

Development of Framework for Feasibility Study of Fabrication of Spare Parts Using Fused Deposition Modeling: A Delphi Approach

Abhilasha Singh, Prabir Jana and Deepak Panghal

Abstract

Additive Manufacturing (AM) has paved its way into various fields like manufacturing, healthcare, aerospace, etc., due to the advantages it provides over traditional manufacturing. It has been an interest area for many researchers for years, and several studies have been conducted to analyze the feasibility of manufacturing products using additive manufacturing. However, there is a gap in the study for manufacturability analysis, particularly for Fused Deposition Modeling (FDM), a method under Additive Manufacturing (AM). FDM, or material extrusion, offers the least expensive and simple installation, setup, and training.

This article tries to fill the gap by identifying the attributes and parameters specifically concerned with FDM. The outcome of this research is a manufacturability assessment framework for FDM, which can be used to evaluate whether the object is suitable to be manufactured by the FDM process or traditional manufacturing. First, all the attributes are collected by secondary research. Thereafter, a Delphi study was conducted to find out the factors that are relevant to FDM. The panel comprised experts from various fields like industry, academia, and the research domain. The attributes identified in the Delphi study were subjected to exploratory factor analysis to find the interconnection among the attributes and identification of factors. Finally, a framework with various screening levels was developed with the help of factors and attributes identified in the previous step. The final structured framework has five levels of screening based on process, machine, and material feasibility (level 1), functional feasibility (level 2), design potential (level 3), business potential (level 4), and environment (level 5). A component needs to qualify for all the levels to receive a go-ahead decision for FDM.

The framework would be useful as a practical tool to assess the manufacturability of a part to be printed by FDM in the early-stage product development cycle. The garment

industry cannot afford to make a wrong decision and restart the process due to high variability and a very short fashion cycle. This framework would eliminate the risk of product failure, thereby saving money, time, and effort.

Keywords: Fused deposition modeling, Delphi method, exploratory factor analysis, manufacturability analysis, 3D printing, spare parts

Introduction

Additive Manufacturing (AM) has found its application in almost every field. To adopt and adapt to Industry 4.0, manufacturers seem very inclined towards switching to advanced manufacturing techniques like AM from the conventional techniques. AM offers several benefits over conventional techniques. The authors of the bestseller *Fabricated—Lipton and Kurman (2018)*—summarize AM into ten principles: 1) Manufacturing complexity is free, 2) Variety is free, 3) No assembly required, 4) Zero lead time, 5) Unlimited design space, 6) Zero skill manufacturing 7) Compact, portable manufacturing, 8) Less waste by-product, 9) Infinite shades of materials, and 10) Precise physical replication. These principles are the foundation of identifying AM potentials.

Prof. Ian Gibson, David Rosen, and Brent Stucker, noted authors in the field of AM, list several benefits of this technology, which is based on the WYSIWYB (What You See Is What You Build) approach and is similar to the WYSIWYG (What You See Is What You Get) approach used in 3D CAD. Also known by other popular names, such as direct digital manufacturing, rapid prototyping, and 3D printing, AM simplifies the multi-stage and multi-resource processes of the traditional method. (Gibson, Rosen and Stucker, 2015).

As with any other manufacturing technique, AM has certain limitations too. In some cases, the limitations can be overcome by changing the material or the design. In other cases, it seems more prudent to opt for conventional manufacturing techniques rather than AM. The latter scenario calls for a screening process or feasibility check for the part being considered for AM. Many researchers have proposed a process to identify the general potential for fabrication using AM. A detailed study is included in the literature review.

This research proposes a comprehensive screening process for spare parts for Fused Deposition Modeling (FDM). Proposed processes by ISO/ASTM (International Organization for Standardization/American Society for Testing and Materials) and other researchers have been studied. Thereafter, all the criteria have been listed down. Classification has been done according to the impact areas. The weights have been assigned with the help of experts using the Delphi method, and finally, a framework

for the FDM potential scorecard has been proposed. The proposed scorecard will assist the manufacturers in making swift decisions regarding the FDM manufacturing of the selected part.

Literature Review

Vaneker, et al. (2020) have divided the DfAM framework into three stages: AM suitability exploration, product (re)design for AM goals, and geometry optimization to enable the product realization chain. The AM suitability exploration stage helps the designer to evaluate and identify go/no-go decisions for AM, as it needs to be understood that not all the parts selected can be eligible candidates for AM. There might be some requirements of design, process parameters, and other changes before the part can be additively manufactured. In some cases, it may be cost-effective; in others, it may not. AM suitability exploration also facilitates the identification and resolution of manufacturability issues, as shown in Figure 1.

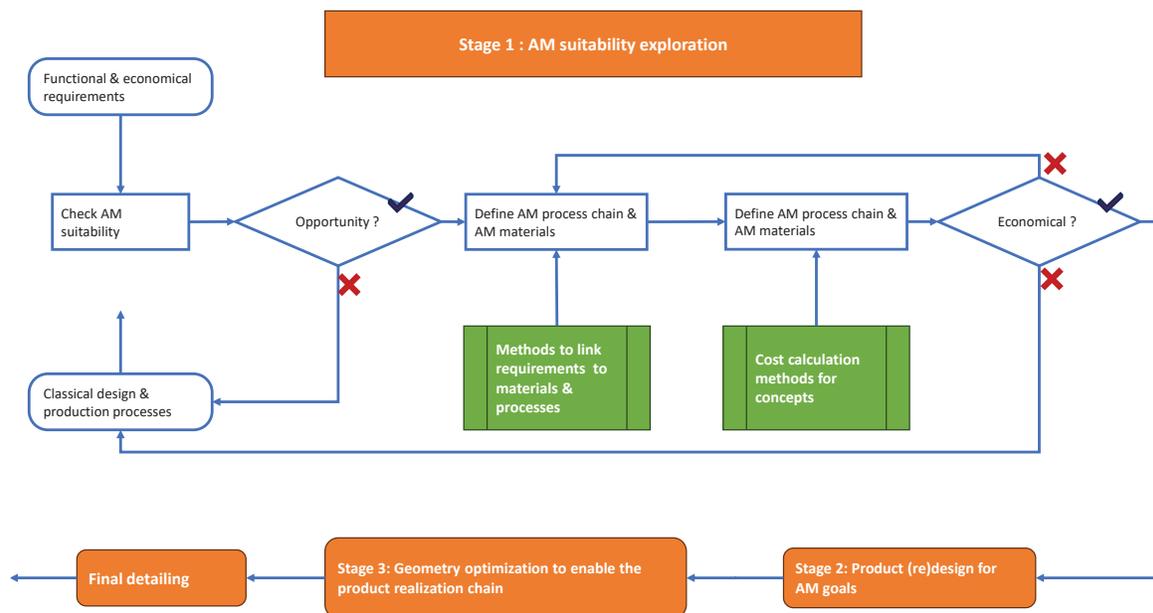


Figure 1: AM suitability exploration

Source: Vaneker et al., 2020

Hague, Mansour and Saleh (2003) have tried to highlight the advantages that AM has to offer. In the course of the project, they have emphasized design complexity, design freedom, material properties, and the changes to the design. Contrary to the previous definition of design complexity that included manufacturing cost, assembly cost, serviceability, etc., researchers have established that design complexity particularly

refers to the shape complexity, and shape is the combination of geometry and topology, as the previous definition does not stand correct in terms of rapid prototyping. Design freedom means that the design limitations are removed when it comes to AM as compared to conventional manufacturing. Finally, as part of the analysis of the material properties, flexural, tensile, and impact tests need to be performed.

