

DEVELOPMENT OF A NEW PRODUCT DESIGN PROCESS TO IMPROVISE DESIGN FOR MANUFACTURING USING 3D/4D PRINTING TECHNOLOGY

**A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of**

DOCTOR OF PHILOSOPHY

In

DESIGN

by

AJAY SOLANKI
(Roll No. 2K22/PHDDES/01)

Under the Joint Supervision of

PROF. RANGANATH M. SINGARI

**Founder Head, Department of Design,
Professor, Department of Mechanical
Engineering, Delhi Technological University,
Delhi**

PROF. AJAY K.S. SINGHOLI

**Professor, University School of
Automation and Robotics, Guru
Gobind Singh Indraprastha
University-EDC, New Delhi**



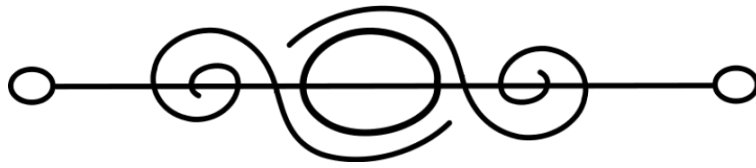
Department of Design

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daultpur, Main Bawana Road, Delhi-110042, India

April 2026



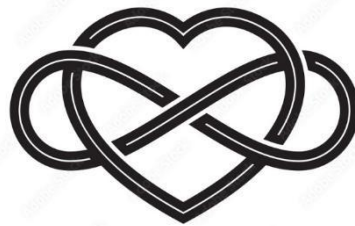
**©DELHI TECHNOLOGICAL UNIVERSITY
ALL RIGHTS RESERVED**



Dedicated

To My

Beloved Parents





DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-42

CANDIDATE’S DECLARATION

I, Ajay Solanki, hereby certify that the work which is being presented in the thesis entitled **“Development of a New Product Design Process to Improve Design for Manufacturing using 3D/4D Printing Technology”** in partial fulfillment of the requirements for the award of the Degree of Doctor of Philosophy, submitted in the Department of Design, Delhi Technological University is an authentic record of my own work carried out during the period from August 2022 to December 2025 under the supervision of Dr. Ranganath M. Singari and Dr. Ajay K.S. Singholi.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

Candidate’s Signature

Ajay Solanki

(2K22/PHDDES/01)

This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

Signature of Supervisor (s)

Signature of External Examiner



DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)
Shahbad Daulatpur, Main Bawana Road, Delhi-42

CERTIFICATE BY THE SUPERVISOR(s)

Certified that **Ajay Solanki** (2K22/PHDDES/01) has carried out the research work presented in this thesis entitled **“Development of a New Product Design Process to Improve Design for Manufacturing using 3D/4D Printing Technology”** for the award of **Doctor of Philosophy** from **Department of Design, Delhi Technological University, Delhi**, under our supervision. The thesis embodies results of original work, and studies are carried out by the student himself and the contents of the thesis do not form the basis for the award of any other degree to the candidate or to anybody else from this or any other University/Institution.

Prof. Ranganath M. Singari
(Supervisor)
Founder Head, Department of Design
Professor, Department of Mechanical Engineering
Delhi Technological University
Delhi

Prof. Ajay K. S. Singholi
(Joint-Supervisor)
Professor, University School of
Automation and Robotics, Guru
Gobind Singh Indraprastha University-
EDC, New Delhi

Date:

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere appreciation to my supervisors, **Dr. Ranganath M. Singari, Professor, DTU** and **Dr. Ajay K.S. Singholi, Professor, USAR, GGSIPU-EDC, Delhi** for their invaluable mentorship and continuous encouragement throughout my PhD journey. Their profound expertise, insightful feedback, and unwavering support have been instrumental in shaping the direction of this research. Their patience and constructive guidance have helped me refine my ideas and navigate the challenges of this academic endeavour.

I extend my deepest thanks to the **Department of Design, Delhi Technological University, India** and **USAR & USDI, Guru Gobind Singh Indraprastha University Delhi-EDC, India** for providing me with the resources and facilities necessary for conducting this research. I am particularly grateful to the faculty members and administrative staff for their assistance and encouragement at various stages of my work.

In addition to the aforementioned contributors, heartfelt gratitude is extended to the esteemed faculty members and industry experts whose professional insights and experiences significantly enriched the depth and practical relevance of this research. **Dr. Rakesh Kumar**, Assistant Professor, Department of Mechanical Engineering, DTU, **Dr. Kamal Kishor**, Assistant Professor, Department of Applied Physics, DTU, **Dr. Vikas Gupta**, Associate Professor, Delhi School of Management, DTU, **Dr. Abhinav Chaudhary**, Assistant Professor, DU, **Dr. Mohd. Shuaib**, Assistant Professor, Department of Mechanical Engineering, DTU, **Sh. Mukesh S. Dadge**, Assistant Professor, Department of Production Engineering, DTU and **Dr. Ravi Butola**, Assistant Professor, USAR, GGSIPU-EDC and **Dr. Ankit**, Project Research Scientist, Department of Applied Sciences, NIT-Delhi.

Sincere appreciation is also due to the academic mentors and research scholars whose guidance was instrumental throughout the research journey. **Dr. Mohd Tayyab** played a pivotal role in helping strategize the research direction, while **Dr. Monica Singh, Dr. Shahid Ahmad** provided continuous motivation and encouragement. The valuable support of **Ms. Bindu Maheshwari**, Associate Professor, USDI, GGSIPU-EDC, **Dr. Shruti Soharia Singh, Assistant Professor**, NIFT, Mumbai, **Dr. Utkarsh Chaudhari, Mr. Meraj Alam, and Ms. Simran Vats** across various phases of the research further enhanced its depth and coherence. Special thanks are also extended to **Dr. Ravindra Singh, Assistant Professor, Dr. Taruna Singh, Assistant Professor, Department of Design, Prof. LK Das and Prof. R.C. Singh, HoD, Department of Design**, Delhi Technological University, for their unwavering support and scholarly guidance throughout this academic pursuit.

On a personal note, I extend my deepest gratitude to my family for their unwavering love and support. My wife, *Rekha Solanki*, and my sons, *Ivaan Solanki and Takshay Solanki*, have been a constant source of inspiration—their patience, sacrifices, and steadfast belief in me have provided immeasurable motivation throughout this journey. I am equally thankful to my parents, *Sh. Harbir Singh Solanki and Smt. Santosh Solanki*, whose values and blessings have guided me at every step. My heartfelt appreciation also goes to my younger brother – *Mr. Vivek Solanki* - for their continuous encouragement and for being pillars of strength during the course of this academic pursuit.

Lastly, I **dedicate** this thesis to my beloved **parents, *Sh. Harbir Singh Solanki and Smt. Santosh Solanki***, whose unwavering faith, sacrifices, and lifelong dedication to my growth have laid the foundation for all my accomplishments. Their unconditional love, resilience, and guidance have been a constant source of strength and inspiration throughout the highs and lows of this academic journey.

This research would not have been possible without the collective support of all these individuals, and for that, I extend my heartfelt gratitude.

Date:

(Ajay Solanki)

Place:

ABSTRACT

Three Dimensional and Four-Dimensional (3D/4D) printing has widespread popularity because of its shape-changing capabilities in various applications. 3D Printing makes only stationary structured products whereas 3D/4D printing enables an object to change its configuration in response with different external stimuli. Researchers from many fields have examined an extensive array of 3D/4D printing using proofs-of-concept. 3D/4D printing needs more advancement in the structural quality and efficiency to satisfy significant industrial applications which ensure cost effective manufacturing. An overview of integrated computation design strategies and its contribution in enhancing efficient use of smart materials in vast applications also presented and concluded with the findings like systematically incorporating sustainability variables into cost- effectiveness analyses with recent advancements in additive manufacturing tailored with human material interaction aids industries to make informed decisions that align with economic goals. Future views are critically explored and encouraging the collaboration with fabrication methods directs research efforts in a way incorporating advanced 3D/4D product design methods that satisfy industry and customer demands.

Three Dimensional and Four-Dimensional (3D/4D) printing is an emerging structure creation process that allows for form morphing in response to external triggering chemicals. Many studies currently concentrate on small to medium-sized 3D/4D printing of structural components. As a result, in order to build industry-based large-scale structures, printing capabilities must be increased without sacrificing quality, cost, and speed. Advances in computer-aided design modeling have led to the development of 3D/4D products, which are essential for the large-scale manufacture of structures for various engineering purposes. Furthermore, cost-effective design and quality assurance control techniques, along with obstacles, are highlighted.

Researchers previously encountered challenges in achieving high material efficiency and precise control in laser metal wire deposition, such as variability in friction, fluctuations in deposition rates, and inconsistent hardness across different scanning speeds and power settings. This research focuses on the single deposition technique within laser metal wire deposition, evaluating material usage and deposition efficiency by analysing factors like wire feed rate, laser power, and deposition speed. Findings indicate that coefficient of friction increases with higher scanning speeds, particularly at a sliding velocity of 0.5 m/sec. Furthermore, there were considerable changes in hardness and deposition rate, with the largest deposition rate occurring at the lowest scanning speed of 0.4 m/min. The research implications are significant for industries requiring complex, high-quality metal

components, positioning laser metal wire deposition as a key solution for modern manufacturing challenges.

Supply chain management is poised for a transformative shift through the adoption of 3D and 4D printing technologies, which enable localized manufacturing, lead time reductions of up to 65%, and inventory cost savings of approximately 67%. These technologies support the growing demand for customized products by fostering a supply chain that is more responsive, adaptive, flexible, efficient, and cost-effective. 4D printing further enhances product lifecycle management by allowing objects to change shape or function over time, improving overall performance and longevity. The proposed impact analysis demonstrates streamlined adaptation of manufacturing processes, contributing to environmental sustainability through significant waste reduction. Integration of high-value design principles and additive manufacturing improved key dimensions like agility, visibility, collaboration, and flexibility by 15–20 points each, while stakeholder support remained strong, with 62.5% endorsing 3D/4D adoption, 67.8% favouring faster delivery, and over 57% supporting digital integration strategies.

Conventional manufacturing methods have always been riddled with shortcomings such as wastage of material, design limitations, and added cost of manufacturing. Conventional methods fail to work efficiently with complex geometries, leading to wasteful use of material and longer production time. In contrast to this, the advent of 3D and 4D printing eliminated such shortcomings by improving design freedom, minimization of waste, and enhancing the manufacturing process. Fishbone diagram analysis is used to identifying the influences of mechanical performance, sustainability, and cost. Mechanical testing indicates hardness is up to 70.3, and young's modulus has a high negative correlation with layer height, which influences the structural integrity. Material selection is the determining factor in establishing the balance of durability, flexibility, and adaptability for optimum performance. Sustainability analysis reflects that additive manufacturing minimizes the wastage of material by nearly 30 percent against conventional means, paving the way for environmental-friendly production. Further, a cost analysis has reflected 25 percent lower production costs, so 3D and 4D printing has become more economical. The evidence points out that incorporating design for manufacturing and design for additive manufacturing boosts the efficiency, performance, and sustainability, establishing additive manufacturing as the revolutionary option beyond conventional means.

