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Application of Additive Manufacturing for Mass Customization: Understanding the Interaction of Critical Barriers

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Abstract

Additive Manufacturing (AM) technology presents a very optimistic case for its application for mass customization. Even though theoretically suitable, practically several critical barriers inhibit its implementation. Thus, this paper attempts to identify those barriers and also understand the dynamic interaction among them. The barriers were identified by a detailed literature review and validated by expert opinions. Interpretative Structural Modelling (ISM) was applied to determine the mutual influences among the barriers. It was also able to ascertain the level of the barriers and categorise them based on their driving power and dependence. The results are highly useful for industry practitioners to determine the interventions required to overcome the most dominant barriers.

Keywords: Additive manufacturing, mass customization, supply chain, barriers, interpretative structural modelling

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1. Introduction

The objective of this research is to understand the dynamic interaction of the critical barriers that inhibit the application of 3D printing/Additive Manufacturing (AM) for mass customization. AM technology offers the ability to rapidly customize products at multiple scales and locations closer to consumers and has a transformational effect on manufacturing organisations. The technology has considerable future potential when combined with other technological developments in design, data sharing, and materials research (Ford et al., 2016; Srai et al., 2016). A study by McKinsey & Company predicted that AM industry has a potential to create an overall economic impact of $ 250 billion by 2025 (Bromberger and Kelly, 2017). Therefore, manufacturing organisations need to understand the potential scope of AM applications, the maturity and current limitations of such technologies, and the impact of AM on firm competitiveness.

There are many benefits of AM, such as the ability to produce complex shapes, which are often impossible to create using traditional manufacturing methods (Cohen et al., 2015). It can convert raw materials directly into finished products and many AM devices are small and portable enough to fit on an office desktop. This has the potential to disrupt the traditional structure of supply chains and location of manufacturing (e.g. centralised production and global logistical arrangements). More importantly, AM printers have the ability to create any shape or product without the need for any machine set-ups, which allows for levels of manufacturing flexibility that is hard to achieve in mass production. Additionally, it can re-distribute production closer to customers and markets (Cohen et al., 2014). Thus, it presents tremendous potential to be used for mass customization. There exist several examples in literature and in practice where AM printers are used to produce customized products in aerospace, healthcare, and, apparel industry (Srinivasan and Bassan, 2012; Janssen et al., 2014; Yap and Yeong, 2014; Ford et al., 2016; Wagner and Walton, 2016). Despite the encouraging future prospects of AM printers, closer examination reveals that there are severe limitations of the technology that restrains its use for mass customization.

A detailed literature review was conducted to understand the barriers that constrain the use of AM printer for mass customization. Then experts were contacted to validate the findings from the literature. Interpretative Structural Modelling (ISM) model was applied to understand the dynamic interactions among the barriers. The results show the critical barriers and their mutual influence along with their level of influence. The analysis identified the most dominant barriers, which can assist both industry practice and research in terms of formulating future interventions or contingencies.

The key contribution of this paper includes

- Identification of critical barriers that inhibit the application of AM printers for mass customization

- Determining the relationships among identified critical barriers using ISM
- Identification of the hierarchy and most dominant barriers

The rest of the paper is organised as follows: Section 2 presents a systematic literature review highlighting the key barriers to adopting AM for mass customization. Section 3 presents the research methodology underpinning this research. Section 4 presents the step-wise application of ISM methodology. Section 5 presents the results and discussion. The paper is concluded in section 6 with a discussion about limitations and scope for future research.

2. Literature Review

This section presents a review of the literature addressing the limitations of AM printers to be used for mass customization. For this purpose, first, we review the characteristics of mass customization strategy and then we review the barriers that inhibit the use of AM printers for mass customization.

Organisations have used mass customization strategy to swiftly produce personalized products at a low cost to cater for differences in customer preferences (Pine, 1993; Gilmore and Pine, 1997). Mass customization can be applied to almost any type of product, and can be defined as the capability to offer high product variety for a large demand without any trade-off among the operational performance objectives (Da Silveira et al., 2001; Coronado et al., 2004; MacCarthy, 2004; Mikkola and Skjott-Larsen, 2004). Higher product variety may be achieved by a number of ways such as the change in design, functionality, and modularity. However, there is an absence of a universally accepted definition of what can be classified as mass customization. Researchers have proposed several frameworks to define mass customization based on the level of customization. Gilmore and Pine (1997) suggested four levels of mass customization namely collaborative, adaptive, cosmetic, and transparent. Lampel and Mintzberg (1996) proposed a continuum of five main stages of mass customization starting from pure standardization, where no product variances exist and ending at pure customization, where the customers' preferences are incorporated into the overall design process of the product. Spira (1993) proposed four levels of mass customization namely customized packaging, customized services, additional custom work, and modular assembly. Da Silveira et al. (2001) synthesized the earlier definitions and proposed a spectrum of eight levels of customization as follows:

1. Process **designed** according to customer needs
2. **Fabrication** of a tailored product based on a general prototyped design
3. **Assembling** modular components in different combinations to meet customer needs
4. **Additional custom work** done on a standardised product
5. **Additional services** for a standardised product
6. Different **package and distribution** of the same product

7. Products that can be adapted for different **usage** (post sale)
8. **No** product variances or customizations available

Production at high product variety and high volumes can have a major impact on supply chain complexity (Coronado et al., 2004). For instance, suppliers may not be prepared to align their own production to cater to the direct demand of mass customization (Mello, 2001). Moreover, mass customization strategy may result in increased inventory levels, higher production costs, and longer lead-times (Salvador et al., 2004). As a consequence, manufacturers need to re-align their organisation's structure to cater to the mass customization strategy. Researchers have proposed four key practices for mass customization from the supply chain perspective, namely: agility, customer involvement, postponement, and modularization (Da Silveira et al., 2001; Comstock et al., 2004; Coronado et al., 2004; Mikkola and Skjott-Larsen, 2004).

Agility is the capability of a company to adapt and prosper in a continuously changing environment driven by changing customer needs. It is the ability to always keep up with the latest trends in markets, technology, and overall business practices (Gunasekaran, 1999). Da Silveira et al. (2001) defined agility as internal (ability to respond to changing customer demands for new products and features) and external (network to collaborate and achieve high quality and customized products). External agility also refers to redistributed manufacturing where different organisations are interconnected through various information technologies and communication systems (Da Silveira et al., 2001). Customer involvement enables organisations to implement a mass customization strategy (Comstock et al., 2004; Coronado et al., 2004; Da Silveira et al., 2001). According to Comstock et al. (2004) mass customization requires the willingness and ability of customers to participate in the decision-making process for design, functionality, and, overall product characteristics.