Taking the benefits that AM has to offer as a base, Schneck et al. (2019) have identified the enablers and the objectives that they fulfil. Initially they identified 64 impact factors and then clustered the factors into four implementation levels, viz., product, process chain, life cycle, and company. Apart from clustering into different levels, the researchers also categorized the collected benefits into enablers and objectives. Enablers described the technical aspects of AM, while objectives referred to the benefits that would be gained by the application of AM to the business case. After merging the similar benefits, 11 enablers and 10 objectives were identified as in Table 1 and Figure 2.

Table 1: Enablers and objectives in four implementation levels

Enabler →	Objective (Improvement in...)
Product – 1st level	
E11- Individualization	011- Part performance
E12- Improvement of design/ aesthetics	012- Lifetime
E13 – Functional integration	013- Maintenance
E14 – Improvement of thermodynamic behavior	
E15 – Reduction of component mass	
E16 – Improvement of mechanical/ flow behavior	
Process Chain – 2nd level	
E21 – Simplified manufacturing process	021- Manufacturing
E22 – Production on demand	022- Lead time
Life Cycle – 3rd Level	
E31 – Faster product development	031 – Development
E32 – Decentralised production	032 – Logistics, installation & recycling
	033 – Sustainability & emissions
Company – 4th Level	
E41 – Development of new business models	041 - Image
	042 – Business case

Source: Schneck et al., 2019

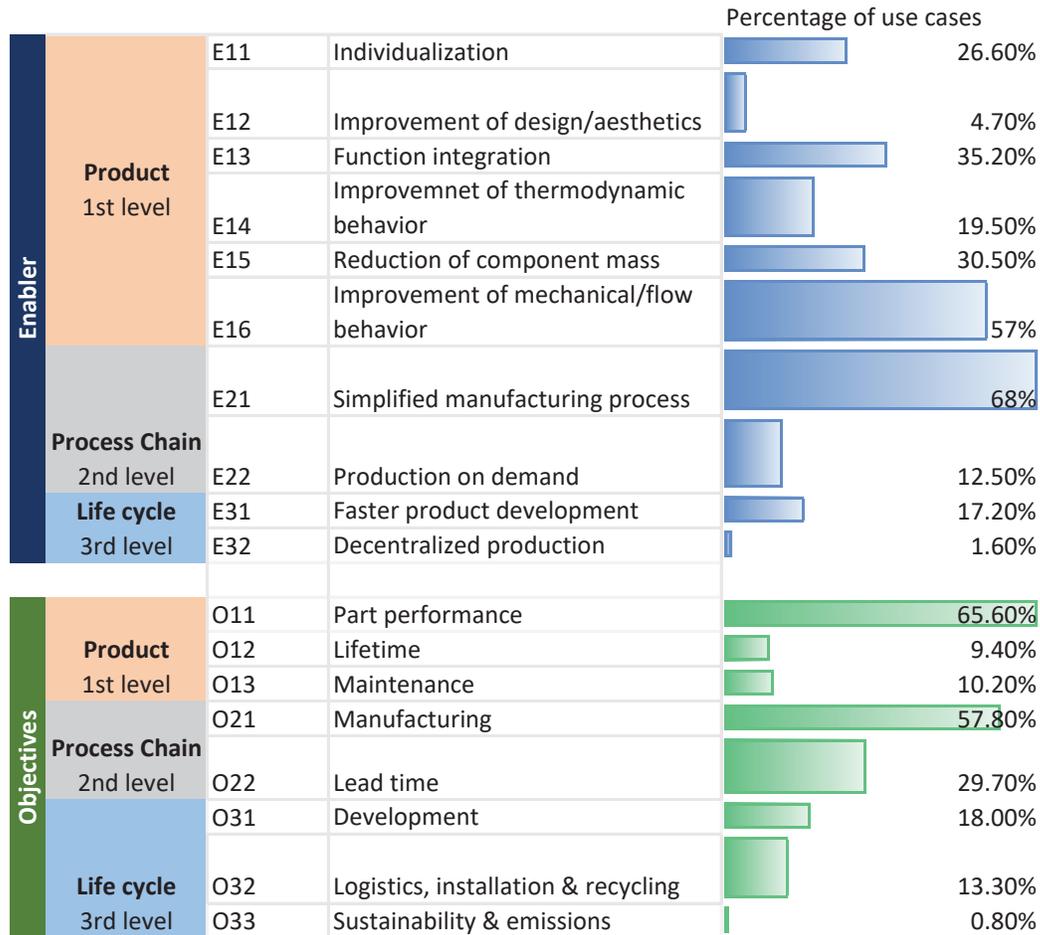


Figure 2: Use of enablers and objectives in industry application

Source: Schneck et al., 2019

Kumke, Watschke and Vietor (2016) have proposed a new classification of DfAM in their research based on the approaches—DfAM in the strict sense and DfAM in the broad sense. While DfAM in the strict sense includes the approaches concerning the product design, DfAM in the broad sense includes additional approaches apart from the core design. One of the components of DfAM in its strict sense is the utilization of AM potentials, which entails the elimination of manufacturing constraints to improve product performance, reduce manufacturing and material costs, and identify items or features that are difficult to manufacture using conventional methods. DfAM in the broad sense talks about the process selection, production strategy, manufacturability analysis, and selection of parts/applications based on strategic attributes like complexity, customization, and volume.

In the overall strategy for design for AM laid down by ISO/ASTM (2018), identification of general AM potential forms one of the crucial preliminary stages. Various aspects like material feasibility, build volume, improvement of functionality, and identification of potentials like customization, lightweight, internal structures, functional integration, designed surface structures, and specific material options are analyzed. As per ASTM, at least one item should display a high or medium potential to proceed with the decision to use AM. Lastly, other factors, like finances and business, are also considered for the final decision. Figure 3 shows a flowchart of the procedure for identifying AM potentials.