Keywords: *Additive Manufacturing, 3D Printing/4D Printing, Integrated Design, Design Optimization, Laser Metal Wire Deposition, Design for Manufacturing (DfM), Design for Additive Manufacturing (DfAM), High-value Design, Customized Design, Material Selection, Sustainability, Cost-effectiveness.*

LIST OF PUBLICATIONS

Publications in Refereed International Journals (Thesis)

- [1] **A. Solanki**, M.S. Ranganath, A.K.S. Singholi, Review on advancements in 3D/4D printing for enhancing efficiency, cost-effectiveness, and quality, *Int. J. Interact. Des. Manuf.* 19 (2025) 3153–3169. <https://doi.org/10.1007/s12008-024-02029-0>. (I.F.= 2.5).
- [2] **A. Solanki**, M.S. Ranganath, A.K.S. Singholi, Laser Metal Wire Deposition for Additive Manufacturing of Complex Solid Structures, *J. Adv. Manuf. Syst.* 24 (2025) 573–594. <https://doi.org/10.1142/S021968672550026X>. (I.F.= 1.1).
- [3] **A. Solanki**, M.S. Ranganath, A.K.S. Singholi, Optimizing 3D/4D Printing for Large-Scale Prototyping: A Comprehensive Review on Speed, Cost, and Quality Challenges, *J. Inst. Eng. Ser. C.* 106 (2025) 1151–1164. <https://doi.org/10.1007/s40032-025-01222-8>. (I.F.= 1.59).
- [4] **A. Solanki**, M.S. Ranganath, A.K.S. Singholi, Transformative Impact of 3D/4D Printing on Supply Chain Dynamics through High-Value Design Concepts, *J. Adv. Manuf. Syst.* (Accepted and published). <https://doi.org/10.1142/S0219686727500375>. (I.F.= 1.1).

International Conferences

- [1] **A. Solanki**, M.S. Ranganath, A.K.S. Singholi, (2024), “Advancements in Laser Wire based Directed Energy Deposition for Additive manufacturing and Repair Applications”, International Conference of Advance Research and Innovation (ICARI-2024) at Delhi State Center, Institution of Engineers (India), New Delhi, India on 28th January 2024.
- [2] **A. Solanki**, M.S. Ranganath, A.K.S. Singholi, (2024), “Future Role of 3D/4D Printing in the supply chain management of railway industry”, International Conference of Advance Research and Innovation (ICARI-2024) at Delhi State Center, Institution of Engineers (India), New Delhi, India on 28th January 2024.

TABLE OF CONTENTS

Title	Page No.
Certificate	i
Acknowledgements	iii
Abstract	v
List of Tables	xiii
List of Figures	xv
List of Abbreviations	xviii
List of Symbols	xix
<hr/>	
CHAPTER 1: INTRODUCTION	2
1.1 BACKGROUND AND SIGNIFICANCE OF 3D/4D PRINTING	2
1.2 INDUSTRY APPLICATIONS AND EMERGING TRENDS	3
1.2.1 Automotive and Aerospace	5
1.2.2 Healthcare and Medical Devices	7
1.2.3 Construction and Infrastructure	9
1.3 COMPARISON OF TRADITIONAL VS. ADDITIVE MANUFACTURING TECHNIQUES	10
1.3.1 Traditional Manufacturing Techniques	10
1.3.2 Additive Manufacturing Techniques (3D/4D Printing)	11
1.4 NEED FOR INNOVATION: DfM AND DfAM CONCEPTS	13
1.5 RESEARCH OBJECTIVES, RESEARCH AIM AND PROBLEM STATEMENT	16
1.6 THESIS OUTLINE AND CHAPTER SUMMARIES	17
CHAPTER 2: LITERATURE REVIEW	21
2.1 HISTORICAL EVOLUTION OF ADDITIVE MANUFACTURING	21
2.2 MATERIAL ADVANCEMENTS IN 3D/4D PRINTING	23
2.3 PROCESS OPTIMIZATION AND DESIGN STRATEGIES	27
2.4 COST-EFFECTIVENESS AND ECONOMIC VIABILITY ANALYSIS	30
2.4.1 Tabulated Cost Comparisons	33

2.4.2	Return on Investment for Additive Manufacturing.....	34
2.5	MATERIAL EFFICIENCY AND SUSTAINABILITY FACTORS	36
2.6	CHALLENGES IN LARGE-SCALE PRINTING	39
2.6.1	Space and Size Constraints	42
2.6.2	Post-Processing and Surface Finishing.....	42
2.6.3	Machine Advancements and Precision Improvements	43
2.7	REAL-WORLD CASE STUDIES.....	43
2.7.1	House Building and Construction.....	45
2.7.2	Shipbuilding and Heavy Machinery	46
2.7.3	Robotics and Automated Production Lines	46
CHAPTER 3: OPTIMIZING 3D/4D PRINTING TECHNOLOGY FOR LARGE-SCALE PROTOTYPING: ADDRESSING SPEED, COST, AND QUALITY CONTROL CHALLENGES		49
3.1	INTRODUCTION	49
3.1.1	Process of 3D/4D printing	52
3.1.2	3D/4D Technology Methods of printing.....	52
3.1.3	Key Components For 3D/4D fabrication.....	53
3.2	LARGE SCALE-BASED PROTOTYPING.....	55
3.2.1	Working principle	56
3.2.2	Materials Used.....	57
3.2.3	Current State of the Art in Large-Scale Prototypes Extrusion Machines	58
3.3	CHALLENGES OF UPSIZING THE 3D/4D PROTOTYPING	61
3.3.1	Speed Control Challenges	61
3.3.2	Quality of the Product Challenges.....	63
3.3.3	Process Standardizing Challenges	64
3.3.4	Cost Challenges	65
3.4	EXISTING SOLUTIONS AND OPPORTUNITIES	65
CHAPTER 4: LASER METAL WIRE DEPOSITION FOR ADDITIVE MANUFACTURING OF COMPLEX SOLID STRUCTURES		68
4.1	INTRODUCTION	68
4.1.1	Key Components of Laser Metal Weld Deposition	69

4.1.2	Printing Process	69
4.1.3	Systematic Protocol to Fabricate a Metal Structure	70
4.2	SYSTEM UNDER CONSIDERATION FOR INVESTIGATING LASER METAL WELD DEPOSITION	71
4.2.1	Laser Metal Wire Deposition System.....	72
4.2.2	Control Software Architecture	73
4.2.3	Mathematical Formulation for Printing Solid 3D/4D Structures	74
4.2.4	Material Usage Efficiency	75
4.2.5	Deposition Efficiency Calculation.....	75
4.3	RESULTS AND DISCUSSIONS.....	77
4.3.1	Testing Configuration	77
4.3.2	Single-Layer Deposition.....	80
4.3.3	Calculation of Deposition Efficiency	80
4.3.4	Effect of Coefficient of Friction at Diverse Loading Scenarios	81
4.3.5	Analysis on Deposition Rate and Hardness of the Printed Solid Structures	82
4.3.6	Scanning Electron Microscope Analysis	85
4.3.7	X-Ray Diffraction Assessment	86
4.3.8	Discussions	87
CHAPTER 5:	TRANSFORMATIVE IMPACT OF 3D/4D PRINTING ON SUPPLY CHAIN DYNAMICS THROUGH HIGH-VALUE DESIGN CONCEPTS.....	90
5.1	INTRODUCTION	90
5.1.1	Methods of 3D/4D Printing	91
5.1.2	Contribution of the Proposed Framework	93
5.2	PROPOSED SUPPLY CHAIN DYNAMICS THROUGH HIGH-VALUE DESIGN FRAMEWORK.....	94
5.2.1	Hypothesis Development.....	94
5.2.2	Technical Assessment	95
5.2.3	Proposed 3D/4D Printing Adoption in Supply Chain Dynamics Control	97
5.2.4	High Value Design Principles Integration with Supply Chain Analysis.....	99
5.3	PROPOSED DESIGN FOR SUPPLY CHAIN OPTIMIZATION.....	99
5.3.1	Advanced Forecasting and Demand Planning.....	99

5.3.2	Lean and Agile Supply Chain Strategies	100
5.3.3	Integration with Industry 4.0 Technology	100
5.3.4	Sustainability and Circular Economy	100
5.3.5	Risk Management and Resilience.....	101
5.4	EMPIRICAL RESEARCH EVALUATION	101
5.4.1	Case Study Selection	102
5.4.2	Survey Design and Instrumentation.....	102
5.4.3	Simulated Model for Supply Chain System Dynamics	103
5.4.4	Key Performance Indicators Assessment.....	105
5.5	RESEARCH SURVEY FINDINGS.....	105
5.5.1	Comparison of Supply Chain Dynamics Model.....	106
5.5.2	Scenario with Impact Assessment Of 3D/4D Adoption in Supply Chain Dynamics	106
5.5.3	Scenario with Impact of Integrated High-Value Design Principle Adoption Analysis	107
5.6	STRATEGIC FRAMEWORK DEVELOPMENT	109
5.7	DISCUSSIONS WITH PROPOSED STRATEGIC FRAMEWORK	110
CHAPTER 6: SUSTAINABILITY AND COST OPTIMIZATION IN 3D/4D PRINTING: USING FISH BONE DIAGRAMS FOR PRINTABILITY IMPROVEMENT		113
6.1	INTRODUCTION	113
6.1.1	Sustainable 3D/4D Printing Development.....	114
6.1.2	Cost Optimization in 3D/4D Printing Implementation.....	115
6.1.3	Fish Bone Diagrams	117
6.2	SUSTAINABILITY AND COST OPTIMIZATION IN 3D/4D PRINTING.....	117
6.2.1	Analysis of Sustainability and Cost Optimization in 3D/4D Printing Through Fishbone Diagram.....	119
6.2.2	Materials	120
6.2.3	Laser Metal Wire Deposition System.....	120
6.2.4	Analysis of Sustainability and Optimization of 3D Printing	122
6.3	RESULTS AND DISCUSSIONS.....	124
6.3.1	Instrumentation Framework	125
6.3.2	Optimal Printing Factors of All Single-Objective Optimizations.....	126
6.3.3	Mechanical Analysis.....	130

CHAPTER 7: RESULTS AND ANALYSIS	135
CHAPTER 8: CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT	140
8.1 INTRODUCTION	140
8.2 MAJOR FINDINGS	140
8.3 FINDINGS REGARDING EFFICIENT PRODUCTION AND MATERIAL WASTAGE 	141
8.4 FINDINGS REGARDING COST-EFFECTIVE SUPPLY CHAIN.....	141
8.5 FINDINGS REGARDING SUSTAINABILITY AND COST OPTIMIZATION	141
8.6 CONCLUDING REMARKS	142
8.7 SIGNIFICANCE OF THE STUDY.....	142
8.8 FUTURE SCOPE.....	142
8.9 SOCIAL IMPACT	144
REFERENCES	145

LIST OF TABLES

Table 1.1 Comparison of Traditional vs. Additive Manufacturing Techniques.....	12
Table 2.1 Summary of Material Advancements in 3D/4D Printing: Advantages and Disadvantages.	25
Table 2.2 Process Optimization and Design Strategies in 3D/4D Printing	29
Table 2.3 Cost-Effectiveness and Economic Viability Analysis in 3D/4D Printing.....	32
Table 2.4 Comparative analysis of key cost factors between Additive Manufacturing (AM) and Traditional Manufacturing (TM).....	33
Table 2.5 Material Efficiency and Sustainability Factors in 3D/4D Printing.....	37
Table 2.6 Challenges in Large-Scale Printing Techniques.....	40
Table 2.7 Real-World Case Studies Demonstrating Additive Manufacturing Techniques, Advantages, and Limitations	44
Table 3.1 Analysis of the large scale-based prototyping.....	55
Table 3.2 Thermoplastic composite filaments that are commercially available.....	58
Table 3.3 Recent extrusion-based 3D/4D printer application in large scale manufacturing	60
Table 3.4 Summary of challenges and optimization approaches for scaling 3D/4D printing	62
Table 3.5 Analysis of key focus areas in additive manufacturing standardization.....	64
Table 4.1 Main parameters of the prototype of LMWD system.....	78
Table 4.2 Chemical constitution of the specimen.....	79
Table 4.3 Outcomes of XRD Analysis	87
Table 5.1 Assessment of technical feasibility with AM integrated supply chain.....	96
Table 5.2 Explanations for the variables mentioned in Figure 5.9.....	104
Table 6.1 Chemical composition of the materials	120
Table 6.2 Major parameters of the prototype of LMWD system	122
Table 6.3 Main parameters of the prototype of LMWD system.....	125
Table 6.4 Mean values and S/N ratios of the analytical outcomes	128
Table 6.5 All multi objective optimal constraints	130