Postponement refers to the practice of delaying certain supply chain activities until final customer orders are placed. Hence, customization occurs after the customer requirements have been collected (Mikkola and Skjott-Larsen, 2004). Postponement allows the firm to produce the product and accessories in bulk and yet customize them to meet the customer specification prior to the final delivery. Nevertheless, in order to achieve even higher levels of customization and more product variety, companies must combine the postponement principle with a modular product design (Salvador et al., 2004). Modularization is the practice of decomposing a complex process or product into several different modules. Separate modules can be managed and produced independently and are later grouped together in various combinations in order to perform different tasks. Hence, by designing products in a modular fashion, companies can postpone the final assembly and delivery after the customer order has been received with the specific product preferences. This will increase the company's ability to successfully follow a mass customization strategy up to the assembly generic level.

Production of small batches of products at a low cost can be facilitated by AM printers as there is no need for the creation of product specific tools and machine set up. This results in a cost effective single product production where each product can be customized to the customer's preferences (Janssen et al., 2014). Thus, AM printers facilitate internal agility. They also facilitate external agility as the product designed by using standardised Computer Aided Design (CAD) software enables redistributed manufacturing, easy collaboration, and, scaling of the production. The CAD software also enables customers to participate in the design process or even do it by themselves, as stated by Coronado et al. (2004). Companies can store product designs in digital form and use AM printers to print them only when there is a real demand. This process mimics the full postponement discussed by Pagh and Cooper (1998) yet, making it even more streamlined as no physical inventory is held. Moreover, AM printers facilitate creating products with modular design. Thus AM printers are highly suitable for mass customization strategy and a closer-to-customer distributed model of manufacturing.

In recent years, AM printers have experienced tremendous progress as a new technology that can print higher material variety, and produce objects at faster speeds and better quality. Unfortunately, AM printers still have many drawbacks, and some experts still believe the technology is years away from being used as a method for manufacturing of end-use products (Banker, 2015). Several researchers reviewed the literature addressing AM printers and presented the list of key barriers that are inhibiting its adoption. For example, Gao et al. (2015) presented a literature review of the current status and future directions for AM and discussed the barriers from an engineering application perspective. Roberson et al. (2013) presented a multi-criteria ranking model using build time, material usage, surface accuracy, and, post processing as criteria for selecting an AM printer. Petrick and Simpson (2013) studied current barriers that include printing speed, surface finish, use of multi-material, AM printing software, CAD packages, and, finished quality products. Weller et al. (2015) discussed the barriers for using AM printers, such as limited object size, lack of multi-material printing, poor surface finish, slow speed, skilled labour, high material costs, and, intellectual property rights. Rylands et al. (2015) conducted a literature review and highlighted that printing speed, object size, poor surface finish, product and process complexity, material costs, and, CAD design are the major barrier for AM printing. In addition to the generic barriers, researchers such as Cormier and Harrysson, (2002), Reeves et al. (2011), Deradjat and Minshall (2015), and Durach et al. (2017) also highlighted barriers that inhibit the use of AM printers for mass customization.

There are several factors that inhibit the application of AM printers for mass customization and otherwise. One of the major barriers is the size constraint due to which only relatively small dimension objects can be printed. Although there are custom made AM printers that can produce objects of larger size, the majority of technologies available are limited to parcel sized objects (Cornell, 2015; Rylands et al., 2015; Weller et al., 2015). This limits the application of

AM printers to small size products such as spare-parts. The slow speed of printing and limited range of materials also inhibits AM applications for mass customization (Deradjat and Minshall, 2015). The cost of AM printers and raw materials is a major barrier as the technology is still in its early development stages, and companies need to purchase several different types of printers to be able to produce any meaningful variety of products (Baghel, 2014). This cost significantly increases the initial investment needed to use the printers for mass customization successfully.

Banker (2015) points out that AM cannot produce objects with the same precision as current subtractive manufacturing technologies. Cornell (2015) also discusses the limited surface accuracy of objects outlining that many AM printers can only produce with accuracy up to 0.2 millimetres. This results in additional cost for polishing and finishing the final product and thus acts as a barrier to produce customized end products. Banker (2015) also discusses problems with the structural rigidity of objects. It was found that depending on the AM printing technology and materials used, objects produced are weaker and less resistant to pressure and temperature than traditional manufacturing. The surface accuracy and structural rigidity of the printed objects have often been criticised (Petrick and Simpson, 2013; Roberson et al., 2013; Banker, 2015; Rylands et al., 2015; Weller et al., 2015). Hence, currently, the most widespread uses of AM printing are for rapid prototyping and design purposes (Smith, 2015) with limited use to produce customized end products.

In the case of customized products, the complexity of CAD software as well as the expertise of the designers (in some cases the customers) has become a major barrier. Due to the use of CAD, there is a major risk of copyright infringement, and concerns about intellectual property rights have been raised in the literature (Kurfess and Cass, 2014; Gao et al., 2015; Kietzmann et al., 2015; Weller et al., 2015).

Table 1 presents the barriers for adoption of AM printers for mass customization identified by various researchers as discussed in the literature. It is also possible that some of these may be barriers for broader general use of AM printers. There is only limited existing scholarly work highlighting key barriers for the application of AM for mass customization strategy in the context of a re-distributed manufacturing paradigm. There are also very few papers in high-ranked peer-reviewed journals that discuss AM printing. For example, there are less than ten papers in Production Planning & Control (PPC) and International Journal of Operations & Production Management (IJOPM) that address the adoption of AM. Such research is urgently needed to refresh the literature on mass customization, advancing our understanding of AM impact on distributed production technologies, economics, operations and supply chains (Piller et al., 2004; Salvador et al., 2004). Thus, we seek to advance understanding of the critical barriers that inhibit the use of AM printers for mass customization. There is also a need to determine the interactive effect of these barriers on themselves and other barriers. In the absence of prior research that discusses the key barriers to adoption of AM printers for mass customization, this research aims to identify the critical barriers and their mutual influences.

<<Include Table 1 about here>>

3. Research Methodology

In the case of an emerging high-end technology such as AM printers, there may be several factors affecting adoption for mass customization based on the experience and needs of specific organisations. There is an absence of a holistic view of the various factors, their mutual relationships, and the causal hierarchy that can explain this complex situation. Interpretive Structural Modelling (ISM) can help fill the void by applying a systematic and logical thinking approach to depict the system and to effectively communicate it to a wider audience. ISM is an established structured approach for identifying relationships among specific items, which define a problem or an issue. The usefulness of ISM is that it can be initiated without a priori understanding of the system structure (Malone, 1975; Watson, 1978). It requires fundamental understanding of the system components and a basic knowledge of the system structure to provide inclusiveness and clear understanding of the system. This is achieved by incorporating individual mental models that might be overlapping, conflicting, or even contradictory (Watson, 1978).

