials scientists and engineers have given innovative materials and products to this world that find uses in all fields. 3D printing technology has come on the horizon with applications ranging from industry items to medical items used at all times- be it peace times or pandemic times [7], [8]. During the Covid-19 pandemic, the new items of masks, shields, and test kits were produced quickly by the 3D printing
industry to serve the humans across the Earth planet [28]. This disruptive technology is environmentally friendly and will go a long way to help society with an inclusive approach [10].

3D is a familiar abbreviation for three dimensions that signifies many things to different people. For the general public 3D means 3D movies watched in a theatre by wearing specs for special effects. Metallurgists and scientists use 3D numerical modeling for studies like microwave heating-based joining process [1]. In science and project management, practitioners use 3D mapping to profile the objects in three dimensions and map the same in the real-world for visualization and information gathering [27]. Engineers and innovators use 3D printing (3DP) for producing functional parts of intricate shapes directly from a digital file [2]. The third dimension accentuates the understanding of a phenomenon [26]. Thus 3D is used frequently in a general sense as well as technical sense.

Because of the great potential of 3D printing technology, this study tried to enumerate critical factors for the development of efficient SCM in the 3DP industry. The review of the literature of the 3DP industry and SCM has contributed to this study. Many factors are responsible for the successful integration of the 3D printing technology in the traditional manufacturing setup [3]. This study used the "Interpretive Structural Modelling (ISM)" methodology for analyzing the factors identified during the review of the literature [4].

Many researchers have predicted new supply chain configurations after the actual large scale adoption of 3D printing technology [5][7][3][10][11]. 3DP is complementing conventional manufacturing methods via designing and improving initiatives that offer new opportunities for the production of novel parts and equipment [2][5][7]. However, some concrete thought process is needed to utilize the full potential of 3DP technology and hence this study is undertaken.

Remaining paper proceeds like this: Section-2 covers the review of literature, Section-3 discusses the methodology to identify the factors and their interactive association, Section-4 covers the discussion of the study, Section-5 speaks about the implications of this study with recommendations for future research programs, and Section 6 deals with conclusions of the study.

2. Review of Literature

2.1. The versatility of 3DP technologies

3DP constitutes several technologies and production techniquesto manufacture solid objects layer by layer from a digital model [2][4]. 3DP is used interchangeably for additive manufacturing(AM) that manufactures three-dimensional solid objects from digital files layer by layer [2][5][6]. 3DP is also termed as "Direct Digital Manufacturing" and "Rapid Manufacturing" [5]. Unlike conventional processes, lubrication is not required in these production processes to cool the tooling parts. The objects manufactured by 3DP are fully workable parts of complex nature [2]. 3DP can manufacture customized objects of high complexity in low quantity at comparatively lower costs than the conventional manufacturing process because the additive manufacturing process does not require special tooling for manufacturing a variety of products [12]. The various types of Additive Manufacturing methods are depicted in Fig. 1.
2.2. Stars of 3D printing technology

3DP has great potential to affect supply chains, market structure, sustainability, and production [5]. 3DP is very useful for manufacturing prototypes, unique models of complex shapes, and low volume production of complex parts [7]. Globally 3DP is responsible for about 36.5% of prototyping jobs [5]. 3DP can provide the complementary supply chains of products required in a low volume but with more complexity. These supply chains can manufacture a product at desired locations in remote areas because it does not require a big plant or factory set up [7][8]. Oropallo and Piegli[3] have mentioned in their paper that Open Source software drives the 3DP equipment without any charges to the software developer. The prices of 3D printing equipment have become less expensive as compared to previous decades [23]. These factors have contributed to the proliferation of the 3D printers. The unique characteristic of 3DP is its capability to manufacture functional objects with multiple materials with complexities within parts [3]. Demand for raw materials used in 3DP is moving up year on year as per Wohlers Report 2019 [23]. 3D printing can create lightweight products/parts for the aerospace, automotive, and medical fields [9].