Table 6.6 Means for energy consumed..... 132

LIST OF FIGURES

Figure 1.1 Comparison Between 3D and 4D Printing Processes	3
Figure 1.2 Integration of 3D Printing Techniques, Materials, and Applications Towards 4D Bioprinting Technology.....	5
Figure 1.3 Applications of Additive Manufacturing in Automotive and Aerospace Industries	6
Figure 1.4 Applications of Additive Manufacturing in Healthcare and Medical Devices	8
Figure 1.5 Technological Innovations in Construction and Infrastructure	9
Figure 1.6 Comparison Between Traditional and Additive Manufacturing Techniques.....	13
Figure 1.7 Transition from Traditional Design for Manufacturing to Design for Additive Manufacturing.....	14
Figure 1.8 Comprehensive Overview of 3D and 4D Printing Technologies and Their Evolution	15
Figure 1.9 Key Challenges in Traditional Manufacturing Processes	17
Figure 1.10 Organization of thesis	18
Figure 3.1 3D/4D printing design and structure of products	50
Figure 3.2 Worldwide Market Scenario forecasts in 3D/4D printing a) Market size (b) Market growth of 3D/4D printing in industry (c) Market growth contribution based on regions.....	51
Figure 3.3 Process of 3D/4D Printing.....	52
Figure 3.4 Architecture for 3D/4D printing processes based on industry design modeling.....	53
Figure 3.5 Architecture of key components for 3D/4D fabrication.....	54
Figure 3.6 Device structure of FDM	56
Figure 3.7 Large scale manufacturing industry framework (a) Using the BAAM-CI method large size automobile chassis are 3D/4D manufactured (b) A printed automobile chassis that has several cracks which are shown by white arrow (c) Using a thermal camera with FDM to print and check the surface temperature (d) Thermal camera picture displaying blue cooling zones and orange hot areas	59
Figure 3.8 Analysis for 3D/4D printing challenges and considerations	63
Figure 3.9 Cost forecasting for the large-scale 3D/4D printing sector.....	65
Figure 4.1 Key components of LMWD.....	69

Figure 4.2 The workflow of the printing process	70
Figure 4.3 Systematic Protocol to Fabricate a Metal Structure	71
Figure 4.4 Proposed architecture for additive manufacturing of complex solid structures	72
Figure 4.5 Working principle of LMWD technique	73
Figure 4.6 Control software architecture	74
Figure 4.7 Specimen setup in the Meltio 3D Printer	77
Figure 4.8 Pictorial representation of (a) Circular insert with internal features (b) Rectangular block with angled channels	79
Figure 4.9 Contour plots for three variable pulse duration (a) speed, $x = 6.5$ ms (b) $x = 8.1$ ms and (c) $x = 9.2$ ms.....	80
Figure 4.10 Deposition efficiency of (a) Single layer deposition (b) multi-layer deposition.....	81
Figure 4.11 Variation of coefficient of friction at diverse normal loads of (a) 20 N, (b) 40 N, and (c) 60 N with different scanning speeds and sliding velocity	82
Figure 4.12 Impact of deposition rate on the solid structures at variable speeds	83
Figure 4.13 Effect of hardness on the solid structures at variable speeds	83
Figure 4.14 Analysis of Vickers Microhardness test (a) Single layer deposition (b) Multilayer deposition.....	84
Figure 4.15 Single layer deposited 3D Material of SS316.....	85
Figure 4.16 XRD Analysis of the single deposited layer of SS316.....	86
Figure 5.1 Overview of supply chain management.....	91
Figure 5.2 3D/4D printed additive manufacturing process strategy.....	92
Figure 5.3 Differences between 3D and 4D printing.....	92
Figure 5.4 Proposed research analysis process workflow	93
Figure 5.5 Developed research hypothesis for the proposed empirical analysis	95
Figure 5.6 Service of 3D/4D printing integrated supply chain dynamics control strategy.....	97
Figure 5.7 Benefits of supply chain dynamics with 3D/4D printed additive manufacturing	98
Figure 5.8 Proposed AM supply chain control with high value design principles.....	98
Figure 5.9 Simplified simulation model of the supply chain dynamics with 3D/4D adoption	103

Figure 5.10 Comparison with simulated and empirical research data.....106

Figure 5.11 Influence of 3D/4D printing adoption on Company X accessory availability107

Figure 5.12 Analysis of cost reduction by proposed integration in supply chain dynamics108

Figure 5.13 Analysis of inventory levels by proposed integration in supply chain dynamics108

Figure 5.14 Analysis of lead time by proposed integration in supply chain dynamics109

Figure 5.15 Analysis of environmental impact by proposed integration.....109

Figure 6.1 Framework for sustainable development of 3D/4D printing.....114

Figure 6.2 Overview of Cost Optimization in 3D/4D Printing Development116

Figure 6.3 Structure of Fishbone Diagram117

Figure 6.4 Sustainability and cost optimization in 3D/4D printing.....118

Figure 6.5 Analysis of sustainability through fishbone diagram.....119

Figure 6.6 Working principle of LMWD technique121

Figure 6.7 Specimen setup in the Meltio 3D Printer124

Figure 6.8 Energy consumption of printing cycle126

Figure 6.9 (a) Circular Insert with Internal Features (b) Rectangular Block with Angled Channels
.....127

Figure 6.10 Mean effects plot: (a) W (Weight), (b) OW (Operational Waste), (c) OL (Overlapping
Layers) (e) carbon dioxide emissions, (f) material cost, (g) labour cost, (h) electricity cost.....129

Figure 6.11 Impact of variables of all single objectives130

Figure 6.12 Mechanical analysis of (a) Wear rate (b) Hardness (c) Young's Modulus.....131

Figure 6.13 Analysis of coefficient of friction of printed materials132

LIST OF ABBREVIATIONS

- 3D/4D: Three dimensional and four-dimensional
- ABS: Acrylonitrile butadiene styrene
- AFRL: Air Force Research Laboratory
- AI: Artificial intelligence
- AM: Additive manufacturing
- APS: Advanced photon source
- ASTM: American Society for Testing and Materials
- BAAM-CI: Big area additive manufacturing-Cincinnati incorporated
- BJ: Binder jetting
- CAD: Computer-aided design
- CAGR: Compound annual growth rate
- CLIP: Continuous liquid interface production
- CNC: Computerized numerical control
- CNT: Carbon nanotube
- DARPA: Defense Advanced Research Projects Agency
- DfM: Design for Manufacturing
- DfAM: Design for Additive Manufacturing
- DED: Direct energy deposition
- DLP: Digital light processing
- ESRF: European synchrotron radiation facility
- FDM: Fused deposition modeling
- HIPS: High-impact polystyrene
- IoT: Internet-of-things
- ISO: International organization for standardization
- MJ: Material jetting
- ML: Machine learning
- MWCNTI: Multiwall carbon nanotube insulator
- NASA: National aeronautics and space administration
- NDE: Non-destructive evaluation
- NIH: National Institutes of Health
- NIST: National Institute of Standards and Technology
- NSF: National Science Foundation
- ONR: Office of Naval research
- PC: Polycarbonate
- PETG: Polyethylene terephthalate glycol
- PLA: Polylactic acid
- PPE: Personal protective equipment
- SLA: Stereolithography
- SLS: Selective laser sintering
- SMA: Shape memory alloy
- SMP: Shape memory polymer
- TC: Technical Committee
- WAAM: Wire arc additive manufacturing
- WF: Wood-fiber

LIST OF SYMBOLS

	Symbols	Description
•	μm	micrometer
•	kW	Kilowatt
•	mm	millimeter
•	K_d	Deposit volume
•	K_w	Wire Volume
•	η	Efficiency
•	PE_j	Print Efficiency
•	Maxi(D)	Maximum energy consumption
•	THR_i	Throughput delay
•	Q_{ry}	Single deposition layer
•	Q_{ty}	Multiple deposition layer
•	V_w	Volume of wire
•	d_w	Wire Diameter
•	$^{\circ}\text{C}$	Degree Celsius
•	e	Constant length
•	γ	Normal constant transverse variable speed
•	$r_i^{(0)}(k)$	Value of K^{th} nominal objectives
•	ω_j	Computed weight of j^{th} objective
•	nm	Nanometer
•	Kg	Kilogram
•	V	Volt
•	K_r	Rejection Volume
•	K_w	Total Product volume

CHAPTER- 1

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND AND SIGNIFICANCE OF 3D/4D PRINTING

Additive manufacturing, popularly called three-dimensional printing, is a technique of producing physical objects by layering them together through a 3D printer from a digital model or computer design. In the 1980s, this technology is simply referred to as rapid prototyping [1]. It is used for creating functional or aesthetically pleasing prototypes. Nevertheless, with improvements in precision, consistency, and material variation, 3D printing has come to be a viable technique for industrial production. Additive manufacturing is now commonly used across numerous sectors such as engineering, manufacturing, healthcare, and aerospace. It is especially appreciated because it is used to create lightweight, complex structures that are challenging or impossible to make with conventional manufacturing techniques. Thus, 3D printing has revolutionized component and equipment design as well as manufacture, one of the most consequential innovations in recent manufacturing. Three decades ago, the technology upon which 3D printing has developed has improved steadily ever since. A 3D printer works by extruding or deposition in three axes to build up a physical part layer upon layer [2]. The process has evolved, and 4D printing emerged, which added a fourth-dimension time. 4D printing involves objects made by 3D printing methods that are engineered to alter their shape or functionality over time through a response to external stimuli like water, light, temperature, pH, electric or magnetic fields. These changing objects, or 4D printed structures, are made with smart materials that are designed to change their shape or properties when subjected to certain stimuli [3]. For instance, contact with water may make certain materials absorb water and become bigger or smaller, and the entire structure folded or bent as a result of the exact positioning of its pieces. The 4D printing process is just like that of 3D printing, with the only difference being the employment of programmable smart materials [4]. The smart materials are sensitive to changes in their environment, and through this sensitivity, the object is able to change or develop over time. The incorporation of smart materials is a major innovation in additive manufacturing. In addition, multi-material 3D and 4D printing is a key focus of current research and development [5]. By integrating multiple materials into one printed product, it is feasible to improve product performance and functionality in ways not possible using conventional manufacturing. Numerous materials, such as polymers, metals, ceramics, and biomaterials, have been used in these processes to produce intricate, multi-functional products.

Figure 1.1 shows the basic difference between 3D/4D processes. 3D printing thermoplastic polymer is taken as an input material, which a 3D printer processes to create a static object with a specific shape and function. On the contrary, 4D printing involves smart polymers that have been designed

with particular geometries and properties, which enable them to react to external stimuli like temperature, light, or water. The smart materials, combined with clever design, are printed by a 3D printer to produce a smart static object that can change to a dynamic object upon activation by a stimulus.

