Framework for Additive Manufacturing Adoption Using Evaluation Model

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Abstract

Additive Manufacturing (AM), also known as 3D printing, has emerged as a transformative technology, revolutionizing various industries by offering enhanced design freedom, reduced lead times, and material savings. As AM continues to gain traction in part production, the need for an efficient and reliable method to identify the most suitable components for AM processes becomes increasingly crucial. This research paper presents a comprehensive framework for selecting the right candidates for Additive Manufacturing part selection, considering various factors to optimize part performance and efficiency.

The proposed framework begins with an extensive review of the current state-of-the-art in AM materials, processes, and design considerations. A structured taxonomy is developed, categorizing candidate parts based on complexity, geometric characteristics, material properties, and functional requirements. This classification lays the foundation for systematic part evaluation and selection. Next, the framework integrates multi-criteria decision-making methods to evaluate and prioritize candidate parts. Key evaluation criteria include geometric complexity, mechanical properties, production volume, economic viability, and the potential for performance improvement through AM. Each criterion is weighted based on its relative significance in the specific application context, providing a tailored approach to part selection. Furthermore, the paper investigates the impact of AM-specific design guidelines on part selection. Specific considerations, such as support structures, build orientation, and surface finishing, are analyzed to ensure successful and efficient part production.

The framework is complemented by a user-friendly decision support tool that enables engineers and designers to apply the proposed methodology effectively. The tool integrates sophisticated algorithms, allowing real-time analysis and comparisons of candidate parts to expedite the decision-making process.

In conclusion, the presented framework empowers industries to identify and select the most suitable components for AM, maximizing the technology's potential and driving its widespread adoption. By streamlining the part selection process and considering multiple critical factors, this research contributes to accelerating AM's integration into various sectors, promoting resource efficiency, and unlocking new possibilities in design and manufacturing.

Introduction

Additive Manufacturing technological capability and value modelled in an objective and transferrable way.

Additive manufacturing, commonly known as 3D printing, has emerged as a revolutionary technology that is transforming the landscape of modern manufacturing. Unlike traditional subtractive methods, which involve cutting and shaping materials to create objects, additive manufacturing builds three-dimensional structures layer by layer. This innovative approach to production offers unique advantages, and its adoption is increasingly driven by considerations of material conservation, geometric complexity, and enhanced functionality.

Quick-screening and decision-making model for AM candidate part.

Sustainability of the AM process in terms of material conservation, geometric complexity, and functionality

Material Conservation:

One of the key motivations behind the growing adoption of additive manufacturing is its inherent efficiency in material usage. Traditional manufacturing processes often result in substantial material waste, as raw materials are cut away to achieve the desired shape. In contrast, additive manufacturing adds material only where needed, minimizing waste, and promoting a more sustainable approach. This conservation of resources not only aligns with environmentally conscious practices but also contributes to cost-effectiveness, making additive manufacturing an attractive option for industries seeking to optimize their material utilization.

Geometric Complexity:

Additive manufacturing empowers designers to break free from the constraints imposed by traditional manufacturing methods. Complex geometries that were once challenging or impossible to produce are now achievable with relative ease. This capability is particularly advantageous in industries such as aerospace, automotive, and healthcare, where intricate and customized designs can significantly enhance performance and functionality. The ability to create complex structures allows for lightweight components, improved aerodynamics, and intricate medical implants that precisely match the patient's anatomy.

Functionality Enhancement:

Another compelling factor driving the adoption of additive manufacturing is its capacity to enhance the functionality of manufactured components. Traditional manufacturing processes may struggle with the integration of multiple parts or the incorporation of intricate features. Additive manufacturing enables the production of consolidated and integrated structures, reducing the need for assembly and potentially improving the overall strength and performance of the final product. This capability is particularly valuable in industries where lightweight yet robust components are crucial, such as in the development of high-performance machinery or advanced medical devices.