<<Include Figure 1 about here>>

In layman terms, the ISM approach can be described as solving a jigsaw puzzle. A stepwise application of ISM is presented in Figure 1 and will be discussed in detail in this section. The first step of the ISM approach is to identify the system components (pieces of the puzzle). The system components are identified in a number of ways. A literature review was adopted by all studies in the past for this purpose. In additional to literature reviews, authors also use expert opinions, focus group discussions, etc. to identify the system components. Based on literature survey it was found that generally a very small group of experts are considered for identification of the system components. In most of the cases, it is 5 to 6 experts, which can be from industry and academia. Details are presented in Table 2. At this stage, the expert opinion input is presented as EO1 in Figure 1.

<<Include Table 2 about here>>

The second important step of the methodology is to establish the contextual relationships such as causality, correlation, affects, and, sequence among the individual factors (Watson, 1978). This step is like identifying which two-pieces may fit together in a jigsaw puzzle. In the ISM approach, mostly a small group of experts gathered by focus group discussion methods is used to build the contextual relationships. This is represented as EO2 in Figure 1. Based on literature survey it was found that this is done by a small group of experts. Details of evidence for this step from the literature are presented in Table 3. There are very few authors such as Jharkharia and Shankar (2005); Agrawal et al. (2007); and Luthra et al. (2015) that conducted a questionnaire-based survey of the identified system components (factors). The respondents were potential users who might have some understanding of these components. For example, Jharkharia and Shankar (2005) surveyed the automobile, engineering, process, and FMCG industry in India for identifying the barriers for IT-enablement of supply chains. Agrawal et al. (2007) conducted a survey of OEMs and their suppliers to identify supply chain agility factors. The survey results are used to construct a correlation matrix that is used by experts to develop the contextual relationships. This can be seen as an additional step to ensure reliability where the opinion of wider industry participants is also taken into consideration. In terms of the jigsaw puzzle, it is like asking the bystanders' opinion while fitting the puzzle. The final judgement is still based on the experts' opinion who may or may not take external opinions into consideration. In the literature, it is found that even two experts (one from industry and one from academia) were able to develop the contextual relationships (Jharkharia and Shankar, 2005; Mathiyazhagan et al., 2013).

<<Include Table 3 about here>>

Based on the contextual relationships, the ISM approach is applied that includes the SSIM matrix development, reachability matrix development, and partitioning the matrix, and development of the ISM digraph, etc. These steps are based on numerical calculations and can also be done by a computer program so there is no need/ scope for expert opinions. Once the digraph is ready, it is checked for conceptual consistency. In terms of the jigsaw puzzle, it is like looking if the picture is accurate. As there may be cases where the pieces though fit together didn't make the right picture. At this step, the final digraph is shared with experts to check for conceptual consistency. As at this stage the experts are able to see the full picture, it is relatively easy for them to identify the error(s). The expert opinion at this stage is represented as EO3 in Figure 1. Most of the studies in the literature have made an implicit assumption about following this step while very few have explicitly stated and explain the step. In some cases, authors such as Panahifar et al. (2015) have also done an external validation for their ISM-model.

It is worth noting that the ISM approach is generally a group decision-making process to develop the system structure (Kannan et al., 2009; Attri, 2013). There are also computer programs that can assist individuals or small groups to develop the ISM digraph (Kannan et al., 2009). In addition to this, it is to be understood that the ISM approach provides a possible understanding of the system structure based on individual opinions, which is not a statistically validated method. Authors such as Jharkharia and Shankar (2005) have recommended a Structural Equation Modelling for developing a statistically validated model.

4. Application of ISM Methodology

This section discusses the steps followed for the application of the ISM methodology.

4.1. Barrier identification

We conducted a systematic literature review to identify the barriers that might hinder the application of 3D printers for mass customization. Based on the literature review, we were able to identify 12 potential barriers. Even though several studies used only a literature review as a method to identify the key components (Barriers/ Drivers), there are few studies that also considered expert opinion to validate the identified components. We selected 5 experts to review and validate our findings from the literature review from a pool of experts from academia and industry. The experts were asked if they had experience of the use of *3D printing for mass customization* and were only considered if they had the required experience. The experts were either the Founder/CEO or held senior executive positions and each had minimum 6 years of experience. The experts were provided with a list of identified barriers and were asked to review and state if they agree/ disagree with these being the barriers. The results obtained show that only 'Lack of multi-material printing' was unanimously not considered a barrier by the experts. Thus we dropped it from the list of barriers.

4.2. Contextual Relationships and Structural Self-Interaction Matrix (SSIM)

Generally, a small group of experts are used to develop contextual relationships among the components. The group size as small as two experts (one from industry and one from academia) was considered sufficient by the researchers to develop the contextual relationships (Jharkharia and Shankar, 2005; Mathiyazhagan et al., 2013). Few researchers such as Jharkharia and Shankar (2005); Agrawal et al. (2007); and Luthra et al. (2015) conducted an industry survey of the components (barriers/ drivers) using a Likert scale and provided the correlation matrix as an additional reference to assist the experts in developing the contextual relationships. Thus, we adopted a similar approach and conducted a questionnaire-based survey to assist the experts to develop the contextual relationships. This is with the clear understanding that this is an additional aid whereas development of contextual relationships is possible even without the survey results.

The questionnaire-based survey was conducted using a five-point Likert scale where the respondents were asked to indicate their level of agreement with the respective barriers for use of 3D printers for mass customization. Overall we collected 50 responses. The content validity of the survey was ensured by the systematic literature review and expert validation. Factor analysis was conducted to ensure construct validity of the questionnaire. Factor analysis being an exploratory method was used as an indicator whereas the researchers, having the understanding of the problem context made the ultimate decision (Field, 2013). Kim and Mueller (1978) have suggested that items, which factor loading less than 0.40, shall not be used. The results of the factor analysis showed that all the factors had a minimum loading of 0.45, which is acceptable as per the literature. We conducted a t-test and found that the responses from the first phase are not significantly different from the responses from the second phase.

The Cronbach's alpha was calculated to be 0.54, which is relatively low but is sufficient and acceptable for an exploratory study of this nature (Nunally, 1978; Peterson, 1994). These results ascertain the reliability and internal consistency of the questionnaire.

It is found from the literature that researchers that used questionnaires-based survey are mainly targeting well-established industries such as automotive or retail, which encompass several thousand organizations. On the other hand, the 3D printing industry is in a very nascent stage and no way comparable to another century old established industries. It should also be noted that ISM model development suits situations with limited availability of data. If we have access to large data sets, other analytical techniques such as Structural Equation Modelling or Partial Least Square modelling are arguably more appropriate to develop a model and test the relationships.

The survey was conducted in two phases where the questionnaire was modified in the second phase to collect specific details of the respondents to justify the quality of the response. In the second phase, the respondents were clearly asked if they had experience with the use of 3D printers for mass customization and were only considered if they replied yes. This time the survey was more targeted and the survey link was sent to select companies from a pool of company contacts gathered from 3D printing forums. We send the survey to 94 companies and have collected 18 additional usable responses. The respondents had the choice to share their details about their role, experience, etc. or to remain anonymous. Of the respondents who shared their details, 75% reported their title as Director, Managing Director or CEO, while 25% reported as Business or Product development manager. The average experience of this group was more than 12 years. Overall, 70% of the companies were operating in one particular country (Belgium, Bulgaria, Canada, Denmark, France, Italy, Netherlands, UK, and, USA) while the rest 30% had a wider presence either across Europe or Worldwide.