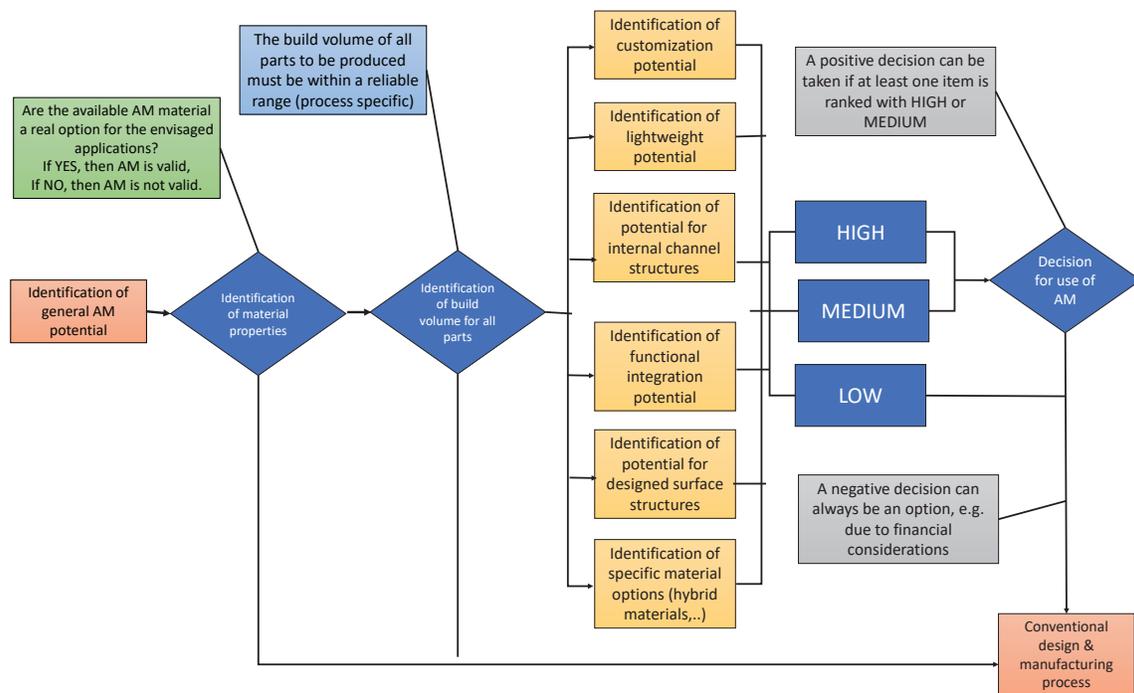


Figure 3: Procedure for identification of AM potential

Source: ISO/ASTM, 2018

Pradel et al. (2018) examine the AM potential and find out that the factors that are important are surface finish, dimensional accuracy, and consistency as compared to the conventional manufacturing process. Furthermore, some of the major concerns that are highlighted in the trade-off with light weightness are the product durability and how the product would respond when exposed to various environmental conditions like daylight, humidity, temperature fluctuations, etc. When choosing the AM process among the seven processes defined by ASTM, important parameters to consider are machine availability, precision, surface finish, build size, feature size, printing speed,

part strength, durability, post-processing, and cost of printing. Small batch size, along with complex geometry, is emphasized because AM provides an advantage over economies of scale; specifically, production costs remain the same regardless of batch size (Montero et al., 2020).

Thomas and Gilbert (2014) have conducted a detailed study on how AM can be cost-effective as compared to traditional manufacturing. They have categorized the benefits into three categories: ill-structured cost, well-structured cost, and product enhancement and quality. Ill-structured cost consists of inventory and transportation, the consumer's proximity to production, supply chain management, and vulnerability to supply disruption, while well-structured cost consists of material cost, machine cost, build envelope and envelope utilization, build time, energy consumption, and labour. In product enhancement and quality, limitations of AM, like support structure, heat dissipation, accuracy, surface finish, and feature details, are highlighted.

Development of the Framework for Objective Evaluation of FDM Potential

To fully leverage the advantages of a manufacturing process and avoid its pitfalls, one must objectively evaluate the potential for manufacturing the selected object using that process. This rule also applies to additive manufacturing before making a final decision. For objective evaluation, a framework was developed. The methodology adopted for developing the framework is presented in Figure 4.

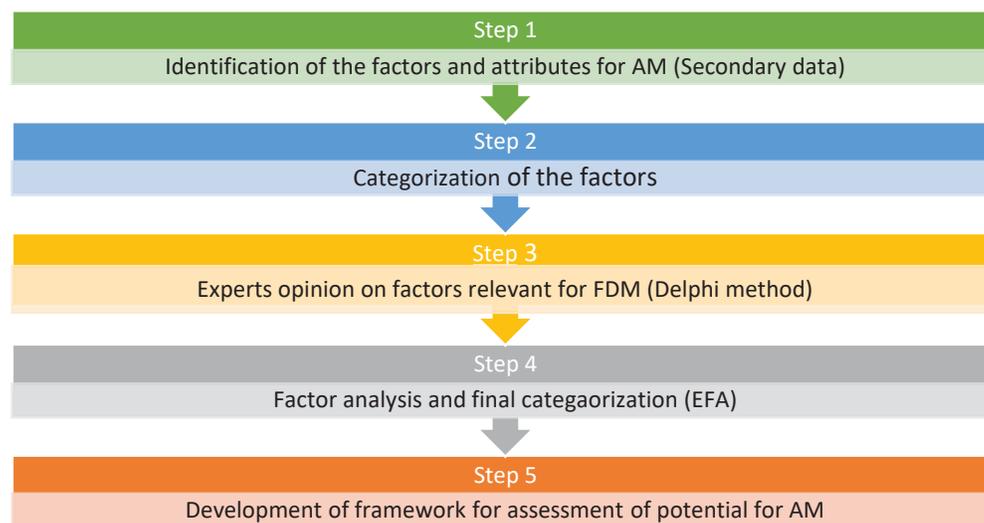


Figure 4: Methodology for framework development

Step 1: Identification of the factors and attributes for AM (Secondary data)

After a comprehensive review of the factors and parameters identified by various researchers for AM, a total of 80 factors were identified in phase one as listed in Table 2.

Table 2: Attributes identified through secondary data

S.No.	Factors	References
1.	Design complexity	(ISO/ASTM, 2018; Schneck et al., 2019; Vaneker et al., 2020)
2.	Design freedom	(ISO/ASTM, 2018; Vaneker, et al., 2020)
3.	Feature size	(Hague, Mansour and Saleh, 2003; Schneck, et al., 2019; Vaneker, et al., 2020)
4.	Object size	(Pradel, et al., 2018; Schneck, et al., 2019; Vaneker, et al., 2020)
5.	Build time	(FormLabs, 2021; Gibson, Rosen and Stucker, 2015; Hague, Mansour and Saleh, 2003)
6.	Build volume	(Gibson, Rosen and Stucker, 2015; Pradel, et al., 2018; Vaneker, et al., 2020)
7.	Machine availability	(Gibson, Rosen and Stucker, 2015; Kumke, Watschke and Vietor, 2016)
8.	Material availability	(ISO/ASTM, 2018; Kumke, Watschke and Vietor, 2016; Vaneker, et al., 2020)
9.	Multi-material	(ISO/ASTM, 2018)
10.	Heat dissipation	(ISO/ASTM, 2018)
11.	Flexural strength	(ISO/ASTM, 2018)
12.	Tensile strength	(ISO/ASTM, 2018)
13.	Impact strength	(ISO/ASTM, 2018)
14.	Lead time	(Kumke, Watschke and Vietor, 2016)
15.	Product life	(Kumke, Watschke and Vietor, 2016)
16.	Batch size	(Kumke, Watschke and Vietor, 2016)
17.	Supply chain management	(Hague, Mansour and Saleh, 2003)
18.	Vulnerability to supply chain	(Hague, Mansour and Saleh, 2003)
19.	Consolidation	(Hague, Mansour and Saleh, 2003)
20.	Accuracy	(Thomas and Gilbert, 2014)
21.	Precision	(Thomas and Gilbert, 2014)
22.	Conceptualization	(Hague, Mansour and Saleh, 2003)
23.	Shop floor complexity	(Rosen, 2014)
24.	Maintenance	(Thomas and Gilbert, 2014)