In conclusion, Figure 1 explains, the adoption of additive manufacturing can be analyzed with Cost, Flexibility and Time. Various key vitals like Scrap, Complex geometry parts, Various material properties requirements in one part, Service parts fast availability, Quick manufacturing solutions development leads to potential candidate identifications. Manufacturing industry recognizes potential of AM to address challenges related to material conservation, geometric complexity, and functionality enhancement. As technology continues to advance and the range of printable materials expands, the transformative impact of additive manufacturing on various sectors is poised to grow, ushering in a new era of more sustainable, intricate, and functionally optimized production processes.

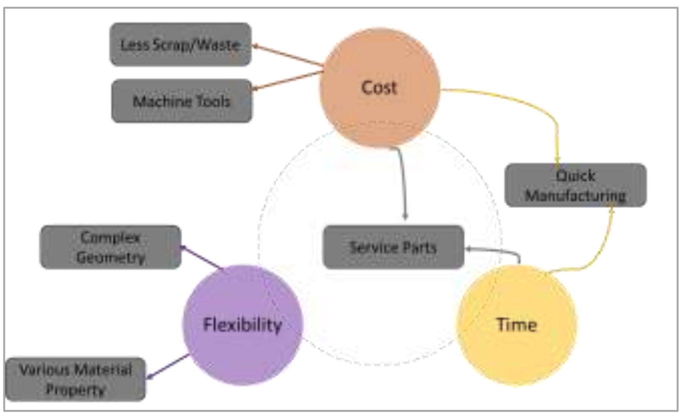


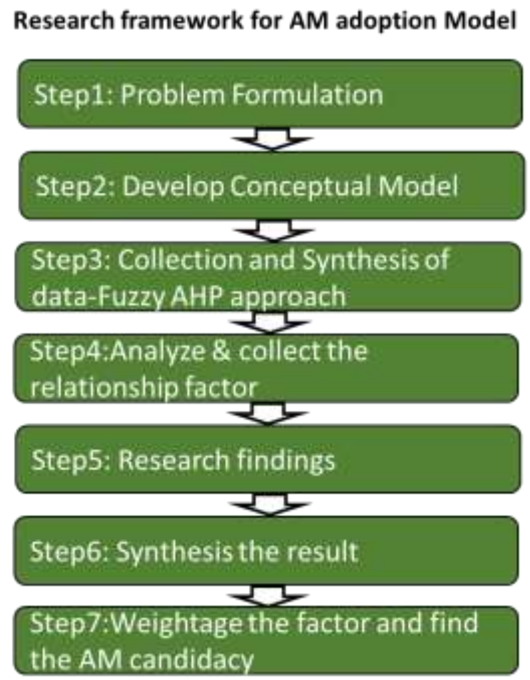
Figure 1. Additive Manufacturing Potentials Identifications Criteria

Need of an Evaluation Model

The adoption of additive manufacturing (AM) necessitates the development and implementation of a robust evaluation model to assess its feasibility and effectiveness in various applications. Such a model is crucial for several reasons, like Harness benefits to apply Additive Manufacturing (AM) as opposed to conventional methods of manufacturing. Non-AM experts can use this model to find suitable AM candidate's part. Minimizes the subjectivity in AM process adoption for a particular part. Integration of components, light weighting, efficient designs and individualization. Widespread use of AM potential. In essence, the implementation of additive manufacturing requires a thoughtful evaluation model to navigate design considerations, financial implications, quality assurance, regulatory compliance, and the evolving landscape of AM technology. This ensures a strategic and informed approach to adopting and integrating AM processes within diverse industrial contexts.

Methodology

Certainly, the steps outlined provide a structured approach to adopting additive manufacturing (AM).



Here's an elaboration on each step:

Step 1: Problem Formulation Identify and articulate the specific challenges or opportunities within your manufacturing process that could be addressed through additive manufacturing. This step involves understanding the limitations of existing methods and pinpointing areas where AM could provide significant benefits.

Step 2: Develop Conceptual Model Create a conceptual model that outlines how additive manufacturing might fit into your overall manufacturing strategy. Define the objectives, scope, and key performance indicators (KPIs) for the adoption of AM. This model sets the foundation for subsequent steps.