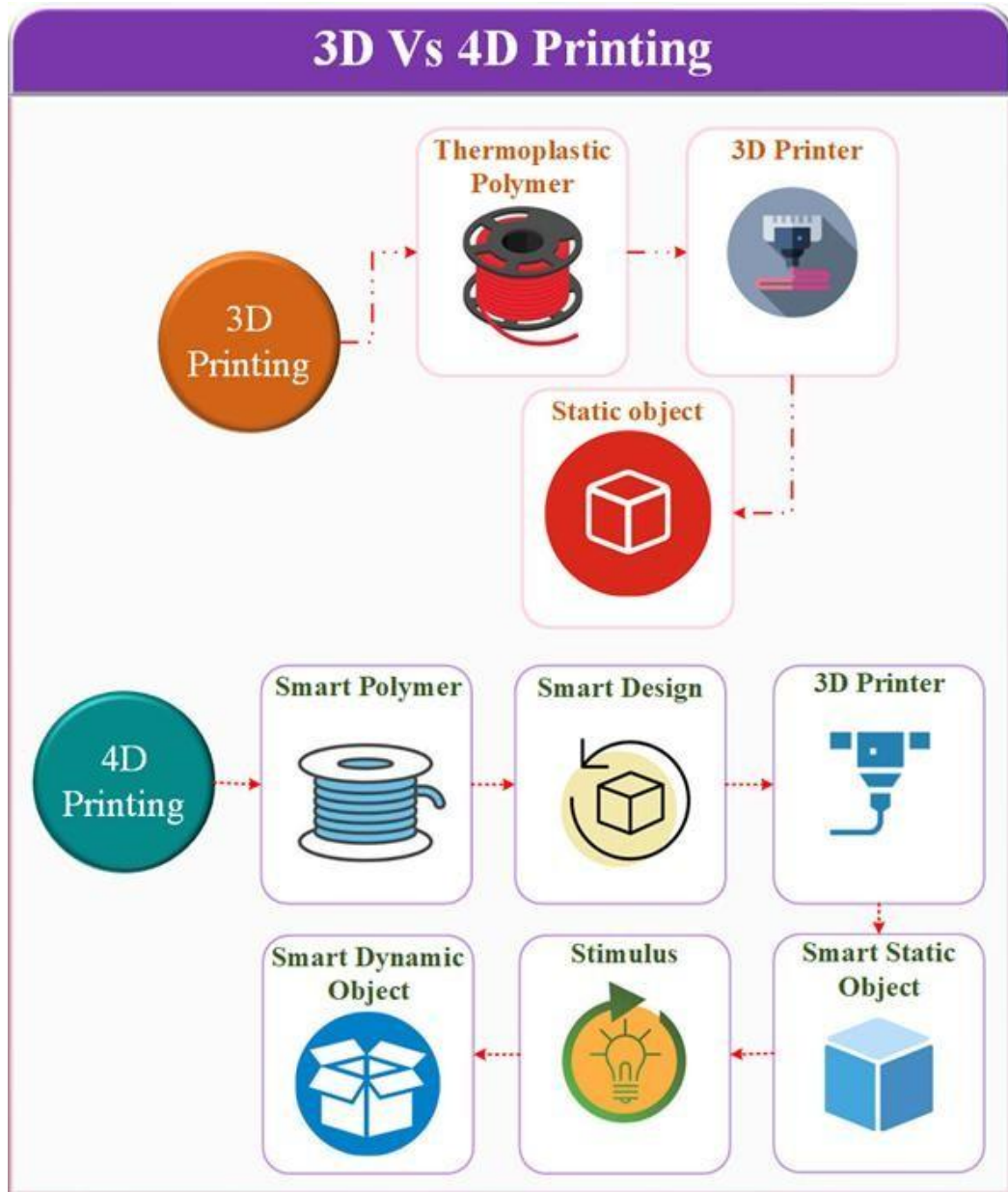


Figure 1.1 Comparison Between 3D and 4D Printing Processes

1.2 INDUSTRY APPLICATIONS AND EMERGING TRENDS

Over the past three decades, additive manufacturing (AM) has seen unrivaled advancement and has become an essential technology for various industries. Initially, other names such as rapid prototyping, layered manufacturing, and solid free-form fabrication, AM has now left its signature in the fields of biomedicine, energy, automobile, and aviation industries. In aerospace, whose geometry is complex and high-technology materials like titanium alloys, nickel-based superalloys,

and high-temperature refractory materials are commonly required, AM provides a cost-effective and faster solution to traditional manufacturing processes. Similarly, AM is beneficial in the automotive industry with its capacity to produce structural and functional complex parts, engine exhausts, drive shafts, gearbox components, and brakes, perfectly suitable for low-production volume runs [6]. In biomedical applications, 3D printing has developed into a tool and research area. It is used to create bone implants, biological scaffolds, artificial organs, medical devices, microvascular networks, and lab-on-chip devices. Most often, the process begins from a computer-aided design (CAD) model, which is cut virtually in layers by software specifically developed for the purpose. Such layers are subsequently printed successively by a 3D printer as part of computer-aided manufacturing (CAM) [7]. The timeline of 3D printing also started with the creation of stereolithography (SLA), a process to create objects of three dimensions through hardening successive layers of photopolymer by ultraviolet light. This began the concept of building objects layer by layer and set the foundation for further advancements to come. One of the most important breakthroughs during this early period is the creation of the standard tessellation language (STL), which bridges the gap between CAD data and hardware used in 3D printing and is still widely used today. As new technologies have emerged, SLA is still one of the most widespread methods used in additive manufacturing [8]. One of the key improvements in the technology is when the technology for fused deposition modelling (FDM) is invented, a process by which material—the most typically thermoplastic polymer in filament—is melted and pushed through a traveling nozzle over a flat plane under computer-actuated movement. This opened up more uses since it is much easier to employ and implement. Another significant advancement is the development of a 3D printing method that utilized an inkjet-type printhead to selectively print a binder over a bed of powder so that parts could be produced with a wide range of materials from plastics to metals to ceramics. This process widened the material capabilities and versatility of AM and paved the way for its eventual widespread use across numerous industries.

Figure 1.2 describes the interrelated aspects of 3D printing, responsible for advancing the 4D bioprinting technology. The basic operations begin with the various 3D printing processes: material jetting, binder jetting, vat polymerization, and powder bed fusion. Materials for 3D printing are categorized according to their properties: mechanical, electrical, thermal, chemical, processing, and biological. Examples of microstructural characteristics include porosity, concentration, crosslink density, and crystallinity. These properties greatly affect the performance and applicability of the printed components. Applications for 3D printing cross industries like aerospace, automotive, electronics, energy, architecture, healthcare, and even tissue and organ fabrication. This accentuates the transition towards 4D bioprinting technology, in which printed structures respond dynamically to stimuli, bridging the aforementioned technologies, materials, and application domains for next-generation biomedical and engineering innovations.

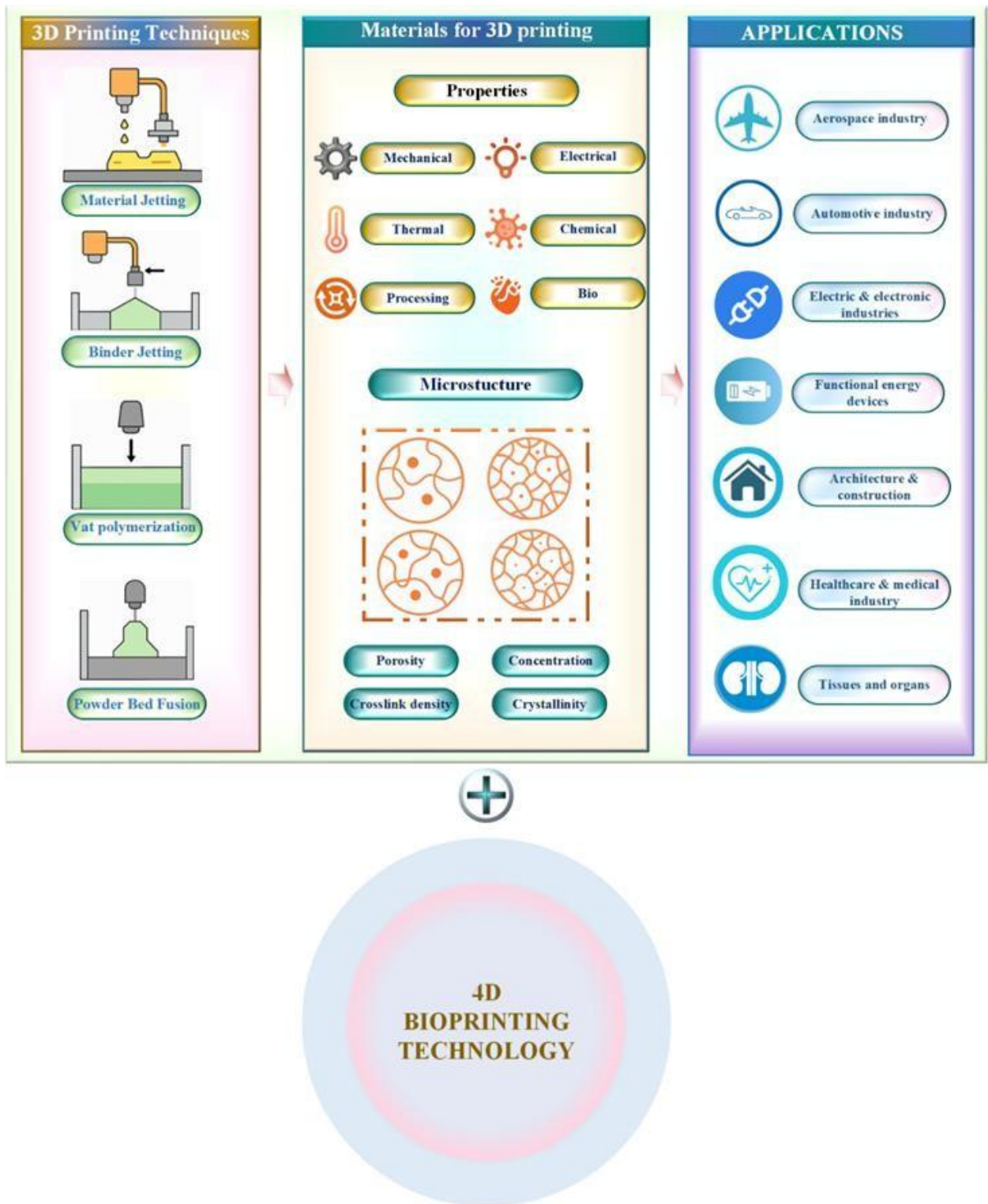


Figure 1.2 Integration of 3D Printing Techniques, Materials, and Applications Towards 4D Bioprinting Technology

1.2.1 Automotive and Aerospace

Additive manufacturing enabled the production of lighter, safer, and greener vehicles with shorter lead times and costs. Another of its important benefits is the ability to easily replicate scarce or out-of-production parts. One main goal in automotive design is to minimize vehicle weight without

sacrificing safety [9]. The AM allows the production of structures with intricate internal geometries, such as honeycomb arrangements and internal voids, that strikes a balance between strength and reduced material utilization. AM has triggered a paradigm shift from traditional design, material choice, and fabrication. It enables the generation of functional components closer to the net shape in rapid time, which supports economic feasibility and reliability. Such technology helps in creating lightweight lattice structures, thereby facilitating the minimization of the total weight of the respective aircraft and maximizing fuel efficiency. Greater use of unmanned aerial vehicles (UAVs) later leads to a requirement for low-cost alternatives to low-volume prototyping and production [10]. Rapid and adaptable manufacturing provided by AM satisfies their need. In the field of space exploration, this technology opens doors to innovative rocket propulsion systems that are capable of supporting bigger payloads. Additionally, having the ability to print pieces directly within space could potentially be the key to the success of forthcoming missions to space.