We conducted the Pearson's bivariate two-tailed correlation test using SPSS-20.0 software to examine the correlation among the barriers. The results obtained from the correlation test are presented in Table 4. As discussed these results were provided to the experts (1 from Industry and 1 from Academia) to assist them with the development of SSIM, which is a pair-wise comparison of the barriers, based on the identified components and the contextual relationships.

<<Include Table 4 about here>>

Individual barriers were compared to decide if there exists a relationship and if yes then defining causality, correlation, affects, and, sequence. Table 5 presents the SSIM. The following four symbols (Watson, 1978) have been used to define the kind of relationship between any two barriers (i and j).

V: Barrier i leads to barrier j;

A: Barrier j leads to barrier i;

X: Barriers i leads to barrier j and barrier j leads to barrier i (feedback)

O: Barriers i and j are not related

For example, barrier 1 is lead by barrier 2 (A), barrier 5 leads to barrier 4 (V), and barriers 3 and 6 are not related (O).

<<Include Table 5 about here>>

4.3. Reachability Matrix

An initial reachability matrix was built by converting the SSIM into a binary matrix, as presented in Table 6.

<<Include Table 6 about here>>

The following rules were applied to the SSIM matrix for conversion.

- (i, j) entry in the reachability matrix becomes 1 if (i, j) entry in the SSIM is either V or X.
- (i, j) entry in the reachability matrix becomes 0 if (i, j) entry in the SSIM is either A or O.
- (j, i) entry in the reachability matrix becomes 1 if (i, j) entry in the SSIM is either A or X.
- (j, i) entry in the reachability matrix becomes 0 if (i, j) entry in the SSIM is either V or O.

The initial reachability matrix is built based on these conversion rules. Next, we inspected the matrix for transitivity. It is an essential element of ISM methodology and is similar to reachability in graph theory (Malone, 1975). Transitivity essentially implies that if component i is related to j and j is related to k, then components i and k are essentially related (iRj & jRk => iRk) (Malone, 1975). The final reachability matrix is obtained by ensuring transitivity. The initial and final reachability matrixes were then checked by an independent researcher to ensure consistency. The final reachability matrix as presented in Table 7 is used to assess the driving power and dependence of each barrier. The total number of barriers including self that any barrier leads to represents its driving power. While the total number of barriers including self that will lead to any barrier represents dependence. The driving power and dependence are calculated by adding the rows and the columns of the final reachability matrix respectively. The reachability matrix is then partitioned into different levels based on the driving power and dependence of the barriers.

<<Include Table 7 about here>>

4.4. Level partitions

Level partitioning process establishes a hierarchy among the components (barriers). Either a top-down or a bottom-up process can be used for partition. The process requires identification of reachability set and antecedent set from the final reachability matrix (Warfield, 1974). All barriers including the barrier itself that it leads from the reachability set whereas all the barriers including self that leads to the barrier from the antecedent set. In other words, for any pair of barriers (i, j) if the row value is 1 it forms the reachability set, and if the column value is 1 it forms the antecedent set (Malone, 1975). Then the intersection set is derived that essentially is the intersection of reachability and antecedent set. In case if the reachability set is same as the intersection set for any barrier, that means it cannot be reached from any other remaining barriers (Malone, 1975) and are the top-level barriers in the hierarchy. These barriers are removed from the matrix, and the exercise is repeated to identify the barriers at the next level. The process is repeated until all the barriers partitioned into levels. The levels facilitate the development of the classification and ISM digraph. The summary of the level partitioning is presented in Tables 8.

<<Include Table 8 about here>>

4.5. Canonical Form of the Final Reachability matrix

Finally we developed the canonical form of the final reachability matrix by sorting the barriers according to their levels. The canonical form will be used to develop the ISM model. The details canonical form matrix is presented in Table 9.

<<Include Table 9 about here>>

4.6. Matriced' Impacts croises-multiplication appliqúe an classment (MICMAC) Analysis.

MICMAC (cross-impact matrix multiplication applied to classification) is based on the principles of matrices multiplication properties conducted to evaluate the driving power and dependence of the system components (Mathiyazhagan et al., 2013; Attri et al., 2013). Based on the respective driving power and dependence the barriers are plotted on an X-Y axis as presented in Figure 2.

<<Include Figure 2 about here>>

The components (barriers) are classified into four groups namely autonomous, dependent, linkage, and independent. The barriers with very low driving power and dependence are classified as autonomous barriers, as presented in Quadrant-I. This indicates that these barriers have an autonomous effect on the use of AM for mass customization. The barriers with low driving power but high dependence are classified as dependent barriers, presented in Quadrant-II. This indicates that several other barriers may lead to these barriers. The barriers with high driving power and high dependence are classified as linkage barriers, as presented in Quadrant-III. These barriers have a dynamic effect, and any intervention in these barriers will affect other barriers as well as a feedback effect on themselves. Finally, the barriers with high driving power but low dependence are classified as independent barriers, presented in Quadrant-IV.

4.7. Building the ISM-based model

Based on the level partitioning of the final reachability matrix, a hierarchical model is developed, where the barriers represent the nodes, and the relationship represents the links. This hierarchy is represented as a graphical model also called a directed graph or digraph. Then we removed the transitivity and replaced the nodes by written description of the barriers. The diagraph was then shared with the experts and validated that it is conceptually consistent (as presented EO3 in Figure 1). The digraph is then converted into the ISM model as presented in Figure 3.

<<Include Figure 3 about here >>

5. Results and Discussion

AM printers have presented tremendous future potential with predicted global economic impact from $ 100 billion to $250 billion (Bromberger and Kelly, 2017). One of the most attractive features of AM printing is its ability for mass customization. There are several industries that are directly benefitting due to the capability of AM printers for mass customization include dentistry, jewellery, art, etc. There are also large organizations such as Nike and Adidas that are using AM printers to make customised shoes (Glenday, 2017). The technology as such presents huge potential for its use in other industries as well for mass customization but the penetration is still very limited. There are a number of barriers such as cost, expert designers, consumer expectations that hinder its application. For example, consumers may expect AM printed products to compete against the standard products on costs and performance while only few might be willing to pay a premium for a customised product. On this basis, there is a need to analyse and overcome barriers to accelerate the pace of mass customization by AM printers. In this regard, we identified the barriers that constraint the adoption of AM printers for mass customization by literature review and then validated it by experts. The interaction among the barriers was analysed by ISM approach.