Step 3: Collection and Synthesis of Data - Fuzzy AHP Approach Utilize a Fuzzy Analytic Hierarchy Process (FAHP) to collect and synthesize relevant data. This involves gathering input from experts, stakeholders, and relevant data sources. Apply fuzzy logic to handle uncertainties and subjective judgments, which are common in the evaluation of complex factors associated with AM adoption.

Step 4: Analyze & Collect Relationship Factors Analyze the relationships between different factors involved in AM adoption. Understand how factors such as geometric complexity, production volume, value for part, design improvement need, functionality of part, time to manufacture, and material removal need interact with each other. Collect data that helps quantify these relationships.

Step 5: Research Findings Based on the collected data, conduct in-depth research to understand the current state of AM technology, market trends, and industry best practices. Stay updated on the latest advancements and case studies related to AM adoption, particularly in your specific industry.

Step 6: Synthesize the Result Synthesize the findings from Steps 3 to 5 to develop a comprehensive understanding of the factors influencing AM adoption. Identify patterns, correlations, and potential challenges. This synthesis lays the groundwork for making informed decisions during the next step.

Step 7: Weightage the Factor and Find the AM Candidacy Assign weightages to the identified factors based on their significance and relevance to your specific context. Use these weights to assess the candidacy of AM for your application. This step involves combining qualitative and quantitative data to determine the overall suitability of additive manufacturing for addressing the identified problem or opportunity.

By following these seven steps, organizations can systematically navigate the complex process of additive manufacturing adoption, ensuring a well-informed decision-making process that aligns with their strategic goals and manufacturing needs.

Weightage Criteria:
When developing a weightage criteria system for the classification of additive manufacturing projects, it's essential to assign appropriate importance to each factor based on the specific needs and priorities of your organization. Here's a suggested weightage criteria system considering factors such as geometric complexity, production volume, value for part, design improvement need, functionality of the part, and time for manufacturing and material removal need.

Criteria/Factors	Classification		
Geometric Complexity	Low 1	Medium 2	High 3
Production Volume	High 1	Medium 2	Low 3
Value for part/Price per part	Low 1	Medium 2	High 3
Design Improvement Need	No Design Improvement 1	At least one design improvement 2	More than one design imorovement 3
Part Functionality	Non Crictical 1	Partially Crictical 2	Crictical 3
Time to manufacture	Manufacture by AM time is more than conventional 1	Equal manufacture time by AM or conventional 2	Manufacture by AM time is less than conventional 3
Material Removal need	Less than 50% material removal by conventional method 1	50% of material removal by conventional metod 2	More than 50% material removal by conventional method 3

Geometric Complexity:

- High weight indicates that projects with intricate or complex geometries are of strategic importance.
- Consider the impact of geometric complexity on traditional manufacturing processes and the unique advantages offered by additive manufacturing.

Production Volume:

- High weight implies that the scalability and efficiency of production are critical.
- Consider the optimal production volume for additive manufacturing in comparison to other manufacturing methods.

Value for Part (Price per part):

- High weight signifies a focus on cost-involved is high and economic viability to be considered.
- Consider the overall cost derived from additive manufacturing in terms of cost savings, reduced material waste, and improved performance.

Design Improvement Need:

- High weight indicates a strategic emphasis on projects requiring design innovation or customization based on market/customer need.
- Consider the extent to which additive manufacturing can contribute to design improvements and innovation.

Part Functionality:

- High weight implies a priority for projects where the functionality of the part is critical.
- Consider Non-Critical, Partially Critical and Critical as classifier.

Time to Manufacturer:

- High weight implies a priority for projects where the AM takes lesser time. One can consider production cycle time to analyze these criteria.
- A moderate weight acknowledges that while AM is generally faster for prototyping, traditional methods may be quicker for certain production volumes.

Material Removal Need:

- The need for post-processing and material removal can impact the overall efficiency of AM.
- A moderate classifier to be considered with respect to 50% of material removal.