Figure 1.3 Applications of Additive Manufacturing in Automotive and Aerospace Industries

The applications of AM in the automotive and aerospace sectors are illustrated through examples in Figure 1.3, including the creation of lighter, safer, and more environmentally sustainable vehicles, along with the near-net-shape functional components and complex lattice structures for aerospace

parts. These innovations bring performance gains, reduced wastage of materials, and increase design flexibility, thus contributing toward environmental innovations in both industries.

1.2.2 Healthcare and Medical Devices

The mass consumer uptake of 3D printing has greatly increased its uses in many different industries. Originally a technology that is mainly employed for industrial production, 3D printing has increasingly become an important asset in the healthcare field. Numerous hospitals are currently purchasing in-house 3D printers, and the use of the technology in healthcare is projected to increase further [11]. Current innovations have made it possible to translate radiological scans into solid 3D models, which are able to be scaled and maneuvered to be added directly into surgery. 3D printing is also revolutionizing the pharmaceutical industry, as well as providing new and affordable solutions for patients who need individual prosthetics. Perhaps the most revolutionary development in this area is the ability to print organs and tissue. As 3D modelling and design tools become more available, medical applications of 3D printing are ready for further growth. This technology has also caught the public's attention by offering cheap cures for various ailments. Identifying the growing popularity of 3D printing for medical purposes—and the part that hospital libraries and support systems can play in its adoption—can influence the way healthcare workers adopt this technology [12]. AM, or 3D printing, is a production process that belongs to a digital fabrication workflow and is typical of its capacity to print personalized objects with precision. In the medical field, AM has offered new and beneficial solutions, particularly categorizing into three primary categories: presurgical tools, intra-surgical tools, and implants or replacements. Each of these categories presents unique challenges and benefits, resulting in the development of commercial products now widely used in surgical mechatronic systems and anatomical simulation training. Used as a presurgical device, AM enables one to create exact 3D-printed models of anatomy based on medical image data. Surgeons have a tangible replica of a patient's anatomy with such models, and they enable large-scale preoperative planning. Benefits of using such models are improved operating outcomes, reduced costs, shorter procedures, and improved postoperative recovery. In the operating theatre, AM has enabled the production of tailored instruments such as 3D-printed surgical guides. The guides are pre-shaped to fit the complex contours of organs, enabling surgeons to cut, drill, or resections with greater precision than freehand methods. Aside from guides, other customized medical devices such as hearing aids, dental aligners, and eyeglass frames are also being produced using AM. One of the most exciting areas of research currently is the use of AM for functional implants and even potentially the future creation of fully functional organs. The ability to generate detailed anatomical models from medical images has enabled new opportunities for the generation of biologically viable structures. Scientists are developing and printing advanced scaffolds that trigger cellular growth and differentiation. Meanwhile, AM is already employed in producing implants of complex geometry, especially for

orthopaedic and maxillofacial procedures. While additive manufacturing is not novel, its adoption in medicine is fairly recent. Applications are continually evolving, pushed by increasing patient, hospital, and insurer demand for the potential of Anatomical Engineering. This is a rapidly growing field, providing innovative solutions to difficult medical problems and dramatically enhancing patient outcomes [13]. With ongoing collaboration between surgeons and engineers, and the incorporation of high-resolution imaging technologies like MRI, CT, and ultrasound, the development and implementation of 3D printing in medicine is poised to have a profound effect on patient care and surgical innovation.

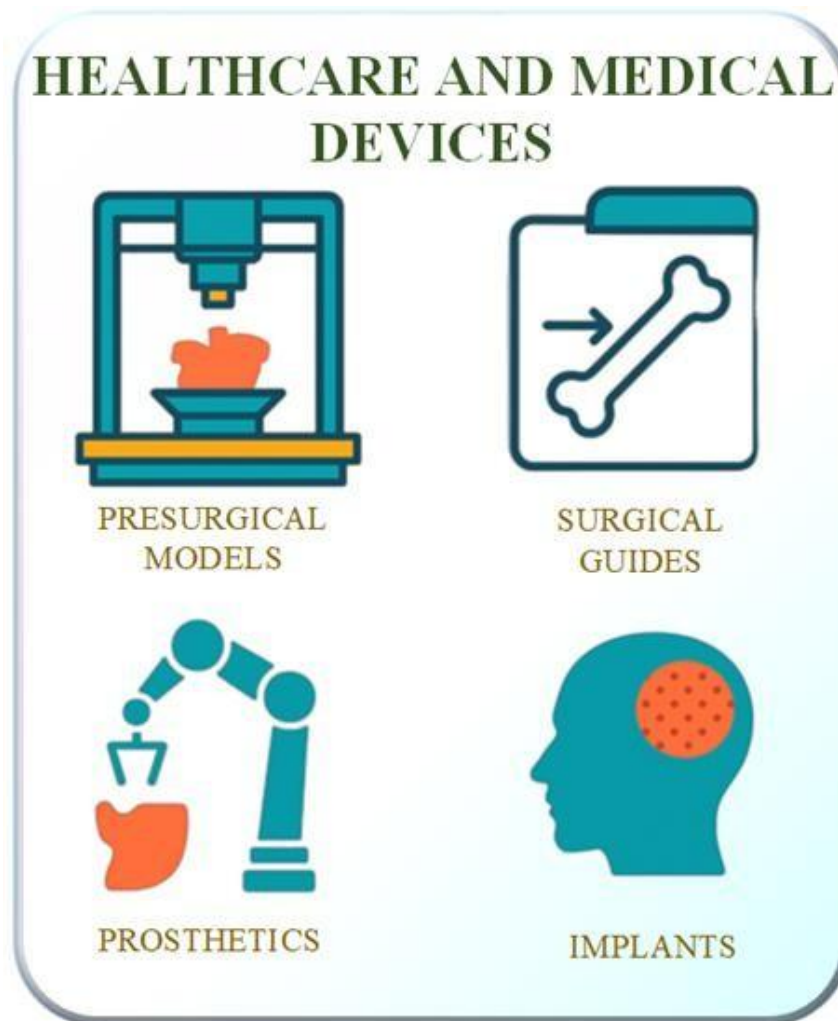


Figure 1.4 Applications of Additive Manufacturing in Healthcare and Medical Devices

The technology of AM in healthcare and medical devices has had a fundamental impact on the regulation of patient care and surgical activities, as demonstrated by the four areas shown in Figure 1.4: presurgical models allowing for more exact planning of complex procedures by surgeons; surgical guides provided at the time of surgery for better precision; prostheses customized for individual patients with better fit and function; and implants designed to match patient anatomy for improved integration and performance. Collectively, these advances offer more efficient, safer, and patient-specific medical solutions.

1.2.3 Construction and Infrastructure

Combining the use of various techniques involving 3D and 4D printing into construction and infrastructural activities deviates from the traditional methods of building and embraces faster, cheaper, and sustainable alternatives [14]. The printing of large architectural components and complete structures layer by layer is possible with 3D printing and entails using materials like concrete, polymers, and composite mixtures. Ultimately, this means less wasted material, reduced construction time, and lowered labor costs, thereby also making the whole process more flexible, allowing how to build customize building elements which are difficult or costly with conventional methods. Four-dimensional printing includes smart materials that function over time according to environmental stimuli like temperature, humidity, or light. It thus introduces in construction self-healing materials, adaptive facades, and infrastructure capable of dynamic environmental response. Bridges and pipelines made with 4D-printed components, for example, could, in theory, respond to thermal expansion or seismic activity during the conflicts, thereby enhancing resilience and longevity [15]. Other trends include using robotic arms and automated systems to assist in large-scale additive manufacturing, the integration of Building Information Modeling (BIM) with 3D/4D printing workflows, and the evolution of eco-friendly materials for 3D/4D printing that support levels of environmentally conscious construction. With these various advances, the additive manufacturing processes have the potential to help in shaping the construction future where infrastructure development would become smart, sustainable, and efficient.

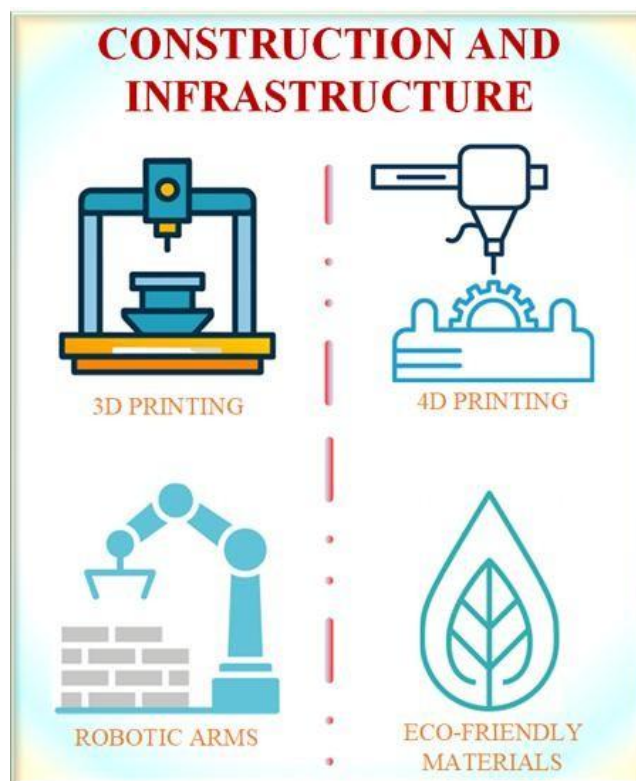


Figure 1.5 Technological Innovations in Construction and Infrastructure

Figure 1.5 shows digital technology processes ranked in order of priority. The glaring technologies highlighted include 3D printing, permitting fast and accurate manufacture of construction components; 4D printing, considered an evolution of 3D printing, where smart materials can transform over a period of time according to environmental stimuli; robotic arms enabling a higher level of automation and efficiency to construction jobs such as bricklaying and assembly; and environmentally friendly materials that are vital for sustainability through the consideration of low environmental impact and promotion of green construction practices. Together, these concepts promote a more efficient building method that is adaptive and sustainable.

1.3 COMPARISON OF TRADITIONAL VS. ADDITIVE MANUFACTURING TECHNIQUES

Manufacturing methods have undergone a transformation in the past decades from subtractive and shape-forming processes to newer advanced additive methods such as 3D/4D printing [16]. It is essential to learn the distinctions among these methods for understanding their purposes in product design, cost savings, customization, and green growth.

1.3.1 Traditional Manufacturing Techniques

This includes some subtractive and formative processes, which have served as the backbone of industrial manufacturing for many years. To be specific, subtractive manufacturing like milling, turning, drilling, etc., is defined as the removal from a solid block through different processes to obtain the desired form. The process provides high dimensions, is extensively used in the production of metallic parts, but results in a great deal of material waste. On the other hand, formative manufacturing processes like injection molding, casting, forging, stamping, etc., reform materials but do not take off material; rather, they use molds or compressive pressure for external shaping. These are capable of bulk production and produce uniform output; however, tooling investments are high at the beginning, and flexibility for design modifications becomes narrow after tooling is done [17]. For most cases, assembly-based production configurations or very few have an assembly-based system because all components are produced separately and later assembled. This could then also lead to complexities in logistics, quality control, and customization, although this is scalable and standardizable. In general, as mature and reliable as these manufacturing techniques may be, they are all limited in that high material wastages, long lead times, low design freedom, and high costs for small-volume or custom production limit them.