2.3. Computer-aided tissue engineering through 3D printing

3D printing can manufacture patient-specific tissue/organ implants. Mathematical modeling designs the porous scaffolds of the tissue/organ for printing with a 3D printer. The porous scaffolds receive the
biological cells to transform them into fully functional bio-compatible organs/tissues after some time. The above process of producing biological tissues/organs using computer technology is known as computer-aided tissue engineering [13]. 3DP is also helping the medical field for manufacturing bio-compatible implants and prosthetics [8]. Fig. 2 shows a 3D printed prosthetic hand indicating the intricacy level of 3D printed parts. There are many challenges in the 3D printing industry as per Oropallo and Piegl[3].

\[\text{Figure 2. Prosthetic hand with flexible digits: 3D printed (courtesy: The Intel Free Press)}\]

2.4. 3D printing and work life balance

S. Agarwal and U. Lenka[14] have reported an increasing trend of women adopting the entrepreneurship route because they prefer work-life balance. Women want more flexibility in time to give balanced attention to their professional roles and family obligations. The women entrepreneurs control their business better with more peace of mind by being nearer to their family members. Women entrepreneurs contribute to nation-building by creating job opportunities through innovative products and services [14]. 3DP provides increased flexibility, reduced costs, faster reactions to demand, needs less energy consumption, and the ability to decentralize production [9]. The entrepreneurs can produce the parts/products at home also by using desktop 3D printers [8]. Thus, the supply chains using the 3D printing method of production could contribute significantly to the work-life balance for entrepreneurs (both women and men). Work-life balance improves the health as well as productivity of humans[14] [22].

\[\text{Figure 3. Work Life Balance [22]}\]
2.5. **3D printing and Entrepreneurship Development**

Entrepreneurship is a mechanism for social and economic advancement as it generates effective and long term solutions for unemployment, gender inequality, and wealth creation [14]. S.Agarwal et al. [15] have found that creative minds are critical for a nation because they generate productive jobs, produce innovative products & services, alleviate poverty, and improve GDP growth. Entrepreneurship relates to creativity and innovation very closely [16]. Advanced cutting-edge technologies like 3DP can support budding entrepreneurs in developing countries to produce innovative products for niche customers [8][17]. 3DP has the potential to create avenues for on-shoring in supply chains in which entrepreneurship can play a significant role[7][8][17]. S.Agarwal et al. [16] have advocated entrepreneurship education in academic institutes to generate entrepreneurial intentions so that entrepreneurship can evolve as an institution. 3DP as an industry might be benefited a lot from the entrepreneurship programs of institutes as it will generate a talent pool mentioned as the critical factor by S.Singh and V.Agrawal in their study [8].

2.6. **New maker movement caused by 3DP technology**

Waller and Fawcett [17] have mentioned in their paper about the emerging maker movement enabled by 3DP that would potentially impact the rapid supply chain evolution. This movement would also lead to a new kind of entrepreneurship. SCM will change due to this movement that helps the designers and innovators to become entrepreneurs[8][17]. This movement will create good opportunities for small designers and innovators to supply their unique hi-tech products globally.

2.7. **Contribution 3D printing to social manufacturing**

The emergence of crowdsourcing solutions on the internet has encouraged the formation and running of a dynamic manufacturing network of manufacturers and their customers to collaborate and co-produce the desired goods. This network is called "Social manufacturing"[18] that can localize the production of customized products in an agile manner with a customer-driven focus [18]. 3DP can come in handy for the social manufacturing sector[17].

2.8. **New supply chain configurations for 3D printing industry**

There is an increasing interest in reverse logistics involving the product recovery for recycling, remanufacturing, and re-use [19]. 3DP simplifies the manufacturing process by reducing steps or stages in production. The development of new materials with greater emphasis on recycling wastes generated in 3DP requires new supply chains. The distribution of tooling costs over many objects over the years is reduced in 3DP as these costs are far lower than in traditional manufacturing[5][12]. Traditional manufacturing is concentrated in geographical locations to achieve economies of scale that causes the long physical distance between the source of generation and the point of consumption. 3DP causes the reduction of this distance between production and consumption points. Thus 3DP improves the supply chain[5][12]. Sasson and Johnson [5] have postulated that 3D printing super-centres would emerge after the co-location of 3D printers with mass manufacturing machines. These 3D super-centres would cater to low volume, highly urgent, and highly customized requirements of customers. Sasson and Johnson [5]
have predicted that manufacturers/suppliers would probably invest in 3DP for manufacturing spare parts for their captive requirements of custom capital equipment. Fig. 4 shows the typical model of 3DP supply chain.