By assigning weights to these criteria, author tailor their evaluation model to align with specific priorities and contextual factors. The total weights should sum to 100%, providing a balanced and quantitative framework for assessing the suitability of additive manufacturing for different applications.

Fuzzy Analytical Hierarchy Process

Fuzzy Analytical Hierarchy Process for Triangular Fuzzy to be done-
Step 1: Fuzzy Matrix from pairwise comparison Matrix.

$$\widetilde{A}^h = \begin{bmatrix} \widetilde{a}_{11}^h & \cdots & \widetilde{a}_{1n}^h \\ \vdots & \ddots & \vdots \\ \widetilde{a}_{n1}^h & \cdots & \widetilde{a}_{nn}^h \end{bmatrix}$$

Step 2:

Criteria	Geometric Mean		
Design Improvement	0.96	1.121	1.334
Geometric Complexity	1.87	2.712	3.469
Production Volume	1.765	2.168	2.686
Value for part	1.219	1.389	1.626
Material Removal	0.266	0.301	0.349
Function	0.944	1.076	1.24
Time to manufacture	0.301	0.338	0.403
Total	7.324	9.105	11.11
Inverse	0.137	0.11	0.09
Reverse	0.09	0.11	0.137

Criteria	Fuzzy weight			Avg.	Norm.
Design Improvement	0.086	0.123	0.183	0.131	0.123
Geometric Complexity	0.168	0.298	0.475	0.314	0.296
Production Volume	0.159	0.238	0.368	0.255	0.24
Value for part	0.11	0.153	0.223	0.162	0.152
Material Removal	0.024	0.033	0.048	0.035	0.033
Function	0.085	0.118	0.17	0.124	0.117
Time to manufacture	0.027	0.037	0.055	0.04	0.038
Total				1.061	1

Geometric Mean of fuzzy comparison values of criteria,

Calculate the geometric mean for each column of the fuzzy matrix to obtain the fuzzy comparison values for each criterion. The formula for the geometric mean (P) of fuzzy numbers is given by:

$$\tilde{p}_i = \left(\prod_{j=1}^{n} \tilde{a}_{ij}\right)^{1/n} = \left(\left(\prod_{j=1}^{n} a_{ij1}\right)^{1/n}, \left(\prod_{j=1}^{n} a_{ij2}\right)^{1/n}, \left(\prod_{j=1}^{n} a_{ij3}\right)^{1/n} \right), \; i = 1, 2, 3, \ldots, n$$

Step 3 Fuzzy weight of criteria,

Normalize the geometric means obtained in Step 2 to get fuzzy weights. The fuzzy weight ('W') for each criterion is calculated by dividing the geometric mean of the fuzzy comparison values for that criterion by the sum of all geometric means.

$$\tilde{w}_i = (w_{i1}, w_{i2}, w_{i3}) = \tilde{p}_i \otimes (\tilde{p}_1 \oplus \tilde{p}_2 \oplus \ldots \oplus \tilde{p}_n)^{-1}, \; i = 1, 2, 3, \ldots, n$$

Step 4 Defuzzify the fuzzy weight,

Defuzzify the fuzzy weights to obtain crisp weights. This can be done using methods like the center of area, centroid, or other defuzzification techniques. For simplicity, you can use the center of area.

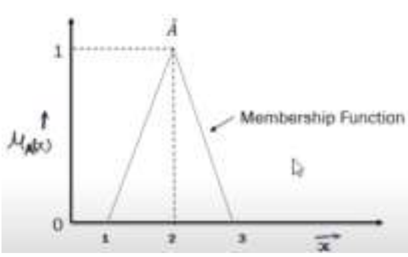
$$Q_i = \frac{(w_{i1} + w_{i2} + w_{i3})}{3}, \; i = 1, 2, 3, \ldots, n$$

Step 5 Normalize

Normalize the crisp weights obtained in Step 4 by dividing each weight by the sum of all weights.

$$R_i = \frac{Q_i}{\sum_{i=1}^{n} Q_i}, \; i = 1, 2, 3, \ldots, n$$

Triangular Fuzzy



The normalized weights represent the importance of each criterion in the decision-making process. These steps help convert the pairwise comparison matrix with triangular fuzzy numbers into normalized fuzzy weights for each criterion, providing a comprehensive and nuanced evaluation in the context of Fuzzy Analytical Hierarchy Process.