S.No.	Factors	References
25.	Design improvement/ aesthetics	(Thomas and Gilbert, 2014)
26.	Support structure	(Pradel, et al., 2018; Vaneker, et al., 2020)
27.	Post-processing	(Gibson, Rosen and Stucker, 2015; Hague, Mansour and Saleh, 2003)
28.	Assembly time	(Hague, Mansour and Saleh, 2003)
29.	Logistics	(Thomas and Gilbert, 2014)
30.	Inventory	(Thomas and Gilbert, 2014)
31.	New business model	(Thomas and Gilbert, 2014)
32.	Product size	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
33.	Inspection	(Pradel, et al., 2018)
34.	Communication	(Thomas and Gilbert, 2014)
35.	Decentralized production	(Thomas and Gilbert, 2014)
36.	Production on demand	(Thomas and Gilbert, 2014)
37.	Logo information	(Thomas and Gilbert, 2014)
38.	Company image	(Thomas and Gilbert, 2014)
39.	Feature details	(Thomas and Gilbert, 2014)
40.	Light weighting	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
41.	Translation	(Gibson, Rosen and Stucker, 2015; Pradel, et al., 2018)
42.	Customization	(Pradel, et al., 2018)
43.	Functional integration	(Pradel, et al., 2018)
44.	Functionality (end-use)	(Pradel, et al., 2018)
45.	Hardness	(Pradel, et al., 2018)
46.	Density	(Pradel, et al., 2018)
47.	Consumer proximity to production	(ISO/ASTM, 2018; Montero, et al., 2020; Vaneker, et al., 2020)
48.	Energy consumption	(Thomas and Gilbert, 2014)
49.	Recycling	(ISO/ASTM, 2018)
50.	Wastage	(ISO/ASTM, 2018)
51.	Emission	(ISO/ASTM, 2018)
52.	Sustainability	(ISO/ASTM, 2018)
53.	Biodegradable	(ISO/ASTM, 2018)
54.	Radiation exposure ionising	(ISO/ASTM, 2018)
55.	Installation cost	(Montero, et al., 2020)

S.No.	Factors	References
56.	Managerial and production/ manufacturing complexity	(Gibson, Rosen and Stucker, 2015)
57.	Process simplification	(Montero, et al., 2020)
58.	Design changes	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
59.	Internal structures	(Gibson, Rosen and Stucker, 2015; Thomas and Gilbert, 2014)
60.	Surface structures	(Pradel, et al., 2018; Vaneker, et al., 2020)
61.	Mathematical expression of the function	(Pradel, et al., 2018; Vaneker, et al., 2020)
62.	Geometry discretization	(Pradel, et al., 2018)
63.	Stiffness	(Pradel, et al., 2018; Vaneker, et al., 2020)
64.	Multi-part mechanism	(Thomas and Gilbert, 2014)
65.	Compliant mechanism	(Montero, et al., 2020)
66.	Operational temperature range	(ISO/ASTM, 2018)
67.	Exposure temperature range	(ISO/ASTM, 2018)
68.	Chemical exposure	(ISO/ASTM, 2018)
69.	Aging of material	(ISO/ASTM, 2018)
70.	Radiation exposure non-ionising	(ISO/ASTM, 2018)
71.	Biological exposure	(ISO/ASTM, 2018)
72.	Readily visible recycling symbol	(ISO/ASTM, 2018)
73.	Reusability	(ISO/ASTM, 2018)
74.	Water consumption	(ISO/ASTM, 2018)
75.	Water stream	(ISO/ASTM, 2018)
76.	Carbon footprint	(ISO/ASTM, 2018)
77.	AM fabrication cost	(ISO/ASTM, 2018)
78.	Total part fabrication cost	(ISO/ASTM, 2018)
79.	Upfront engineering cost	(ISO/ASTM, 2018)
80.	Special packaging and shipping requirements	(ISO/ASTM, 2018; Montero, et al., 2020)

Step 2: Categorization of the factors

Various researchers have tried to classify the factors as per the impact area. One of the categorizations worth mentioning is done by Matthias Schneck and his team, who have clustered the impact factors into four levels of implementation. The first level, known as product, encompasses all the factors that directly benefit AM at the product level. The second level is the process chain, and as the name suggests, this level addresses the benefits to the process chain of the product. The third level, called the life cycle, lists down the factors impacting the life cycle, including the supply chain. Finally, the fourth level, i.e., the company, emphasizes the factors that have influence on the organizational aspects, like the company image and business model (Schneck, et al., 2019).

The ISO/ASTM has laid down a framework for the overall potential analysis for AM, although a clear categorization is not given. The procedure for AM potential identification begins with the identification of material options followed by the identification of build volume. The next step involves identifying a range of potentials, including customization, lightweight design, internal structures or channels, functional integration, designed surface structures, and specific material options. These potentials are placed on the same hierarchy level, and the requirement for proceeding to the next stage is that any one of the mentioned factors would have high or medium potential. If the potential is low, the traditional approach can be considered. The final stage involves considering financial or other business goals before proceeding with AM for the selected object (ISO/ASTM, 2018).

Vaneker and his fellow researchers have developed a framework for AM suitability exploration, in which they have mentioned functional and economical requirements. These two broad categories are carried forward for the feasibility check. Functional requirements are verified by defining AM process chain and AM materials, while economical requirements are checked by conducting cost-benefit analysis by implementing various cost calculation methods (Vaneker et al., 2020).

The identified parameters were categorized into seven domains, viz., machine, material, process, function, design, business, and environment, for streamlining the analysis. These domains were identified by considering all the attempts taken by the researchers and the factors for identification of AM potential. The 80 factors identified in step 1 were clustered into different categories (Table 3).

Table 3: Categorization of attributes

Machine	Material	Process	Function	Design	Business	Environment
Availability	Multi-material	Support structure	All Intended functions	Design complexity	Lead time	Energy consumption
Build volume	Heat dissipation	Simplification of manufacturing	Some additional functions	Design freedom	Production time	Recycling
Envelop utilisation	Thermal conductivity	Process visualisation	Durability	Translation (Design changes)	Production volume	Emission
Product size	Flexural strength	Assembly time		Feature details	Supply chain management	Sustainability
Print time	Tensile strength	Shop floor complexity		Customisation	Vulnerability to supply chain	Material wastage
	Compressive strength	Post processing		Accuracy	Consumer proximity to production	Biodegradable
	SN curve	Surface finish		Precision	Inventory	Radiation
	Melting point	Printing speed		Consolidation	Transportation	Carbon footprint
	Impact strength	Installation		Feature size	Decentralized production	Water consumption
	Hardness	Maintenance		Aesthetic improvement	Batch size	Special packaging and shipping requirements
	Density	Consistency		Functional integration	Logistics	
	Thermodynamic behavior	Non-destructive testing		Decal/ Information	After sales service	
	Young's modulus	Curing/ Finishing			Company image	
	Poisson's ratio				Business case	
	Yield strength				New business model	
	Colour				Production on demand	
	Cost				Communication	
	Availability of material				Fabrication cost	
					Total cost	
					Upfront engineering cost	
5	17	13	3	12	20	10

Step 3: Experts opinion on factors relevant for FDM (Delphi method)

The categorization of the parameters done in step 2 is laid out by the researchers, keeping in mind the general process of AM. However, it is imperative that the weightage of some of the parameters change as per the change in the method of AM. For example, curing time is not relevant for material extrusion, while it is of utmost importance when the object is manufactured through Stereolithography (SLA). Similarly, SLA is known for high accuracy and resolution, and hence it is preferred over material extrusion when it comes to manufacturing small objects like jewellery, which requires high precision (FormLabs, 2021).