1.3.2 Additive Manufacturing Techniques (3D/4D Printing)

Additive manufacturing is more widely referred to as 3D or 4D printing, regarded as a disruptor for the product development and manufacturing industries, constructing an object layer upon layer from a digital model. It reduces wasteful materials and enables designers to create extremely complex geometries, which could not or hardly be produced by conventional subtractive or formative methods. Fused Deposition Modeling (FDM), Selective Laser Sintering (SLS), and Stereolithography (SLA) in 3D printing comprise layer-wise material deposition of varying types including thermoplastics, metals, ceramics, and composites. By contrast, the fourth dimension of 4D means that a printed item can transform or alter in function or shape due to environmental stimulation such as heat, light, or humidity; such technology opens up uses from biomedical implants to self-assembly structures and adaptive wearables. AM also stimulates Design for Additive Manufacturing (DfAM), which encourages innovation in part consolidation, weight reduction, and customization at little tooling cost [18]. It also adds resilience to supply chains by giving them the ability to produce on demand and relatively close to the point of consumption. Challenges still persist with speed, scalability, surface finishing, and consistency in mechanical strength. Nonetheless, these challenges are being addressed, and 3D/4D printing is evolving quickly as a sustainable and agile alternative to traditional manufacturing techniques.

Table 1.1. Conventional manufacturing tends to be based on a subtractive process, where materials are cut, drilled, or milled off from a solid block, with vast amounts of waste and energy. Additive manufacturing (3D/4D printing) adds materials in layers, practically building the geometries without waste and more energy-efficient. Traditional processes are actually targeted toward high-volume, mass production but have poor flexibility against speed-to-market design change and any customization, additive methods on the other hand are more favourable at low production, high complexity, and custom applications. Furthermore, additive manufacturing reduces reliance on highly complicated tooling and molds, thereby significantly shortening lead times. Another factor that makes additive manufacturing stand apart regarding manufacturing geometry is its high design freedom, as this technology can produce geometries that are usually very difficult or impossible to achieve in more traditional means. 4D printing also adds smart materials, which function over a while, bringing forth innovation in applications like health care and aerospace. This comparison is pertinent for understanding the growing significance of additive manufacturing in satisfying modern industrial requirements on efficiency, customization, and sustainability.

Table 1.1 Comparison of Traditional vs. Additive Manufacturing Techniques

Criteria	Traditional Manufacturing	Additive Manufacturing (3D/4D Printing)
Material Usage	Subtractive - significant material wastage	Additive - minimal material wastage
Production Approach	Mass production; centralized facilities	Customization and decentralized/on-demand production
Design Flexibility	Limited due to tooling and machining constraints	High enables complex and intricate geometries
Tooling Requirement	Requires molds, dies, jigs, and fixtures	Minimal or no tooling required
Lead Time	Longer due to setup and tooling	Shorter direct from digital model
Cost Efficiency (Low Volumes)	High cost for low-volume production	Cost-effective for low-volume and custom products
Adaptability to Changes	Inflexible redesign needs new tooling	Highly adaptable quick design changes possible
Energy Consumption	Higher due to machining and material removal	Lower layer-wise material usage
Sustainability	Generates more waste, energy-intensive	Promotes sustainable practices with less waste
Application Fields	Automotive, Aerospace, Industrial Machining	Medical, Aerospace, Construction, Wearables, Robotics

Figure 1.6 indicates a comparative profile of Traditional Manufacturing and Additive Manufacturing with an accentuation of chief differences in procedures, efficiency, and adaptability. Traditional manufacturing is established upon subtractive and formative practices with the likelihood of great amounts of material waste, tool and mold dependence, and limited design adaptability as a feature fitting mass production more appropriately. In contrast, additive manufacturing encompasses a material-saving, tool-free layer-by-layer production method with great customization and complexity capability. Furthermore, additive methods also significantly reduce time-to-market, offering a more agile and sustainable option for today's manufacturing needs.

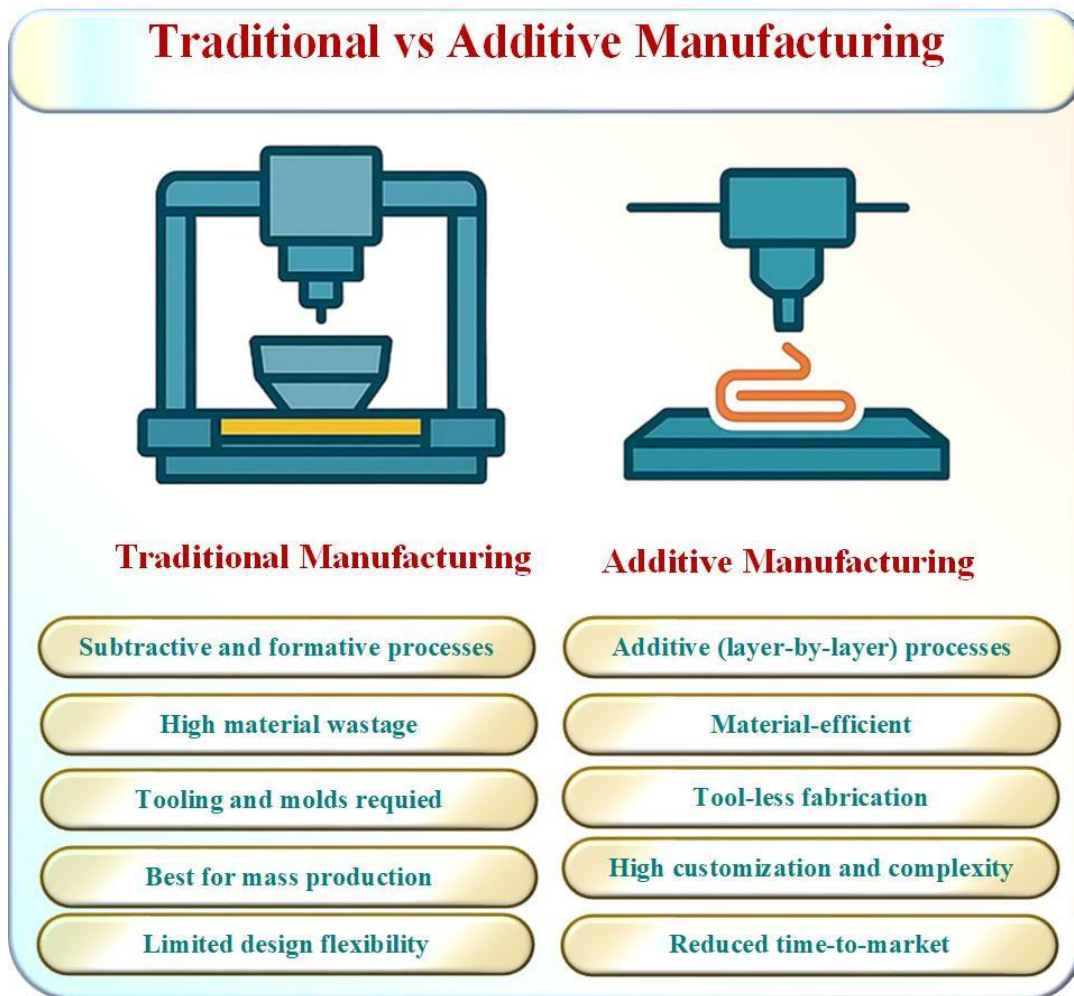


Figure 1.6 Comparison Between Traditional and Additive Manufacturing Techniques

1.4 NEED FOR INNOVATION: DfM AND DfAM CONCEPTS

Innovation speed is quickly becoming an imperative feature in product development. Over the past decades, traditional manufacturing sectors have adopted the Design for Manufacturing (DfM) lines, so that their products can be produced efficiently, cost-effectively, and reliably. DfM primarily minimizes complexity, reduces the number of components involved, and conforms to classical production methods like injection molding, CNC machining, stamping, and casting [19]. This method applies well to high-volume, mass-standardized production but usually restricts the geometrical, customized, and rapid prototyping aspects. With advancing technologies like 3D and 4D printing, the shortcomings have become glaring in DfM. These technologies set the basis for Design for Additive Manufacturing (DfAM), which is a growing and evolving approach in design intended for additive processes. Unlike DfM, designers using DfAM will be empowered to transcend these ordinary confines to design highly complex inner geometries, lattices, and bio-structures that could not be, or would be excessively uneconomical to fabricate, with subtractive technologies. It potentially creates on-demand production, fewer required parts, more highly efficient material use, and personalization at no extra expense of special tooling or intensive runs in production. This

movement from DfM to DfAM provides the dimension of innovation required on an overall basis against completely new industrial challenges. They brought reduced product development time, green design, agile manufacturing systems, and responsive supply networks in modern markets [20]. All these and many more are part of what DfAM requires and offers, as it leads to the new design paradigms generated by computational design, generative modeling, and topology optimization. DfAM does not displace DfM, but it is built on the foundation established by DfM, and from that emerges the demand for hybrid conditions that bring together the reliability of conventional manufacturing with the flexibility and imagination of digital fabrication. This is necessary for the next generation of intelligent, sustainable, and high-performance products.

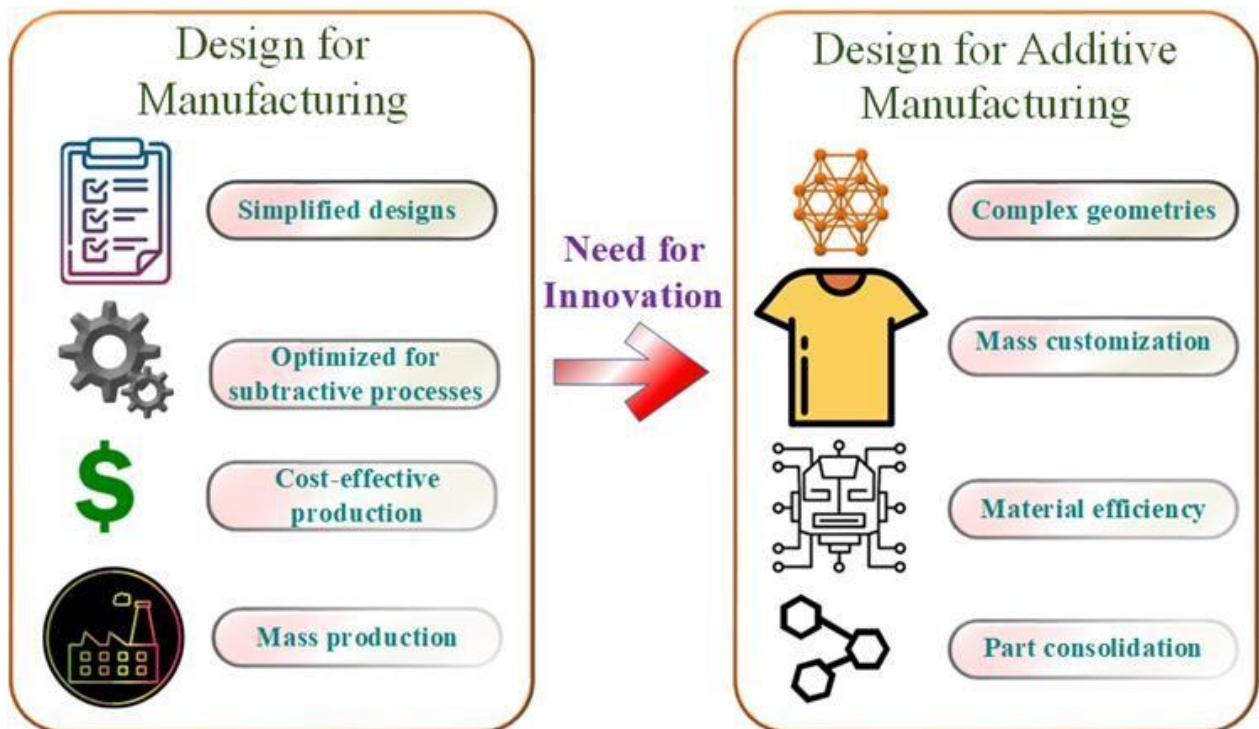


Figure 1.7 Transition from Traditional Design for Manufacturing to Design for Additive Manufacturing

Figure 1.7 explains the transformation from traditional DfM to DfAM, and it also emphasizes innovation in engineering and production strategies. The essential objective of traditional DfM lies in its simplicity in design and production costs and optimization for subtractive manufacturing: what could call for it is mostly mass production. DfAM, on the contrary, is today concerned with much more complex geometry, provides mass customization, is efficient in the use of materials, and allows consolidation of parts—nothing of this nature can be handled in conventional approaches. The shift indicates that how additive manufacturing will now reshape design potential exceeds the limits of customization, efficiency, and performance.