Triangular Saaty Scale		
1	Equally important	(1,1,1)
3	Weakly Important	(2,3,4)
5	Fairly important	(4,5,6)
7	Strongly important	(6,7,8)
9	Absolutely important	(9,9,9)
2	The intermittent values between two adjacent scales	(1,2,3)
4		(3,4,5)
6		(5,6,7)
8		(7,8,9)

Case Study:

Pairwise Comparison Matrix																					
Criteria	Design improvement			Geometric complexity			Production volume			Value for part			Material Removal			Function			Time to manufacture		
Design Improvement	1.00	1.00	1.00	0.25	0.33	0.50	0.25	0.33	0.50	1.00	1.00	1.00	4.00	5.00	6.00	1.00	1.00	1.00	3.00	4.00	5.00
Geometric Complexity	2.00	3.00	4.00	1.00	1.00	1.00	1.00	2.00	3.00	1.00	2.00	3.00	5.00	6.00	7.00	2.00	3.00	4.00	4.00	5.00	6.00
Production Volume	2.00	3.00	4.00	0.33	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	5.00	6.00	7.00	4.00	5.00	6.00	4.00	5.00	6.00
Value for part	1.00	1.00	1.00	0.33	0.50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	4.00	5.00	6.00	1.00	1.00	1.00	3.00	4.00	5.00
Material Removal	0.17	0.20	0.25	0.14	0.17	0.20	0.14	0.17	0.20	0.17	0.20	0.25	1.00	1.00	1.00	0.17	0.20	0.25	1.00	1.00	1.00
Function	1.00	1.00	1.00	0.25	0.33	0.50	0.17	0.20	0.25	1.00	1.00	1.00	4.00	5.00	6.00	1.00	1.00	1.00	4.00	5.00	6.00
Time to manufacture	0.20	0.25	0.33	0.17	0.20	0.25	0.17	0.20	0.25	0.20	0.25	0.33	1.00	1.00	1.00	0.20	0.20	0.25	1.00	1.00	1.00

Cold forming tool for an axle for heavy machinery powertrain. The part is considered a primary function element of the powertrain which is produced in low volumes. The shape of the tool was similar that it doesn't have space for promised channels to allow for thorough cooling of the part during cold forming. As a result, the tool was exposed to increased thermal wear and tear and the produced corridor didn't have the invariant hardness as demanded. The conventional tool is considered to have a medium complex figure because it didn't have internal heating channels. The tool is produced as a special unit; hence, the product volume is considered low. The tool manufactured with AM SLM had innovative adaptive cooling channels slots. According to the results, the cooling time was reduced from 10 to 3 s, which translates to a reduction of 70. also, the quality of the corridor bettered to increase the hardness uniformity. The additively manufactured tool was anticipated to be more durable because of the reduced thermal wear and tear.

Criteria/Factors	Weight	Classification			Case 1	
Geometric Complexity	0.296009933	Low 1	Medium 2	High 3	2	0.59202
Production Volume	0.24048076	High 1	Medium 2	Low 3	3	0.721442
Value for part	0.152495362	Low 1	Medium 2	Highn 3	1	0.152495
Design Improvement	0.123301114	No Design Improvement 1	Atleast one design improvement 2	More than one design imorovement 3	2	0.246602
Function	0.11724771	Non Crictical 1	Partially Crictical 2	Crictical 3	3	0.351743
Time to manufacture	0.037538935	Manufacture by AM time is more than conventional 1	Equal manufacture time by AM or conventional 2	Manufacture by AM time is less than conventional 3	1	0.037539
Material Removal	0.032926185	Less than 50% material removal by conventional method 1	50% of material removal by conventional metod 2	More than 50% material removal by conventional method 3	1	0.032926
Total (V)						2.486511