Figure 4. Supply chain – Traditional and AM model [17].

2.9. Impact of 3DP on International supply chain

As per C. Feldmann and A. Pumpe [12], in international supply chains, 3DP can reduce the companies' stress regarding compliance with "local content" and "country of origin" aspects. Hence, administrative costs and customs duties decrease significantly. Customs duties go down hugely by importing the digital data required for 3DP rather than importing the physical products. Moreover, the countries involved in a supply chain can evade the trade barriers to a great extent. These effects would materialize without having a big factory locally [12]. Additionally, conventional manufacturing can help the 3DP industry in their post-processing activities by having collaboration and joint ventures with 3DP firms [8].

2.10. Contribution of 3-D printing industry to sustainable social development

3DP is impacting the supply chains with respect to several dimensions [20]. The Brundtland Report can be referred for sustainable development [24]. SCM also has to look for the sustainability of businesses of small firms and individuals. Ahmad Beltagui et al. [10] reported in their study about the increasing social sustainability concern in SCM due to the prevalence of questionable practices by the market-leading firms that prohibit the market entry of small firms and individuals. 3DP can come to the rescue of these players through the route of Open Design and Distributed production that can enable social sustainability by overcoming many constraints by encouraging market entry and generating better demand that would change the dominant supply chain practices of market leaders in the industry [10]. According to the Global Reporting Initiative, social sustainability requires suitable measures for ensuring good human rights practices, labour practices, a decent workplace atmosphere, and communication with the community [25]. 3DP allows more engagement with customers to produce more customized products. The digital nature of 3DP allows the small firms and innovators to share the resources and innovate more creatively and
efficiently. Customers can contribute through Open Design and Open Source software and also support the maker movement [10].

2.11. Futuristic Supply Chain Ecosystem of 3-D printing industry

3DP can help create futuristic supply chains characterized by agility, cost-effectiveness, sustainability, environment friendly with less waste generation and overall less energy consumption. 3DP cannot replace traditional supply chains in total but would complement the same in more productive ways [5][7][8]. Several factors: printer costs & technical capabilities, hinder the adoption of 3DP on a big scale[7][3][8]. Firms could avoid large capital investments in 3DP equipment by utilizing the range of services provided by 3DP players in the market to manufacture the desired products [7]. Manufacturing is perceived as a factory with many machines, supply & distribution of finished products, and large scale production. 3DP can change this perception in the long run because the tooling and processes are innovatively quite different [9]. A 3D printed part often requires post-processing activities like removal of supports, surface quality improvement, and tweaking of certain features [3]. 3DP service could collaborate with the conventional manufacturing firm for economical procurement of post-processing services to optimize the costs [8].

3. Methodology

3.1. Interpretive structural modelling (ISM) methodology

ISM identifies the directional cum contextual association among identified factors of a phenomenon by exploiting theoretical, conceptual, and computational leverages[4][21]. The output (digraph) provides useful insights to stakeholders to make well-informed decisions for course correction [21].

3.2. Identification of factors for ISM

Literature review and subsequent discussion with experts helped authors identify the following fifteen factors for establishing an effective eco-system of supply chains in the 3DP industry [7][8]:

1. Sourcing of skilled talent (F-1),
2. Association with conventional industry (F-2),
3. Optimization of investment and costs (F-3),
4. Agile marketing strategies for growth of sales (F-4),
5. Convincing clients about the optimum cost of 3DP items (F - 5),
6. Interaction with academia for research and development (F-6),
7. Suitable infrastructure for cybersecurity (F-7),
8. Extended network of 3DP entrepreneurs (F-8),
9. Safeguarding patents & copyright (F-9),
10. Deploying adequate financial resources for securing the supply of raw materials (F-10),
11. Procuring technological resources (F-11),
12. Meeting variable customer demands on a sustainable basis (F-12),
13. Building resilient and flexible supply chains to cater to increased demand (F-13),
14. Development of universal standards for 3D printing as a service (F-14),
15. Compliance with standards (F-15).
3.3. Structural self-interaction matrix (SSIM)

The following symbols indicate the focus of the factors (M and N) in the SSIM matrix [4]:
V: M will help obtain N
A: N will help obtain M
X: M and N will help obtain each other
O: M and N are not related

The authors developed the SSIM matrix shown in Table-1 after discussion with experts.