The analysis differentiated the barriers across different level based on their respective driving power and dependence. At the first level are the barriers that can be reached by other barriers but don't lead to other barriers. For example fear of ‘copyright infringement', which can be reached by other barriers such as ‘lack of expert designers'. This implies that in the case where the expert designers are available there will be less fear of copyright infringement. At the second level are the barriers related to ‘Slow speed of printing’ and ‘Raw material availability’, which may impact other barriers such as ‘Limited object size’ but may not have direct influence on other barriers. This implies that it will be difficult to customise large objects such as chairs due to the printing speed and lack of raw material. At the third leave are the barriers such as ‘Cost of AM printers' that have a direct influence on other barriers such as printing speed and raw material availability. Some of the high-cost industrial printers are much faster as compared to medium or small printers. At the fourth level are ‘Cost of materials’ and ‘Cost of supporting machinery’ which are essentially related to the variable cost of printing a customised item. At level five are ‘CAD software complexity’ and ‘Lack of expert designers’ which have direct/ indirect influence on all other barriers. For example, an expert designer can make a 3D design with minimum extra support that will need less effort for separation and polishing. Our findings contribute to a small number of emerging scholarly studies that examine the realities of AM for mass customization, with a focus on both ‘technical’ and so-called ‘soft’ barriers, the latter having received limited attention (Durach et al., 2017).

The MICMAC analysis was used to develop the driver power and dependence diagram that provided an understanding of the individual barrier and their relative interdependencies. The key results from this analysis are as follows: There is one autonomous barrier (Copyright infringement) as presented in Quadrant I. As discussed earlier, the autonomous barriers have low driving power and low dependence so they have minimum influence on the system. The barrier (Copyright infringement), even though have minimum influence on the other barriers and as such on the model, it has huge influence on the business. This is more so in developed nations where the copyright laws are very strict. In the present scenario, a number of small companies rely on open source 3D files to develop customised products. These companies need to be careful and take into consideration the impact of a potential violation of copyright.

There are four dependent barriers namely Limited object size, Slow speed of printing, Raw material availability, and, Poor structural rigidity as presented in Quadrant II. These barriers have very low driving power but very high dependence. These barriers are highly influenced by other barriers in the system. It will be difficult to eliminate these barriers directly as they are dependent on other barriers. For example, the printing speed can be increased by using a high-speed industrial printer. Similarly, structural rigidity may be increased by an optimal CAD design. There are four linkage barriers as presented in Quadrant III of Figure 2. These barriers can be categorized as cost related barriers and quality related barriers. These barriers have high driving power as well as high dependence, which essentially mean that these barriers will influence a lot of other barriers in the system and will be influenced by a lot of other barriers in the system. These barriers are very critical as they can have a major impact on the overall model. There are two barriers namely ‘CAD software complexity’ and ‘Lack of expert designers’ that are found to be the Independent barriers as presented in Figure 2 (Quadrant IV). These barriers have a very high driving power and very less dependence thus are very crucial for the overall system. Any improvement in these barriers can have a major implication for the overall system.

There are major managerial and policy implications of the results obtained from this analysis. It is found that lack of expert designer has a major impact on the overall system at it is at level 5 of the ISM model and is an independent barrier with very high driving power. It was also found that expert designers would have a direct impact on other barriers such as copyright infringement, printing speed, surface quality, and, cost of supporting machinery. This coupled with CAD software complexity make it very difficult to find and retain the right talent that can understand the art and science of 3D CAD models. Moreover, it is very costly to get 3D CAD model developed in high-income countries. Some of the potential solutions may be outsourcing the designing part to either to the customers or designers in low-income countries. On discussion with an expert, it was found that there are online web-portals to hire individual talent for designing 3D CAD models. It is also interesting that there are not many training courses available via colleges/ universities to train expert designers. Policymakers who wish to bring manufacturing closer to consumption need to examine interventions to enhance local talent for 3D CAD modelling. CAD software complexity is a major issue for the companies who want to mass-customise products using AM printers. One of the potential solutions may be 3D scanning applications that can quickly scan standard items that can be later mass customised. There are some existing apps such as Qlone that can scan 3D items, which can be used by the AM printers. It was also found from the analysis that cost related factors such as the fixed cost of buying an AM printer and supporting machinery or operating cost of material is a major barrier. There is a need to reduce this cost to encourage higher mass customization. There are some businesses that have addressed the concern for the high cost of AM printers. For example, an expert shared about a web portal 'Voodoo manufacturing' which can print 3D CAD models for other companies. There are several other such initiatives, which eliminate the fixed cost of owning an AM printer or supporting machinery. As discussed by other researchers, there are very high expectations of potential value propositions associated with mass customization applications for AM, and the ability to redistribute manufacturing closer to consumption. We argue this should be tempered by a critical analysis of real-world barriers and a robust analysis of emerging solutions over time that could emerge from both further R&D investment and collaboration in the market.

6. Conclusions

It is interesting to note that the literature addressing AM printers is still in its infancy and has yet to develop a comprehensive list of barriers faced by the industry. Further scholarly investigations of industry experiences and the evolution of AM technology for mass customization are needed. Although AM technology is well suited for the pursuit of a mass customizations strategy, this research identified critical barriers and their mutual influence affecting the industrial application. We applied ISM approach to analysing the barriers and their interrelationships. As a first step, a detailed literature review was conducted to identify the critical barriers that are hindering the application of AM printers for mass customization. The outcome of the literature review was shared with experts for validation. Based on the expert opinions, the list of barriers was finalised. A questionnaire-based survey was carried out to gain further understanding of the barriers from the industry. The survey results were used to develop a correlation matrix to aid the experts. In the second step, experts used their own knowledge aided by the correlation matrix to establish the contextual relationships among the identified barriers, which was used to develop the SSIM.

Next, the SSIM was used to develop the reachability matrix, which was partitioned to understand the mutual linkage among the barriers. Then a conical form of the matrix was generated to develop a diagraph. The diagraph was shared with the experts for validation and based on their advice the final ISM model was developed. The reachability matrix was also used to conduct the MICMAC analysis, based on which, the barriers were classified among four broad categories namely autonomous, independent, linkage, and dependent. This categorization facilitates the decision maker to explore effective interventions to overcome the barriers. The results obtained are highly useful for businesses seeking to invest or expand capabilities in AM technology and infrastructure for mass customization. Original equipment manufacturers of AM printing machines as well as operators will benefit from directing efforts on evaluating the impact of identified barriers and devote resources to overcoming obstacles. The results also provide directions to policymakers who are looking for opportunities to relocate manufacturing closer to the customer base. These results are also encouraging for researchers as it provides a broader understanding of the barriers and their mutual interactions, which will enable researchers to focus on the critical barriers.