Since very little research has been conducted to study the feasibility of FDM considering these parameters, a Delphi study was conducted. A Delphi study is conducted to find a consensus among experts when exact knowledge is not available in the required field. The process can be divided into three stages: 1) Obtaining anonymous responses from the members of the expert panel by circulating a formal questionnaire, 2) Repeating step 1 until a consensus is reached, 3) Statistical analysis of the group response to remove biases (Dalkey, 1969).

As Chitu Okoli and his fellow researchers discussed, the Delphi method has proven its utility and established itself as a popular tool in research studies by obtaining the consensus of an expert group (Okoli and Pawlowski, 2004). To validate the steps of developing the framework for a potential check for FDM, various research papers on the Delphi method were studied in detail. The review paper by McMillan, King, and Tully (2016) explains the process of running the Delphi technique.

The Delphi method has been used by various researchers in different fields like government planning, business and industry, health, manufacturing, information systems, knowledge management, etc., for concept and framework development (Linstone and Turoff, 1975; Nambisan, Agarwal and Tanniru, 1999; Mulligan, 2002; Holsapple and Joshi, 2002; Kragelj, 2013; Bacon and Fitzgerald, 2001; Schmidt et al., 2001).

A questionnaire was developed to gather expert opinion for finding out the parameters relevant for FDM, or the material extrusion method. Section one contained questions pertaining to the general information of the experts, like designation, organization, and level of awareness of AM and its seven methods as per the ASTM F42 technical committee (ISO/ASTM 52900:2021(en), 2021).

The second part consisted of seven main questions with each factor and their respective parameters covering the entire 80 parameters, which were identified from the literature

review. The questions were designed on a Likert scale based on feasibility importance with the following ratings as shown in Table 4.

Table 4: Scale development

S.No.	Importance scale	Ratings
1	Not at all important	1
2	Somewhat important	2
3	Neutral	3
4	Very important	4
5	Extremely important	5

Sampling frame and adequacy of factor analysis

The expert panel comprised 15 experts with varied profiles, like academics, researchers, and industry professionals. The names are not disclosed due to confidentiality reasons; however, the profiles are mentioned in Table 5. The experts demonstrated adequate experience in the field of additive manufacturing, especially in fused deposition modeling. The experts belonged to different domains to ensure sufficient diversity and get suitable responses from across all the fields. The sampling technique in identifying the sample was purposive sampling, which is a non-probability technique where the participants are selected intentionally as per the relevance to the study.

For exploratory factor analysis, while larger sample sizes are preferred, some researchers like Hinkin (1995) and Costello (2005) have confirmed that in the case of higher communalities and stronger factor loading, small sample sizes are relevant too. In this research paper smaller sample sizes are justified as the factor loading values range from -0.854 to 0.960.

Table 5: Profiles of Delphi experts

S.No.	Designation	Organization	Experience	Profile
1.	Application Manager	Phillips	Expert	Industry
2.	Assistant Professor	Erode Sengunthar Engineering College	Proficient	Academics
3.	Regional Manager - Sales	Imaginarium Solutions (I) Pvt. Ltd.	Expert	Industry
4.	Research Scholar	NIT, Warangal	Proficient	Researcher
5.	Research Scholar	Vellore Institute of Technology	Proficient	Researcher

S.No.	Designation	Organization	Experience	Profile
6.	Assistant Professor	Bannari Amman Institute of Technology	Expert	Academics
7.	Assistant Professor	NIFT Patna	Expert	Academics
8.	Deputy Manager	Forza Medi (India) Pvt. Ltd.	Expert	Industry
9.	Professor	NIFT, Varanasi	Proficient	Academics
10.	6 Sigma Head	Indium	Expert	Industry
11.	Technology Manager	Vfuse Metal 4 Manufacturing Pvt. Ltd.	Proficient	Industry
12.	Assistant Professor	NIFT, Kolkata	Expert	Academics
13.	Technical Manager	WOL3D India Ltd.	Expert	Industry
14.	Technical Manager	WOL3D India Ltd.	Expert	Industry
15.	Research Scholar	Anna University	Proficient	Researcher

The responses were recorded and coded as per the attributes listed in Table 1. The mean for each parameter was calculated. Subsequently, the mean of all the means was calculated, which resulted in 3.864198. The responses with the mean rating less than the total mean, i.e., 3.864198, were dropped from subsequent steps (Table 6). Along with the mean ratings, the standard deviations were also calculated to understand the variation in the responses of the experts. Most of the retained parameters exhibited low standard deviation values, showing a strong consensus among panel members. For selected parameters, the SD values ranged from 0.3 to 0.6. Following analysis of the responses from the Delphi method (Table 7), 42 parameters were selected and taken forward for factor analysis.

Table 6: Selection of parameters based on Delphi response

S.No.	Factors	Parameters	Ratings	Selected/Dropped
1.	Design	Design complexity	4.4000	Selected
2.		Design freedom	4.2667	Selected
3.		Translation (Design changes)	4.3333	Selected
4.		Feature details	3.8000	Dropped
5.		Customisation	4.4000	Selected
6.		Accuracy	4.0667	Selected
7.		Precision	3.8667	Selected
8.		Consolidation	4.0667	Selected
9.		Feature size	3.8667	Selected

S.No.	Factors	Parameters	Ratings	Selected/ Dropped
10.		Aesthetic improvement	3.9333	Selected
11.		Functional integration	3.8667	Selected
12.		Decal/Information	3.7333	Dropped
13.	Machine	Availability	3.6667	Dropped
14.		Build volume	4.2000	Selected
15.		Envelop utilisation	3.5333	Dropped
16.		Product size	3.8667	Selected
17.		Print time	4.4667	Selected
18.	Process	Support structure	4.5333	Selected
19.		Simplification of manufacturing	4.1333	Selected
20.		Process visualisation	3.4667	Dropped
21.		Assembly time	3.4667	Dropped
22.		Shop floor complexity	3.3333	Dropped
23.		Post processing	4.0667	Selected
24.		Surface finish	4.7333	Selected
25.		Printing speed	4.5333	Selected
26.		Installation	3.6667	Dropped
27.		Maintenance	3.7333	Dropped
28.		Consistency	4.0667	Selected
29.		Non-destructive testing	3.2000	Dropped
30.		Curing/Finishing	3.9333	Selected
31.	Business	Lead time	3.9333	Selected
32.		Production time	4.3333	Selected
33.		Production volume	3.8000	Dropped
34.		Supply chain management	3.8000	Dropped
35.		Vulnerability to supply chain	3.4667	Dropped
36.		Consumer proximity to production	3.7333	Dropped
37.		Inventory	3.8000	Dropped
38.		Transportation	3.6667	Dropped
39.		Decentralized production	3.5333	Dropped
40.		Batch size	3.6667	Dropped
41.		Logistics	3.3333	Dropped
42.		After sales service	3.3333	Dropped
43.		Company image	3.4000	Dropped
44.		Business case	3.4000	Dropped
45.		New business model	3.2000	Dropped