**Table 1:** SSIM of critical factors for 3DP supply chain

| Factors | F-15 | F-14 | F-13 | F-12 | F-11 | F-10 | F-9  | F-8  | F-7  | F-6  | F-5  | F-4  | F-3  | F-2  | F-1  |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| F-1     | V    | O    | A    | V    | O    | O    | V    | V    | V    | O    | V    | O    | O    | O    | O    |
| F-2     | X    | V    | X    | O    | A    | O    | O    | O    | O    | O    | O    | O    | O    | V    |     |
| F-3     | A    | A    | V    | V    | A    | A    | O    | A    | A    | O    | A    | A    | A    |     |     |
| F-4     | A    | O    | X    | V    | A    | A    | A    | A    | A    | A    | A    | A    |     |     |     |
| F-5     | O    | O    | X    | V    | A    | A    | A    | A    | A    | O    |     |     |     |     |     |
| F-6     | O    | X    | O    | O    | V    | O    | X    | O    | V    |     |     |     |     |     |     |
| F-7     | V    | O    | V    | O    | A    | O    | V    | V    |     |     |     |     |     |     |     |
| F-8     | O    | O    | V    | V    | A    | A    | O    |     |     |     |     |     |     |     |     |
| F-9     | O    | A    | V    | O    | O    |     |     |     |     |     |     |     |     |     |     |
| F-10    | V    | O    | X    | V    | O    |     |     |     |     |     |     |     |     |     |     |
| F-11    | V    | O    | V    | V    |     |     |     |     |     |     |     |     |     |     |     |
| F-12    | O    | O    | A    |     |     |     |     |     |     |     |     |     |     |     |     |
| F-13    | V    | A    |     |     |     |     |     |     |     |     |     |     |     |     |     |
| F-14    | V    |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
| F-15    |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
3.4. *Initial Reachability matrix (IRM)*

SSIM matrix is transformed into the IRM (Table-2) through substitution of V, A, X, and O symbols with 0 and 1 by following the below criteria:

- If (M, N) cell in the SSIM is V, then substitute (M, N) cell in the IRM as 1, and (N, M) as 0.
- If (M, N) cell in the SSIM is A, then substitute (M, N) cell in the IRM as 0, and (N, M) as 1.
- If (M, N) cell in the SSIM is X, then substitute (M, N) cell in the IRM as 1, and (N, M) as 1.
- If (M, N) cell in the SSIM is O, then substitute (M, N) cell in the IRM as 0, and (N, M) as 0.

**Table 2: IRM of factors**

| Factors | F -15 | F -14 | F -13 | F -12 | F -11 | F -10 | F -9  | F -8  | F -7  | F -6  | F -5  | F -4  | F -3  | F -2  | F -1  |
|---------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| F -1    | 1    | 0    | 0    | 1    | 0    | 0    | 1    | 0    | 1    | 1    | 1    | 1    | 1    | 1    | 0    | 1    |
| F -2    | 1    | 1    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 1    | 0    |     |
| F -3    | 0    | 0    | 1    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 0    | 1    |     |
| F -4    | 0    | 0    | 1    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 1    | 1    | 0    | 0    |     |
| F -5    | 0    | 0    | 1    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 1    | 0    | 0    | 0    |     |
| F -6    | 0    | 1    | 0    | 0    | 1    | 0    | 1    | 0    | 1    | 1    | 0    | 1    | 1    | 0    | 1    |     |
| F -7    | 1    | 0    | 1    | 0    | 0    | 0    | 1    | 1    | 1    | 0    | 1    | 1    | 1    | 0    | 0    |     |
| F -8    | 0    | 0    | 1    | 1    | 0    | 0    | 0    | 1    | 0    | 0    | 1    | 1    | 1    | 0    | 0    |     |
| F -9    | 0    | 0    | 1    | 1    | 0    | 0    | 1    | 0    | 0    | 1    | 1    | 1    | 0    | 0    | 0    |     |
| F -10   | 1    | 0    | 1    | 1    | 0    | 1    | 0    | 1    | 0    | 0    | 1    | 1    | 1    | 0    | 0    |     |
| F -11   | 1    | 0    | 1    | 1    | 1    | 0    | 0    | 1    | 1    | 0    | 1    | 1    | 1    | 1    | 0    |     |
| F -12   | 0    | 0    | 0    | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    |     |
| F -13   | 1    | 1    | 1    | 1    | 0    | 1    | 0    | 0    | 0    | 0    | 1    | 1    | 0    | 1    | 1    |     |
| F -14   | 1    | 1    | 0    | 0    | 0    | 0    | 1    | 0    | 0    | 1    | 0    | 0    | 1    | 0    | 0    |     |
| F -15   | 1    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 0    | 1    | 1    | 1    | 1    | 0    |     |
Table-3 shows the Final Reachability Matrix arrived at by applying the rule of transitivity on IRM.