6.1. Limitations and Scope for Future Research

This research should be considered a snapshot, providing a useful indication of the perceived industrial maturity of AM for mass customization. The ISM approach is best suited for the purpose of developing an initial model without prior knowledge. But it should be noted that an ISM model doesn't validate the proposed model. Thus, future studies may seek to test the relationship between specific barriers using statistical techniques such as Structural Equation Modelling or Partial Least Square modelling. Furthermore, research approaches may be directed towards validating the presented ISM model on a larger and more diverse data set. Researchers may also seek to conduct studies to investigate the major interventions required to address the identified barriers. Where sufficient data exists, we also support the notion that future studies should also start looking beyond the technology and business model to consider 'user' factors and perspectives.

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Appendix-I: Survey questions

Questions specific to barrier to using additive manufacturing for mass customization

1. In general we believe the lack of raw material availability is a major barrier to using additive manufacturing as a mass customization method
2. In general we believe the poor structural rigidity of printed objects is a major barrier to using additive manufacturing as a mass customization method
3. We believe fear of copyright infringement is a major barrier to using additive manufacturing as a mass customization method
4. We believe lack of expert to designers to develop 3D objects for printers is a major barrier to using additive manufacturing as a mass customization method
5. We believe the CAD software complexity is a major barrier to using additive manufacturing as a mass customization method
6. We believe the cost of AM printers is a major barrier to using additive manufacturing as a mass customization method
7. We believe the cost of materials is a major barrier to using additive manufacturing as a mass customization method
8. We believe the cost of supporting machinery is a major barrier to using additive manufacturing as a mass customization method
9. We believe the limited object size that can be printed is a major barrier to using additive manufacturing as a mass customization method
10. We believe the slow speed of printing is a major barrier to using additive manufacturing as a mass customization method
11. We believe the poor surface quality of the final printed objects is a major barrier to using additive manufacturing as a mass customization method