Using total weight (V) obtained, following conditions apply,

$1 \leq V \leq 1.5$: Not Suitable for AM

$1.5 \leq V \leq 2.0$:Suitable for AM after changes

$2.0 \leq V \leq 2.55$: Suitable for AM without changes

Summary/Conclusions

In conclusion for evaluation model with Fuzzy AHP for studied case study of Cold forming tool for an axle with cumulative manufacturing, an evaluation model for choosing part campaigners for AM operation in the manufacturing sector is developed. To formulate the model, the Fuzzy AHP processes was used to rank the criteria and assign weights.

The calculated weights attained from the colorful case studies agreed with the evaluation model. The proposed model is a suitable tool that can be used to guide the stoner to identify corridor suitable for AM operation. Value addition of the named part campaigners through design enhancement. The case study performed Fuzzy model to speed up the process while reducing bias in the result. This research work further opens the avenues to work on Cost–benefit analysis to further provide the economic justification of the proposed model. Diverse field user of AM technologies to model the candidacy. Other MCDM methods to be explored, compared, and can be validated. Also, Machine Learning part models with synthetic data can be leveraged for smart solution development.

References

1. William E. Frazier " Metal Additive Manufacturing: A Review ," ASM International 1059-9495, 2014, DOI: 10.1007/s11665-014-0958-z
2. Ehsan. Yadollahi , El-Houssaine Aghezzaf , and B.T. Hang Tuah Baharudinb, " Comparing Entropy Weighting Method and AHP for JIT implementation ,
3. Maimouna Diouf 1 and Choonjong Kwak, " Fuzzy AHP, DEA, and Managerial Analysis for Supplier Selection and Development; From the Perspective of Open Innovation," MDPI Technical Paper ,1 Sustainability 2018, 10, 3779, doi:10.3390/su10103779
4. Abhijeet K. Digalwar, Atul Borade, Bhimaraya Metri " A Fuzzy AHP Approach for Supplier Selection," OPERATIONS AND SUPPLY CHAIN MANAGEMENT, Vol. 7, No. 2, 2014, pp. 46 – 53, ISSN 1979-3561 | EISSN 1979-3871,
5. Mustafa Batuhan AYHAN, “A FUZZY AHP APPROACH FOR SUPPLIER SELECTION PROBLEM: A CASE STUDY IN A GEARMOTOR COMPANY,” IJMVSC, Vol.4, No. 3, September 2013, DOI: 10.5121/ijmvsc.2013.4302
6. Sheng Yang , Thomas Page ,Ying Zhang , Yaoyao Fiona Zhao ,”Towards an automated decision support system for the identification of additive manufacturing part candidates”, Journal of Intelligent Manufacturing, Received: 19 September 2019 / Accepted: 6 February 2020, https://doi.org/10.1007/s10845-020-01545-6
7. Page, T.D., Yang, S., Zhao, Y.F. (2019) ‘Automated Candidate Detection for Additive Manufacturing: A Framework Proposal’, in Proceedings of the 22nd International Conference on Engineering Design (ICED19), Delft, The Netherlands, 5-8 August 2019. DOI:10.1017/dsi.2019.72
8. A. Sandeep Kranthi Kiran, Jagadeesh Babu Veluru, Sireesha Merum, A.V. Radhamani, Mukesh Doble, T. S. Sampath Kumar & Seeram Ramakrishna (2019): Additivemanufacturing technologies: an overview of challenges and perspective of using electrospraying,Nanocomposites, DOI: 10.1080/20550324.2018.1558499
9. A. Sandeep Kranthi Kirana,b,c, Jagadeesh Babu Veluruc, Sireesha Merumc, A. V. Radhamani “Additive manufacturing technologies: an overview of challenges and perspective of using electrospraying” NANOCOMPOSITES, 2018, VOL. 4, NO. 4, 190–214, https://doi.org/10.1080/20550324.2018.1558499

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Definitions/Abbreviations

AM	Additive Manufacturing
AHP	Analytical Hierarchy Process