| Factors | F - 15 | F - 14 | F - 13 | F - 12 | F - 11 | F - 10 | F - 9 | F - 8 | F - 7 | F - 6 | F - 5 | F - 4 | F - 3 | F - 2 | F - 1 | Driving Power |
|---------|--------|--------|--------|--------|--------|--------|-------|--------|--------|--------|--------|--------|--------|--------|--------|----------------|
| F - 1   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 14              |
| F - 2   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 12              |
| F - 3   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 13              |
| F - 4   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 6               |
| F - 5   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 10              |
| F - 6   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 14              |
| F - 7   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 14              |
| F - 8   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 11              |
| F - 9   |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 14              |
| F - 10  |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 12              |
| F - 11  |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 14              |
| F - 12  |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 1               |
| F - 13  |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 14              |
| F - 14  |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 13              |
| F - 15  |        |        |        |        |        |        |       |        |        |        |        |        |        |        |        | 9               |

| Dependence Power | 13 | 13 | 14 | 15 | 5 | 9 | 10 | 7 | 8 | 8 | 14 | 14 | 14 | 13 | 14 |

The level partitioning process of ISM methodology produced seven levels as shown in Table-4.
Table 4: Levels with corresponding factors

| Levels identified | Factors in levels |
|-------------------|-------------------|
| I                 | F-12              |
| II                | F-4, F-5, F-13    |
| III               | F-1, F-2, F-3, F-14, F-15 |
| IV                | F-8, F-9, F-10    |
| V                 | F-7               |
| VI                | F-11              |
| VII               | F-6               |

Note: Due to limitation of pages the detailed calculations are not presented here.

3.5. ISM Model- Digraph

Table-4 has provided inputs for making the ISM model known as Digraph (Fig. 5). The Digraph is made based on the level of factors. The Digraph receives Level I factor(s) on the top of the followed by level II factors, and so on [4]. The Digraph depicting the relationships among the factors can serve as an insightful tool for further study/research.
Figure 5. ISM Digraph

Meeting Variable Customer Demands on a Sustainable Basis

Building Resilient and Flexible Supply Chains

Sourcing of skilled talent (F-1)

Convincing clients about the optimum cost of 3DP items (F-5)

Building Resilient and Flexible Supply Chains

Suitable infrastructure for cybersecurity (F-7)

Compliance with Standards (F-15)

Optimization of investment and costs (F-3)

Agile marketing strategies for growth of sales (F-4)

Association with the conventional industry (F-2)

Development of Universal Standards (F-14)

Safeguarding patents & copyright (F-9)

Interaction with academia for research and development (F-6)

Extended network of 3DP entrepreneurs (F-8)

Deploying adequate financial resources

Procuring Technological Resources

Figure 5. ISM Digraph
3.6. MICMAC analysis

Impact Matrix Cross-Reference Multiplication Applied to a Classification (MICMAC) tool categorizes the factors into four distinct groups: Independent, Dependent, Autonomous, and Linkage, based on their dependence and driving power of a problem/phenomenon [4]. Dependent factors have less driving power with more dependency power and hence need appropriate treatment for sustainability. Fig. 5 shows that factor F - 12 (Meeting Variable Customer Demands on a Sustainable Basis) depends on all factors. Linkage factors need utmost management attention to avoid disturbance in the phenomenon or business because these have high driving & high dependence powers and can influence other factors more [4]. The Independent factors need good support from the management for better strategic decision making because these factors possess high driving power even though relatively less dependence power. As per Fig. 6, ‘Extended network of 3DP entrepreneurs’ and 'Procurement of Technological Resources' are Independent factors that need appropriate efforts by 3DP players to establish a strong network to leverage their resources and meet customers' demand promptly in case of a surge in demand. 3D printing companies need to procure suitable technology from a long-term perspective of the business [8]. The Autonomous factors do not require management support as these factors have weak driving & weak dependence powers and do not influence other factors.