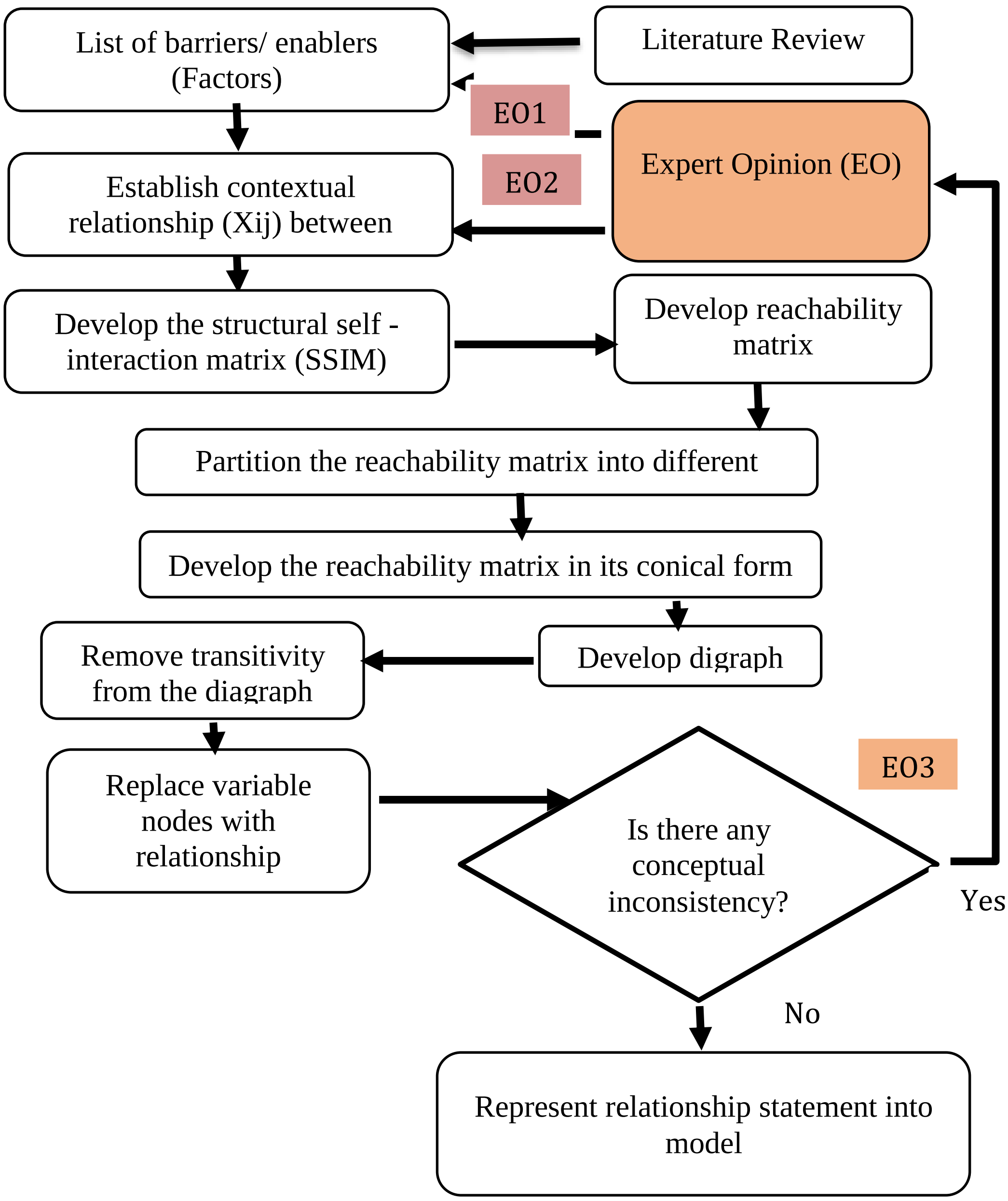

Figure 1: Stepwise application of ISM methodology

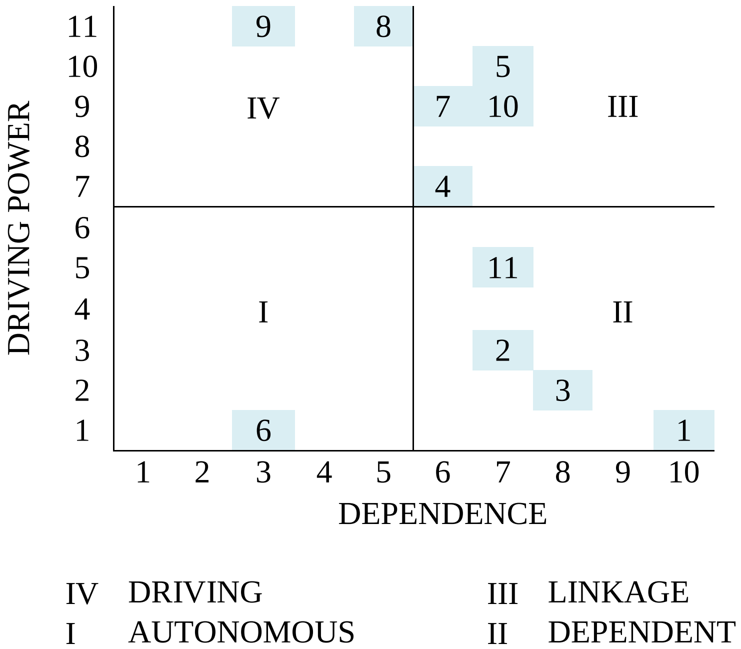

Figure 2: Driving Power and Dependence diagram

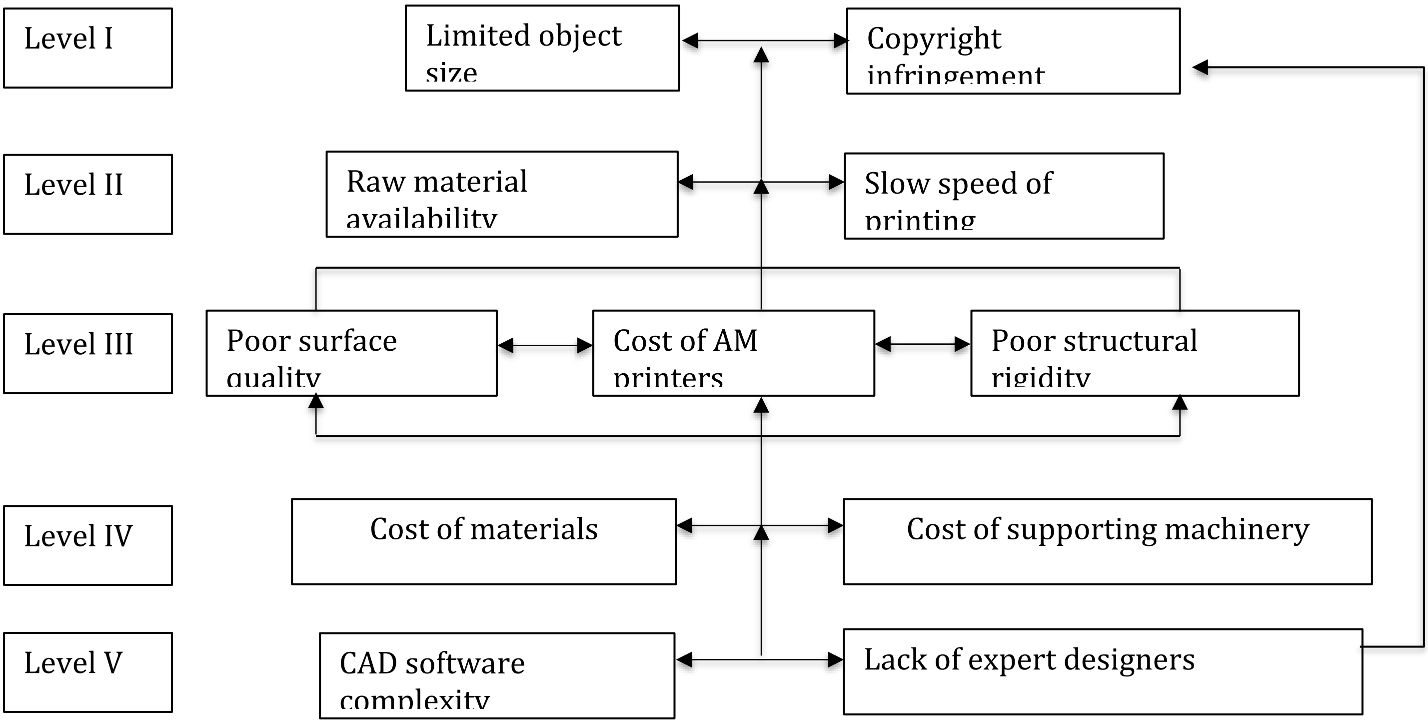

Figure 3: Final ISM based model for barriers

Table 1: List of barriers that hinder the application of AM printers for mass customization

Barriers	References
Limited object size	Cornell, 2015; Rylands et al., 2015; Weller et al., 2015
Slow speed of printing	Roberson et al., 2013; Petrick and Simpson, 2013; Weller et al., 2015; Rylands et al., 2015
Raw material availability	Petrick and Simpson, 2013; Weller et al., 2015; Rylands et al., 2015
Cost of materials	Rylands et al., 2015; Weller et al., 2015
Cost of AM printers	Baghel, 2014
Copyright infringement	Kurfess and Cass, 2014; Gao et al., 2015; Kietzmann et al., 2015; Weller et al., 2015
Cost of supporting machinery	Roberson et al., 2013
CAD software complexity	Petrick and Simpson, 2013; Rylands et al., 2015; Weller et al., 2015
Lack of expert designers	Weller et al., 2015
Lack of multi-material printing	Weller et al., 2015; Petrick and Simpson, 2013
Poor surface quality	Petrick and Simpson, 2013; Roberson et al., 2013; Banker, 2015; Cornell, 2015; Rylands et al., 2015; Weller et al., 2015
Poor structural rigidity	Banker (2015)

Table 2: Identification of system components: evidence from literature

Authors	Literature Review	Expert Opinion
Purohit et al., 2016	Yes	40 Experts (8 companies, 5 experts each)
Hughes et al., 2016	Yes	No Experts
Luthra et al., 2015	Yes	Expert Opinion
Cherrafi et al., 2017	Yes	5 industry experts and 3 academic scholars
Haleem et al., 2012	Yes	Team of experts from industry and academia
Gopal and Thakkar, 2016	Yes	3 Managers of the same organization
Panahifar et al., 2015	Yes	2 Expert group (6 members and 7 members)
Agarwal et al., 2007	Yes	5 Experts from the company and its trading partners
Mathiyazhagan et al., 2013	Yes	Industry experts
Kannan et al., 2009	Yes	5 Experts (3 from the industry and 2 from academia)

Table 3: Developing contextual relationships: evidence from literature

Authors	Option
Purohit et al., 2016	Expert opinion
Hughes et al., 2016	Expert opinion (9 participants)
Luthra et al., 2015	Expert opinion (industry and academics)
Cherrafi et al., 2017	Expert opinion (5 from Industry and 3 academics)
Haleem et al., 2012	Expert opinion (industry and academics)
Gopal and Thakkar, 2016	Expert opinion (3 managers from same company)
Panahifar et al., 2015	Expert opinion (7 participants)
Agarwal et al., 2007	Expert opinion
Mathiyazhagan et al., 2013	Expert opinion (1 from Industry and 1 from academics)
Kannan et al., 2009	Expert opinion (3 from Industry and 2 from Academics)
Jharkharia and Shankar, 2005	Expert opinion (1 from Industry and 1 from academics)