S.No.	Factors	Parameters	Ratings	Selected/ Dropped
46.		Production on demand	3.8000	Dropped
47.		Communication	3.2667	Dropped
48.		Fabrication cost	4.2000	Selected
49.		Total cost	3.9333	Selected
50.		Upfront engineering cost	3.6667	Dropped
51.	Environmental	Energy consumption	4.3333	Selected
52.		Recycling	3.4667	Dropped
53.		Emission	3.6667	Dropped
54.		Sustainability	3.8667	Selected
55.		Material wastage	4.1333	Selected
56.		Biodegradable	3.7333	Dropped
57.		Radiation	3.2667	Dropped
58.		Carbon footprint	3.5333	Dropped
59.		Water consumption	2.8667	Dropped
60.		Special packaging and shipping requirements	3.2000	Dropped
61.	Functional	All intended functions	4.0000	Selected
62.		Some additional functions	3.6667	Dropped
63.		Durability	4.2000	Selected
64.	Material	Multi-material	3.4667	Dropped
65.		Heat dissipation	3.3333	Dropped
66.		Thermal conductivity	3.4667	Dropped
67.		Flexural strength	4.0000	Selected
68.		Tensile strength	4.3333	Selected
69.		Compressive strength	4.4000	Selected
70.		SN curve	4.4000	Selected
71.		Melting point	4.0667	Selected
71.		Impact strength	4.3333	Selected
72.		Hardness	4.1333	Selected
73.		Density	4.1333	Selected
74.		Thermodynamic behavior	3.8000	Dropped
75.		Young's modulus	4.2667	Selected
76.		Poisson's ratio	4.2000	Selected
77.		Yield strength	4.3333	Selected
78.		Colour	3.0667	Dropped
79.		Cost	4.5333	Selected
80.	Availability of material	4.3333	Selected	

Step 4: Factor analysis and final categorization

For further study, the structure and relevance of the parameters selected from the Delphi responses were subjected to factor analysis. Factor analysis was performed with three basic objectives: 1) to determine the number and nature of the variables. 2) to determine the influence of common factors on the attributes. 3) to analyse the inter correlation among the variables and determine common factors (Tucker and MacCallum, 1997).

IBM SPSS Statistics was used to perform Exploratory Factor Analysis (EFA), as presented in Table 7. The Varimax rotation method was used in SPSS, and the extraction method used was Principal Component Analysis. The rotation converged in 24 iterations. The minimum loading value was -0.854, while the maximum loading value was 0.960. There is no clear recommended cut-off for the loading value, but usually researchers have considered 0.4 as a suitable cut-off (Hinkin, 1995). 0.3 has also been proposed by many researchers (Costello and Osborne, 2014). As the values below 0.3 are considered insignificant, the attributes with a loading value below 0.3 were discarded. A total of 7 factors were identified, and the attributes were grouped based on higher loading value (Phogat and Gupta, 2019).

Table 7: Exploratory Factor Analysis

Rotated Component Matrix ^a										
Rate the following design parameters in response to its importance towards FDM feasibility:	Component									
	1	2	3	4	5	6	7	8	9	10
Design complexity	0.375	-0.168	0.172	-0.466	0.592	-0.284	0.077	0.296	-0.134	0.063
Design freedom	0.357	0.535	0.061	0.269	0.145	-0.030	-0.295	-0.350	-0.498	-0.033
Translation (Design changes)	0.055	0.163	0.321	-0.095	0.675	0.030	0.036	-0.332	0.255	-0.390
Customisation	0.179	-0.316	0.010	0.213	0.730	0.321	0.068	-0.298	0.048	0.102
Accuracy	-0.061	0.315	0.303	0.029	0.743	0.286	0.054	-0.169	0.025	0.291
Precision	-0.613	0.334	0.223	0.046	0.461	-0.105	-0.303	-0.206	-0.174	-0.055
Consolidation	-0.254	0.298	-0.075	0.116	0.716	-0.208	-0.231	-0.044	0.396	-0.067
Feature size	-0.178	0.148	-0.096	0.448	0.660	-0.217	-0.358	0.226	-0.012	-0.063
Aesthetic improvement	-0.804	0.098	0.177	0.358	-0.143	0.162	-0.130	-0.044	0.162	-0.053
Functional integration	-0.607	0.201	0.286	0.535	0.112	0.308	-0.017	0.051	0.154	0.108
Build volume	-0.167	-0.200	0.089	0.044	-0.006	-0.020	0.678	0.095	0.014	0.624
Product size	0.113	0.090	0.033	0.130	0.121	-0.854	0.276	-0.151	-0.142	0.291

Print time	0.240	-0.115	0.181	-0.191	0.103	-0.094	0.225	-0.088	0.234	0.823
Support structure	0.117	-0.146	0.684	0.276	-0.073	-0.034	0.124	0.535	-0.050	0.180
Simplification of manufacturing	-0.433	-0.177	0.807	0.000	0.161	0.035	-0.143	0.118	0.032	0.057
Post processing	-0.271	0.036	0.763	0.366	0.062	-0.041	0.302	-0.039	0.203	0.021
Surface finish	0.176	0.004	0.880	0.079	0.173	-0.132	0.126	0.064	-0.063	-0.003
Printing speed	0.019	0.414	0.353	-0.284	0.099	0.063	-0.220	0.639	-0.125	0.363
Consistency	-0.543	-0.113	0.087	0.704	0.169	0.099	0.189	-0.015	0.290	-0.121
Curing/ Finishing	-0.302	0.075	0.194	0.826	0.176	-0.222	0.091	0.005	-0.208	-0.025
Lead time	-0.133	-0.126	0.059	0.061	-0.189	0.124	0.007	0.907	-0.011	-0.154
Production time	0.275	-0.560	0.383	-0.057	0.088	0.131	0.209	0.534	0.054	0.040
Fabrication cost	0.379	0.060	0.450	0.005	0.182	0.354	0.592	-0.053	-0.175	-0.033
Total cost	-0.578	0.180	0.228	0.558	0.168	0.100	0.352	0.193	-0.212	-0.036
Energy consumption	-0.231	-0.140	0.087	0.333	0.598	0.151	-0.136	0.393	-0.227	0.368
Sustainability	-0.473	0.194	0.045	0.544	0.006	0.131	0.510	0.076	-0.305	-0.144
Material wastage	-0.056	-0.050	0.083	0.108	-0.199	0.080	0.925	-0.038	0.174	0.146
All Intended functions	0.295	0.003	-0.046	0.034	0.203	0.866	0.287	-0.019	-0.143	-0.006
Durability	0.205	0.024	-0.092	0.210	0.005	0.850	0.229	0.106	-0.099	0.191
Flexural strength	0.160	0.008	0.493	0.693	-0.020	0.246	-0.109	-0.092	-0.254	-0.014
Tensile strength	0.934	0.068	-0.037	-0.096	0.028	0.112	0.137	-0.057	-0.104	0.186
Compressive strength	0.896	0.146	0.096	0.005	0.113	0.175	-0.119	-0.060	-0.033	0.184
SN curve	0.839	0.285	-0.119	0.160	0.042	-0.095	-0.331	0.016	0.021	-0.009
Melting point	0.088	0.960	0.052	0.008	-0.059	-0.002	-0.014	0.046	0.173	-0.098
Impact strength	0.389	0.872	0.047	-0.020	0.159	0.154	-0.040	-0.147	0.003	-0.072
Hardness	0.134	0.912	-0.163	0.161	0.168	-0.006	-0.065	0.007	-0.193	-0.030
Density	0.225	0.680	0.073	-0.087	-0.073	-0.369	0.293	-0.029	0.479	0.112
Young's modulus	0.909	0.282	0.027	-0.132	-0.073	0.128	0.008	-0.060	-0.091	-0.075
Poisson ratio	0.783	0.208	0.125	-0.280	-0.233	0.271	-0.032	0.118	0.156	-0.215
Yield strength	0.716	0.299	0.074	-0.281	-0.111	0.399	0.104	-0.129	0.098	-0.221
Cost	-0.064	0.055	0.072	-0.099	0.160	-0.015	0.032	-0.089	0.951	0.103
Availability of material	-0.104	0.418	0.629	0.125	-0.079	-0.210	0.061	0.146	0.371	0.392
Extraction Method: Principal Component Analysis.										
Rotation Method: Varimax without Kaiser Normalization. ^a										
a. Rotation converged in 24 iterations.										