Figure 1.8 prototypes an overview of the history and impact of 3D/4D. Beginning with the elegy for traditional manufacturing, it cried against material waste, time requirement, and a lack of

personalization. The emergence of 3D printing offered enough benefits of additive manufacturing to include less material wastage and faster prototyping. This eventually led to 4D printing, where one would deploy time-responsive materials with shape transformation and smart features. Material innovation through shape-memory polymers and bio-inks underpins such advances. Additionally, the synergism of DfM and DfAM ideas allows optimized shapes, reduced numbers of parts, and internal features. The chart winds up with the future potential of these technologies, with a focus on decentralized manufacturing, responsive smart products, and eco-friendly manufacturing processes, charting a revolutionary change in contemporary production models.

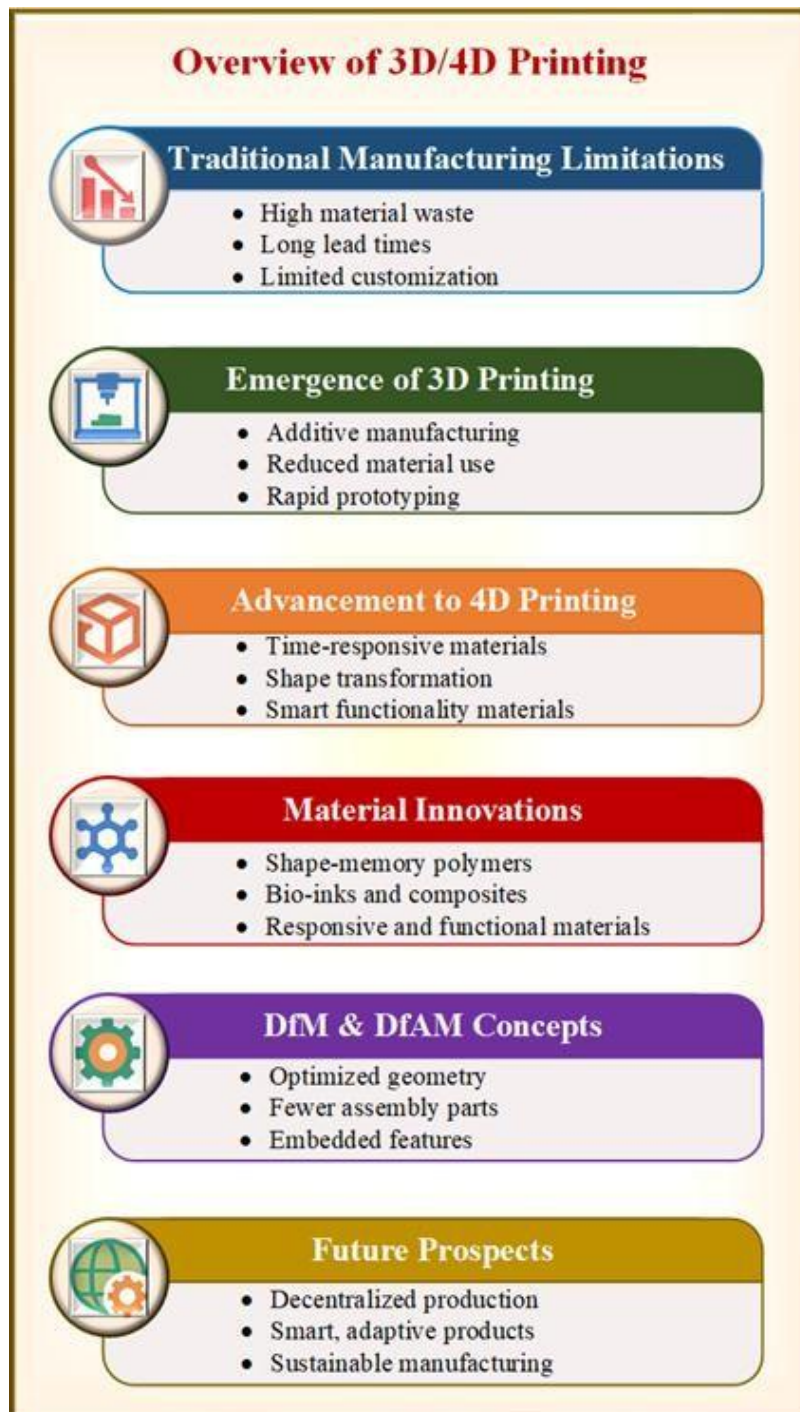


Figure 1.8 Comprehensive Overview of 3D and 4D Printing Technologies and Their Evolution

1.5 RESEARCH OBJECTIVES, RESEARCH AIM AND PROBLEM STATEMENT

To address this issue, the research sets out with the following key objectives:

- A. To explore the technological advancements of emerging 3D/4D printing that can contribute to enhancing the efficiency, cost-effectiveness and improved quality.
- B. To identify and address challenges that arises when transitioning from small scale prototyping to large scale prototyping using 3D/4D printing technology like speed, cost and quality control.
- C. To analyse how 3D/4D printing influences design flexibility and customized design which affects the innovation potential of products.
- D. To examine how 3D/4D printing technologies might disrupt supply chain by enabling localized production and customized products.
- E. To develop a framework for a new product design process aimed at improvising design for manufacturing using 3D/4D printing technology

Research Aim: -

- To analyse the limitations of DfM in the context of modern manufacturing demands.
- To explore the principles and advantages of Design for Additive Manufacturing (DfAM).
- To propose a hybrid product design methodology that integrates DfM and DfAM strategies for optimized functionality and manufacturability.
- To evaluate the role of 3D/4D printing in enabling advanced product designs, including material reduction, lightweighting, part consolidation, and customizable geometries.
- To develop case studies and simulations that compare the effectiveness of traditional and additive design processes.
- To assess how the proposed hybrid design framework can reduce production cost, enhance sustainability, and increase design flexibility.

Figure 1.9 illustrates today's Industry 4.0 age, and there is a steadily rising challenge to conventional manufacturing practices by the need for rapid prototyping, improved product personalization, lightweight structural designs, sustainable manufacturing techniques, and on-demand manufacturing. Conventional Design for Manufacturing (DfM) methods have been in use for decades for successful implementation of subtractive manufacturing processes, yet they are not adequate when used in AM and novel 4D printing technologies. These new manufacturing processes call for entirely novel design paradigms to which classical frameworks are ill-suited. Today's industries have critical

bottlenecks that range from a lack of capability to integrate complicated internal geometries or multi-material compositions, to limitations placed on the industry by the physical boundaries of subtractive tools, difficulty in attaining mass customization without a significant cost increase, and trouble in maximizing products for sustainability both in material use and in energy consumption. Consequently, there is an urgent need to re-engineer and rethink the product design process by incorporating Design for Additive Manufacturing principles. This method presents new opportunities for geometry freedom, part consolidation, resource efficiency, and environmentally friendly design, leading to more innovative and adaptive manufacturing solutions.

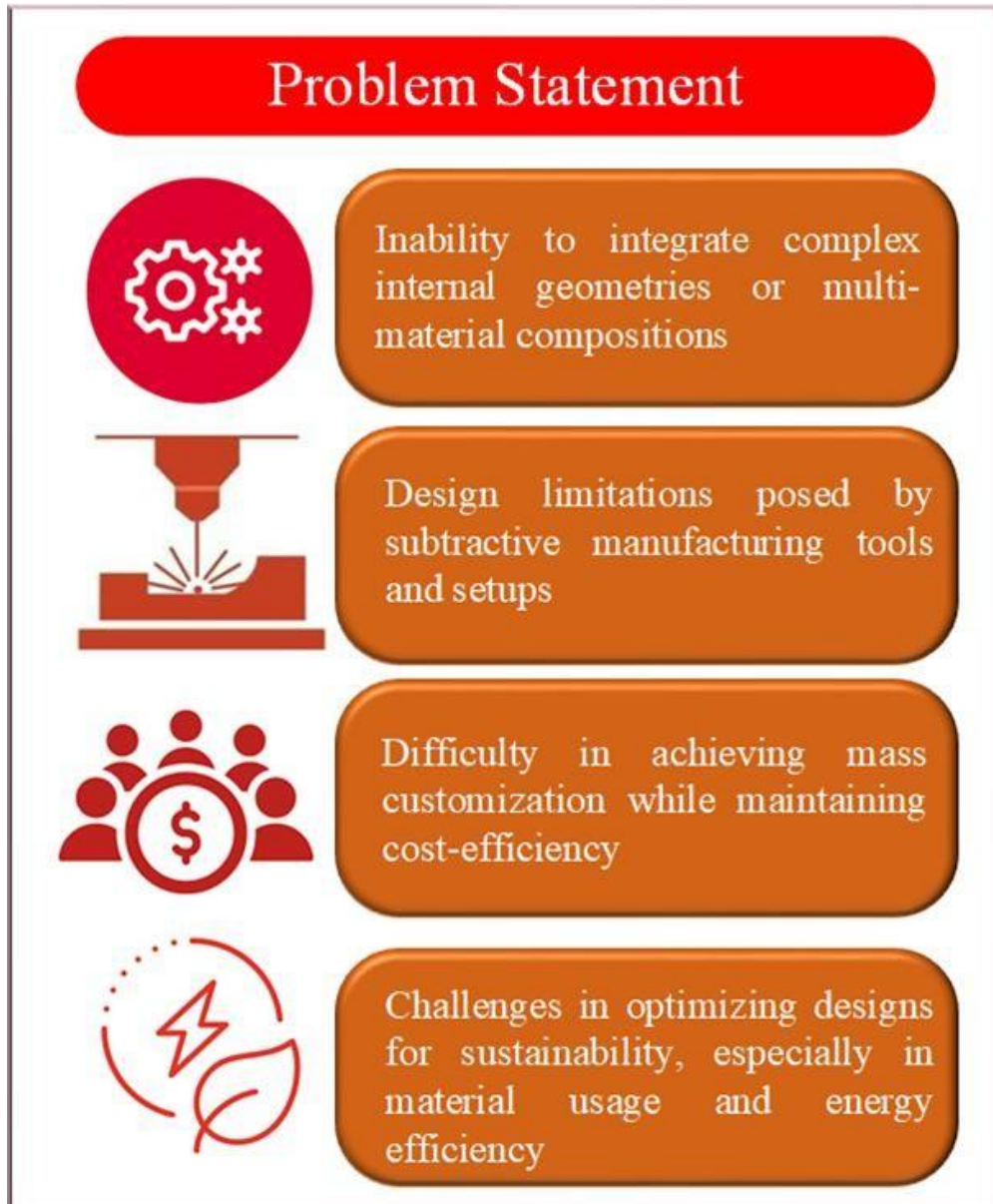


Figure 1.9 Key Challenges in Traditional Manufacturing Processes

1.6 THESIS OUTLINE AND CHAPTER SUMMARIES

This thesis is systematically organized into seven comprehensive chapters, each addressing a key facet of the new product design process aimed at enhancing Design for Manufacturing (DfM) using

advanced 3D and 4D printing technologies. The chapter flow is designed to ensure a coherent progression from foundational concepts to technical experimentation and future-oriented implications.