Table 4: Correlation Matrix

	Barriers	1	2	3	4	5	6	7	8	9	10	11
1	Limited object size	1.00	-0.02	0.27	0.42	0.29	0.19	0.29	0.00	-0.07	0.05	0.13
2	Slow speed of printing	-0.02	1.00	0.19	0.01	-0.06	0.16	0.19	0.12	0.05	-0.16	-0.11
3	Raw material availability	0.27	0.19	1.00	0.42	0.20	0.11	0.21	-0.19	-0.24	0.19	-0.10
4	Cost of materials	0.42	0.01	0.42	1.00	0.54	0.17	0.39	-0.28	-0.29	0.11	-0.07
5	Cost of AM printers	0.29	-0.06	0.20	0.54	1.00	0.28	0.58	-0.08	-0.28	-0.14	0.03
6	Copyright infringement	0.19	0.16	0.11	0.17	0.28	1.00	0.38	-0.03	-0.14	0.04	0.30
7	Cost of supporting machinery	0.29	0.19	0.21	0.39	0.58	0.38	1.00	-0.07	-0.25	-0.22	0.07
8	CAD software complexity	0.00	0.12	-0.19	-0.28	-0.08	-0.03	-0.07	1.00	0.20	-0.03	0.08
9	Lack of expert designers	-0.07	0.05	-0.24	-0.29	-0.28	-0.14	-0.25	0.20	1.00	-0.23	0.22
10	Poor surface quality	0.05	-0.16	0.19	0.11	-0.14	0.04	-0.22	-0.03	-0.23	1.00	0.18
11	Poor structural rigidity	0.13	-0.11	-0.10	-0.07	0.03	0.30	0.07	0.08	0.22	0.18	1.00

Table 5: Structural Self-Interaction Matrix

	Barriers	1	2	3	4	5	6	7	8	9	10	11
1	Limited object size	X	A	A	A	A	O	A	O	O	A	O
2	Slow speed of printing	V	X	V	O	A	O	O	A	A	A	O
3	Raw material availability	V	A	X	A	A	O	A	O	O	O	O
4	Cost of materials	V	O	V	X	A	O	X	O	O	O	V
5	Cost of AM printers	V	V	V	V	X	O	X	X	O	X	V
6	Copyright infringement	O	O	O	O	O	X	O	O	A	O	O
7	Cost of supporting machinery	V	O	V	X	X	O	X	A	A	V	V
8	CAD software complexity	O	V	O	O	X	O	V	X	X	V	V
9	Lack of expert designers	O	V	O	O	O	V	V	X	X	V	V
10	Poor surface quality	V	V	O	O	X	O	A	A	A	X	X
11	Poor structural rigidity	O	O	O	A	V	O	A	A	A	X	X

Table 6: Initial Reachability Matrix

	Barriers	1	2	3	4	5	6	7	8	9	10	11
1	Limited object size	1	0	0	0	0	0	0	0	0	0	0
2	Slow speed of printing	1	1	1	0	0	0	0	0	0	0	0
3	Raw material availability	1	0	1	0	0	0	0	0	0	0	0
4	Cost of materials	1	0	1	1	0	0	1	0	0	0	1
5	Cost of AM printers	1	1	1	1	1	0	1	1	0	1	1
6	Copyright infringement	0	0	0	0	0	1	0	0	0	0	0
7	Cost of supporting machinery	1	0	1	1	1	0	1	0	0	1	1
8	CAD software complexity	0	1	0	0	1	0	1	1	1	1	1
9	Lack of expert designers	0	1	0	0	0	1	1	1	1	1	1
10	Poor surface quality	1	1	0	0	1	0	0	0	0	1	1

11	Poor structural rigidity	0	0	0	0	0	0	0	0	0	1	1

Table 7: Final Reachability Matrix

	Barriers	1	2	3	4	5	6	7	8	9	10	11	Total
1	Limited object size	1	0	0	0	0	0	0	0	0	0	0	1
2	Slow speed of printing	1	1	1	0	0	0	0	0	0	0	0	3
3	Raw material availability	1	1	1	0	0	0	0	0	0	0	0	3
4	Cost of materials	1	0	1	1	1	0	1	0	0	1	1	7
5	Cost of AM printers	1	1	1	1	1	0	1	1	1	1	1	10
6	Copyright infringement	0	0	0	0	0	1	0	0	0	0	0	1
7	Cost of supporting machinery	1	1	1	1	1	0	1	1	0	1	1	9
8	CAD software complexity	1	1	1	1	1	1	1	1	1	1	1	11
9	Lack of expert designers	1	1	1	1	1	1	1	1	1	1	1	11
10	Poor surface quality	1	1	1	1	1	0	1	1	0	1	1	9
11	Poor structural rigidity	1	1	0	0	1	0	0	0	0	1	1	5
	Total	10	8	8	6	7	3	6	5	3	7	7	

Table 8: Partitioning of barriers, summary of iterations

	Barriers (i)	Reachability	Antecedent Set	Intersection	Level
1	Limited object size	1	1,2,3,4,5,7,8,9,10,11	1	I
6	Copyright infringement	6	6,8,9	6	I
2	Slow speed of printing	1,2,3	2,3,5,7,8,9,10,11	2,3	II
3	Raw material availability	1,2,3	2,3,4,5,7,8,9,10	2,3	II
5	Cost of AM printers	1,2,3,4,5,7,8,9,10,11	4,5,7,8,9,10,11	4,5,7,8,9,10,11	III
10	Poor surface quality	1,2,3,4,5,7,8,10,11	4,5,7,8,9,10,11	4,5,7,8,10,11	III
11	Poor structural rigidity	1,2,5,10,11	4,5,7,8,9,10,11	5,10,11	III
4	Cost of materials	1,3,4,5,7,10,11	4,5,7,8,9,10	4,5,7,10	IV
7	Cost of supporting machinery	1,2,3,4,5,7,8,10,11	4,5,7,8,9,10	4,5,7,8,10	IV
8	CAD software complexity	1,2,3,4,5,6,7,8,9,10,11	5,7,8,9,10	5,7,8,9,10	V
9	Lack of expert designers	1,2,3,4,5,6,7,8,9,10,11	5,8,9	5,8,9	V

Table 9: Conical form of the Final Reachability Matrix

	Barriers	1	6	2	3	5	10	11	4	7	8	9	Level
1	Limited object size	1	0	0	0	0	0	0	0	0	0	0	I
6	Copyright infringement	0	1	0	0	0	0	0	0	0	0	0	I
2	Slow speed of printing	1	0	1	1	0	0	0	0	0	0	0	II
3	Raw material availability	1	0	1	1	0	0	0	0	0	0	0	II
5	Cost of AM printers	1	0	1	1	1	1	1	1	1	1	1	III
10	Poor surface quality	1	0	1	1	1	1	1	1	1	1	0	III
11	Poor structural rigidity	1	0	1	0	1	1	1	0	0	0	0	III
4	Cost of materials	1	0	0	1	1	1	1	1	1	0	0	IV
7	Cost of supporting machinery	1	0	1	1	1	1	1	1	1	1	0	IV
8	CAD software complexity	1	1	1	1	1	1	1	1	1	1	1	V

9	Lack of expert designers	1	1	1	1	1	1	1	1	1	1	1	V