The number of factors was retained based on the criterion that the eigenvalue ≥ 1 . This requirement is also known as Kaiser’s rule and is usually used in defining the threshold for extracting the factors. This rule states that only factors that have an eigenvalue greater than or equal to 1 should be retained. This is because they explain more variance (Hinkin, 1995). Along with the eigenvalues, the convergence and high factor loading also validate the data suitability.

Although EFA is a statistical method that defines the relationship between factors and attributes, it is known to have some amount of subjectivity, by virtue of which the researcher is endowed with the freedom to group two or more similar factors together. This leads to a shorter scale, thereby reducing complexity in subsequent steps (Maskey, Fei and Nguyen, 2018; Goretzko, Pham and Bühner, 2019). The result is tabulated in Table 8.

Table 8: Final factors

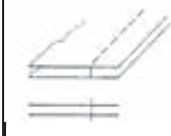
Process	Machine	Material	Functional	Design	Business	Environment
Support structure	Design Freedom	Hardness	Functional integration	Design complexity	Fabrication cost	Printing speed
Curing/ Finishing	Build volume	Impact strength	All functions	Translation (Design changes)	Total cost	Lead time
Consistency		Melting point	Durability	Customization	Simplification of manufacturing process	Production time
Post processing		Tensile strength		Accuracy		Sustainability
		Material availability		Precision		Material wastage
		Density		Consolidation		Energy consumption
		Compressive strength		Feature size		
		SN Curve		Surface finish		
		Young’s modulus				
		Poisson’s ratio				
		Yield strength				
		Flexural strength				

Step 5: Development of a framework for assessment of the potential for FDM

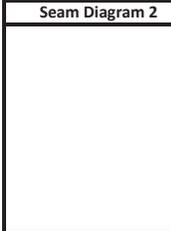
Based on the final factors identified after factor analysis and prioritization of the factors, a framework was developed for the assessment of manufacturability feasibility by FDM, a method of AM, as shown in Figure 6.

The first step is part selection using a preliminary study in which function, feature, and performance studies are performed. The findings are recorded in a data sheet. An example data sheet is given in Figure 5.

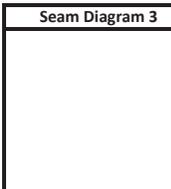
General Information	
Part name	Spring hinged presser foot
Category	Industrial single needle lock stitch basic hinged non-compensating
Description	Standard Spring hinged twin toe presser foot
Application	For joining two plies of fabric by an industrial SNLS machine
Material	Stainless steel
Dimension mm	35x35x7
Weight g	50

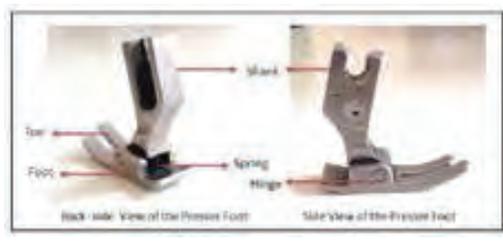
Seam Diagram 1	
	

Seam properties	
Fabric	100% cotton
Fabric GSM	150
No. of plies	2-4
SPI	10-12
Stitch number	301
Thread ticket	120
Machine RPM	3000
Force applied	15-40 N
Seam type	Superimposed

Seam Diagram 2	
	

Mechanical Properties	
Density	8.00 g/cm ³
Melting Point	1400°C
Modulus of Elasticity	193 GPa
Tensile Strength (MPa)	500 - 700
Proof Stress (MPa)	200 Min
Elongation A50 mm	40 Min %
Hardness Brinell	215 Max HB

Seam Diagram 3	
	

Part Diagram/ Image	
	

Additional Notes and Remarks	

Created by:

Created on:

Signature

Figure 5: Sewing machine spare parts data sheet

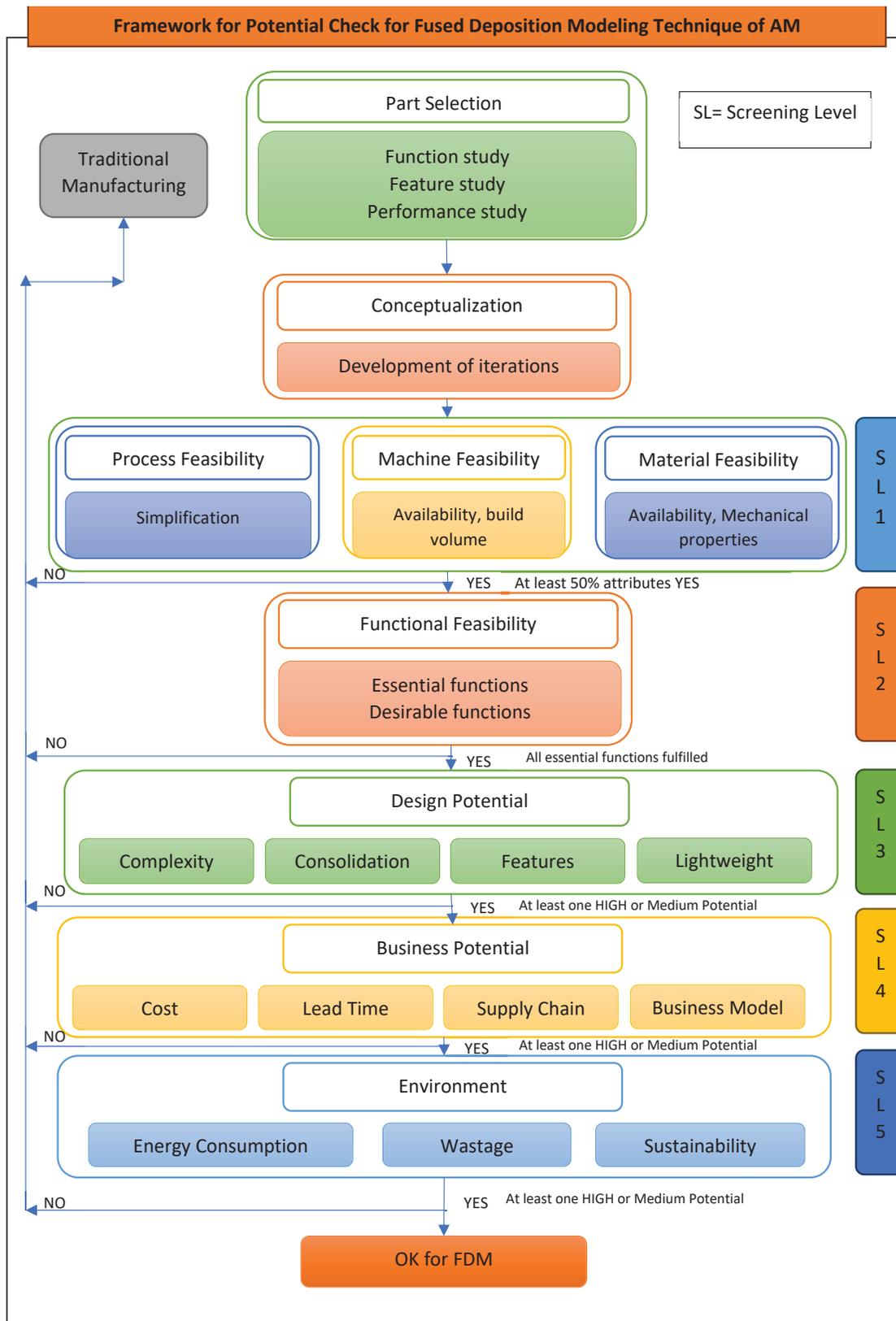


Figure 6: Framework for manufacturability assessment by FDM

The second step, according to the framework, is conceptualization, i.e., considering the functionality, available and compatible materials, assembly, etc. The basic shape needs to be identified and checked for the basic intended functions. The subsequent step is divided into five screening levels.

The screening framework is divided into five levels. The first level of screening consists of process feasibility, which focuses on the simplification of the manufacturing process; machine feasibility, which determines the availability and build volume of the printer; and material feasibility, which determines the availability of the material and its mechanical properties. The screening process advances to level 2 if the object achieves a score of at least 50 percent in level 1.

Level 2 of the screening assesses functional feasibility by studying how the additively manufactured object performs for both essential and desirable functions. If the essential functions are fulfilled by the object, then the design potential is analyzed in screening level 3, which consists of the design complexity of the object, part consolidation, number of small features, and the lightness of the part.

To qualify for screening level 4, at least one factor in screening level 3 needs to be high or medium. Screening level 4 checks the potential of the object from a business perspective. The factors like cost, lead time, supply chain, business model, and scalability are considered for the same. Again, at least one factor needs to be high or medium potential for the object to qualify for the last screening level, i.e., level 5.

Screening level 5 concerns the environmental aspects. The factors considered for this level are energy consumption, wastage, and sustainability. If at least one of the factors in screening level 5 scores high or medium potential, then the part qualifies for being manufactured by the FDM method of AM. If the object fails on any level, then the traditional method of manufacturing may be preferred.

Conclusion and Future Scope

The framework developed is exhaustive, as maximum numbers of attributes are considered from secondary literature, and the attributes that are relevant for fused deposition modelling (FDM) are retained by a systematic approach. The approach includes the inputs of the experts in the field of additive manufacturing, particularly FDM.

The framework can be incorporated in a garment factory during the early stages of developing a product that would aid in the production of a garment order. If there is a requirement of a specific work aid that is crucial for executing a garment order, it could

be either manufactured in-house using an FDM setup, or it could be procured from a place where it is manufactured using a traditional method. However, even though the FDM provides immense benefits like drastically shorter lead time and cost savings, sometimes it is not feasible for the product to be manufactured by FDM because of reasons like material feasibility or certain geometrical limitations. Thereby, it becomes important that the manufacturability analysis for the work aid or other spare parts is done beforehand to take an informed decision to avoid the chances of failure.

The framework, which includes technical, functional, design, business, and environmental factors, serves as a well-structured decision-making tool with a five-level screening model. It is helpful for the manufacturers to evaluate the manufacturability of a component with respect to FDM and make informed decisions. It has strong potential for practical applications in the garment industry as well as for manufacturing small parts. This framework aligns with Industry 4.0 by promoting decentralization, on-demand production, and sustainability.

The future scope of this framework is to implement it in the garment manufacturing industry. This framework will be useful to analyze the feasibility of manufacturing sewing machine spare parts in-house using the fused deposition modeling technique of additive manufacturing. This study would become an integral part of the adoption of a new business model, which would greatly curtail the supply chain, thereby providing a competitive edge in the industry.

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About the authors

Abhilasha Singh is Assistant Professor in the Department of Fashion Technology, NIFT, Patna. She is currently pursuing her Ph.D. in the area of additive manufacturing from NIFT. She is a NIFT Delhi and Gandhinagar alumnus, with over five years of industry experience before joining NIFT as faculty. A keen interest in research and development has led her to take and complete various research projects of national and international repute. Her paper presented at QUT, Australia, on Automatic Seam Ripping System (ASRS) was recognized globally and applauded by the Confederation of Indian Textile Industry (CITI). She holds seven patents and has published 13 research papers in international journals and conferences. Her research interests include additive manufacturing, textiles, supply chain and merchandising, pattern making, garment construction, and education.

abhilasha.abhilasha@nift.ac.in

Prabir Jana, a visionary in the development, application, and management of technology in apparel manufacturing, started his professional career with a private garment manufacturing enterprise in 1991. After a brief stint with manufacturing and buying organizations, he joined the NIFT Delhi. Currently he is the Shahi Chair Professor of Industry 4.0 at NIFT, Delhi. During his 30+ illustrious years at NIFT, he has served as Chairperson of the Department of Fashion Technology, Head of Industry Linkages, Head of Information Technology, and Head of Research. His special research interests include technology improvisation, sewing automation, industrial engineering, ergonomics, 3D printing, and smart garments. A prolific contributor for technology columns in various journals, he has written over 300 articles, edited and authored 15 books, and filed 5 patents. Prabir Jana is a graduate in Textile Technology from Calcutta University, a postgraduate in Garment Manufacturing Technology from NIFT, New Delhi, and a PhD from Nottingham Trent University, UK.

prabir.jana@nift.ac.in

Deepak Panghal is a seasoned academic and industry professional specializing in mechatronics, Industry 4.0, and low-cost automation systems. With over 18 years of experience, he serves as a faculty member at NIFT, New Delhi, and is the co-founder of Apparel 4.0 Technologies Pvt. Ltd., a start-up that has received prestigious accolades like the H&M Global Innovation Award and ITMA Startup Valley Award. Deepak holds a PhD in mechanical engineering and has developed innovative solutions for the apparel manufacturing industry. The University of Canterbury, New Zealand, recently awarded him the prestigious Erskine Fellowship, acknowledging his contributions to both academia and industry. With 3 granted patents, 4 under examination, and research projects worth approximately ₹10 million, he has a robust portfolio of impactful work. An accomplished author, he has numerous high-impact journal publications and book chapters. He has also established advanced labs at NIFT, guided postgraduate and doctoral students, and integrated cutting-edge research with practical industry applications globally.

deepak.panghal@nift.ac.in