![Figure 6. MICMAC Analysis of factors](image-url)
4. Discussion

Materials scientists and engineers are working on research projects of innovative materials and applications in various fields ranging from civilian uses to defense uses. There are continual attempts to produce light material products like shafts of carbon fiber material for running big fans of cooling towers in the power plants. The light products increase the energy efficiency of the equipment immediately. The increased energy efficiency enables payback of investment within four to five years in many cases. 3DP technology produces light products by reducing the number of parts of the final equipment compared to conventionally assembled products. 3DP is a fabulous technology to satisfy the varying requirements of the masses. Each individual has his/her aspirations for owing some unique materialistic possessions that can be cost-effectively met by 3DP. 3DP would help establish efficient supply chains to meet the complex requirements of global customers. 3DP firms share product designs over the internet to 3D printers situated in the vicinity of the customers. 3D printer prints the product and delivers the same to the customer. Thus 3DP would shorten the supply chains to a great extent. Designers and innovators using 3DP tools have the extreme power & flexibility to create and modify the designs without worrying about the complexity and related manufacturing costs, even when the object is under the manufacturing stage. 3DP enables the production of complex parts with less material and less energy consumption. The complexity and cost of manufacturing do not relate directly to each other in the 3DP scenario. In traditional manufacturing, the cost of the item goes up with the increase in complexity. 3DP is most suitable for single or small batch production of parts of very high complexity.

5. Implications, and future scope

Looking at the great potential of the 3DP industry, it is a must to know the critical factors and address the same suitably to benefit the supply chains of the 3DP industry. The identification of supply chain factors, their interactive relationships, and their classification into four categories are insightful output of this study. The supply chain practitioners/professionals can draw useful insights from this report and take suitable decisions for enriching their supply chains by sourcing and operating the 3DP tools, at least on small scale basis to begin with. The research scholars can use the Digraph and MICMAC graph to conduct further research to refine the existing knowledge about more influential factors. The industry professionals can pick up some take-aways from this report like the commitment & deployment of adequate financial resources in 3DP infrastructure, long-term agreements with 3DP raw material suppliers, and setting up the right information systems to protect their business interests. Researchers need to unearth some more unknown factors by conducting further research. Addressing those unknown factors might create a useful scenario for 3DP supply chains. It is recommended to conduct further research on this subject by using “Total Interpretive Structural Modelling” (TISM) and “Decision-making trial and evaluation laboratory” (DEMATEL) approaches.

6. Conclusions

3DP being a disruptive and futuristic manufacturing technology, it provided strong motivation to know the factors that can help it flourish exponentially. This study identified fifteen critical factors for developing the supply chain ecosystem for the 3DP industry. The ISM methodology produced the Digraph that shows that meeting the variable customer demands on a sustainable basis is the single most critical factor that depends on all other factors. Variability of production is thus the main driver of the 3DP industry. Three factors: Agile marketing strategies for growth of sales, convincing clients about the optimum cost of 3DP items, and building resilient & flexible supply chains, will help meet the variable customer demands on a sustainable basis. Sourcing of skilled talent, association with the conventional industry, optimization of investment & costs, development of universal standards, and compliance with standards are critical factors for building capability, capacity, and competency of the 3DP industry to serve global customers in a most
agile and competitive manner. The networking of 3DP firms, commitment to deploy adequate financial resources and system of safeguarding patents & copyright are vital factors for sustainable and resilient supply chain operations of the 3DP industry. A suitable cybersecurity infrastructure is a must to protect intangible assets like patents, designs, and copyrights. Procurement of technological resources requires strategic management decisions & management support for its realization. Interaction with academia for research and development is coming at the bottom of the digraph showing that a firm should always have an inquisitive mind to learn about new technologies and business scenarios to remain a competitive manufacturer or service provider. Knowledge is the basis for success.

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