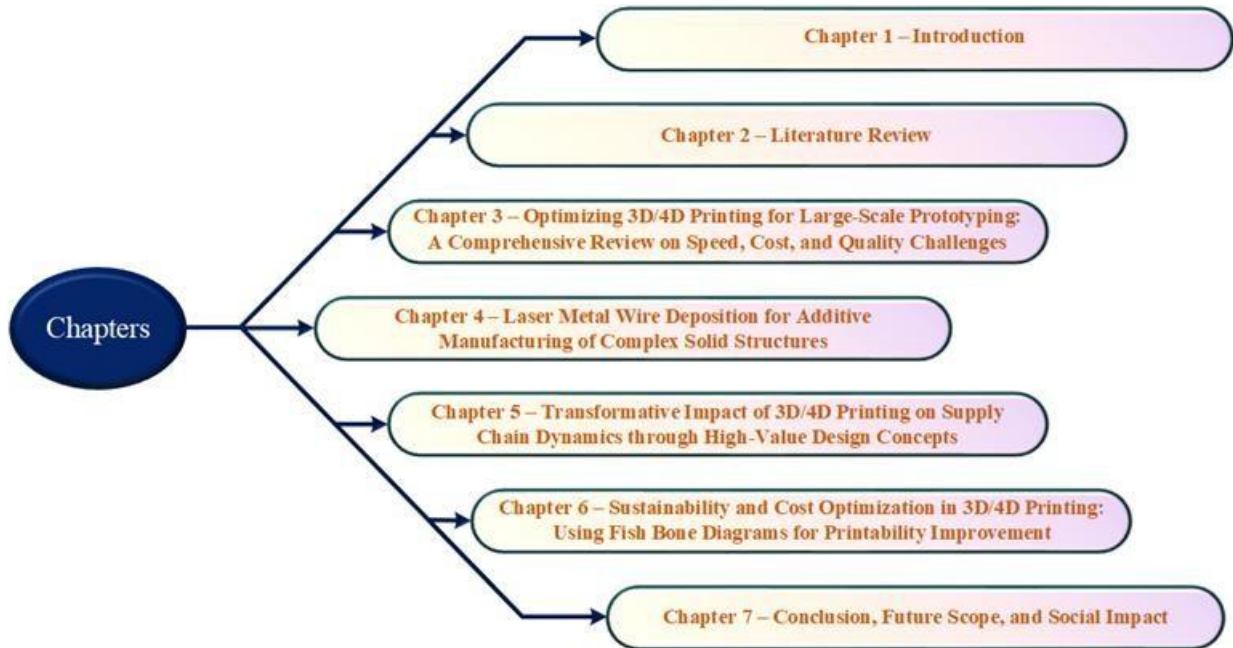


Figure 1.10 Organization of thesis

Figure 1.10 illustrates the chapter-wise structure of the study, beginning with the introduction and literature review, followed by focused chapters on 3D/4D printing optimization, laser metal deposition, supply chain impacts, sustainability, and concluding with future scope and societal implications. Each chapter builds upon the previous to form a comprehensive analysis of additive manufacturing technologies.

➤ **Chapter 1 – Introduction**

This chapter introduces the motivation behind adopting 3D and 4D printing technologies in modern manufacturing. It discusses their growing relevance across various industries such as automotive, aerospace, healthcare, and construction. It contrasts traditional and additive manufacturing processes while highlighting the need for innovation in DfM and DfAM approaches. The chapter concludes with clearly defined research objectives, the central problem statement, and a roadmap for the thesis.

➤ **Chapter 2 – Literature Review**

This chapter delves into the historical evolution and recent advancements in additive manufacturing. It evaluates material innovations, process design strategies, economic feasibility, and sustainability factors. Challenges in scaling up and post-processing are examined, and the discussion is supported by relevant real-world case studies.

➤ **Chapter 3 – Optimizing 3D/4D Printing for Large-Scale Prototyping: A Comprehensive Review on Speed, Cost, and Quality Challenges**

This chapter focuses on the key research questions (RQs) concerning materials, processes, and upscaling challenges in large-scale 3D/4D printing. It analyzes the trade-offs between speed, cost, and quality and proposes integrated solutions and strategic opportunities for optimization.

➤ **Chapter 4 – Laser Metal Wire Deposition for Additive Manufacturing of Complex Solid Structures**

A detailed technical investigation of Laser Metal Wire Deposition (LMWD) is presented in this chapter. It includes mathematical formulations, simulation tools, deposition efficiency calculations, and experimental results such as surface morphology and mechanical behavior analyses using SEM and XRD.

➤ **Chapter 5 – Transformative Impact of 3D/4D Printing on Supply Chain Dynamics through High-Value Design Concepts**

This chapter introduces a high-value design framework that integrates 3D/4D printing into supply chain systems. Empirical evaluations are conducted through case studies, surveys, and simulation models. It analyses how additive manufacturing can drive value creation and flexibility in supply chain operations.

➤ **Chapter 6 – Sustainability and Cost Optimization in 3D/4D Printing: Using Fish Bone Diagrams for Printability Improvement**

The chapter employs Fish Bone Diagrams to analyze and improve sustainability and cost-efficiency in 3D/4D printing. It focuses on optimizing printing parameters, reducing waste, and aligning with eco-friendly manufacturing practices. Discussions include material selection, system efficiencies, and expert insights.

➤ **Chapter 7 – Results and Analysis**

The research points to the use of 3D and 4D printing in product development, focusing on role in DfM and DfAM. It is analysed through mechanical analysis that the selection of the material has a noteworthy effect on durability and performance.

➤ **Chapter 8 – Conclusion, Future Scope, and Social Impact**

The final chapter summarizes the research findings and highlights the key contributions and limitations. It outlines future research possibilities and discusses the broader social and industrial implications of additive manufacturing, such as supply chain resilience, employment opportunities, and personalized healthcare.

CHAPTER- 2

CHAPTER 2: LITERATURE REVIEW

2.1 HISTORICAL EVOLUTION OF ADDITIVE MANUFACTURING

Darabi, R. et al. [21] developed a coupled phase-field model to research the coprecipitation of metastable γ'' (Ni_3Nb) in IN625 alloy, capturing microstructural evolution under additive manufacturing conditions. The model reveals that thermal cycles, stress, and alloy composition affect γ'' morphology and volume fraction to enhance material strength.

Abar, B.M. et al. [22] highlighted 3D printing revolutionized orthopedic surgery by enabling rapid, cost-effective production of customized medical devices. Their work outlines the evolution, methods, and regulatory aspects of 3D printing, laying the groundwork for deeper exploration in specialized medical applications.

Prashar, G. et al. [23] highlighted Additive Manufacturing (AM) as a cornerstone of Industry 4.0, enabling cost-effective, energy-efficient, and customizable production. The research explains AM's evolution, industrial applications, and future potential, projecting a \$2 trillion market by 2030.

Panchenko, O. et al. [24] investigated microstructural evolution in HSLA steel during WAAM using CMT and C-GMAW modes, linking thermal history to mechanical properties. Their research demonstrated that controlled cooling rates and tempering times enable the fabrication of functionally graded components with tailored strength and fracture behavior.

Wang, Z. et al. [25] explored thermal history during laser-directed energy deposition affects microstructure and mechanical properties of Al–Mg–Sc–Zr alloys. They showed that controlled cooling rates influence grain structure and in-situ precipitation, with water cooling significantly enhancing yield strength post-aging.

Ness, K.L. et al. [26] developed a data-driven control framework using extremely randomized trees to predict thermal fields in additive manufacturing with high accuracy. Their approach reduces dependence on time-consuming finite element simulations, enabling efficient and transferable thermal history prediction across various geometries.

Ljunggren, S.A. et al. [27] investigated metal exposure in an AM facility and found that, despite low dust levels, AM operators faced significant cobalt exposure, especially from ultrafine particles. Preventive actions effectively reduced bio monitored metal levels, highlighting the importance of exposure control and regular health monitoring.

Carneau, P. et al. [28] proposed a process-aware design approach for 3D printing of cementitious materials by drawing inspiration from traditional masonry techniques like cantilevers, vaults, and

domes. By analysing structural strategies and adapting them to robotic toolpath generation, the research expands the printable shape possibilities in concrete additive manufacturing.

Author Name	Technique	Advantage	Disadvantage
Darabi, R. et al. [21]	Phase-field modeling of γ'' precipitation in IN625 alloy	Captures microstructural evolution under AM conditions to improve strength	Requires complex simulation setup and high computational resources
Abar, B.M. et al. [22]	3D printing in orthopedic surgery	Rapid, cost-effective, and customized medical device fabrication	Regulatory challenges and limited material biocompatibility
Prashar, G. et al. [23]	Additive Manufacturing in Industry 4.0	Cost-effective, energy-efficient, and highly customizable production	Scalability and quality consistency remain challenges
Panchenko, O. et al. [24]	WAAM with CMT and C-GMAW modes	Enables tailored strength and fracture behavior via thermal control	Process complexity and control of cooling rates
Wang, Z. et al. [25]	Laser-directed energy deposition of Al–Mg–Sc–Zr alloys	Improved grain structure and yield strength with controlled cooling	Requires precise thermal management and post-aging treatment
Ness, K.L. et al. [26]	Data-driven thermal field prediction using ML	Fast and accurate prediction, reduces dependence on FEM	Model generalization may vary with different materials and geometries
Ljunggren, S.A. et al. [27]	Exposure assessment in AM environments	Highlights need for preventive actions and effective monitoring	Operator exposure to ultrafine toxic particles like cobalt remains a concern

Carneau, P. et al. [28]	Process-aware cementitious 3D printing design	Expands printable shapes using structural strategies from masonry	Requires complex toolpath planning and structural validation
Jiménez, M. et al. [29]	General AM technology analysis	Custom geometry, material savings, and cost reduction	Technology selection must match specific application needs
Roy, M. and Wodo, O. et al. [30]	Surrogate modeling for thermal profile prediction	Fast, real-time thermal history prediction for optimization	Dependent on quality and quantity of training data

The above comparison compiles various research that has examined contemporary manufacturing techniques: their costs, merits, and demerits. The methods that have been considered include everything from phase-field modeling for precipitation of alloy to 3D printing relating to orthopedic surgery and advanced manufacturing in Industry 4.0, WAAM processes, laser-directed energy deposition, etc. These techniques have been good for cost, customization along with better material properties and quicker predictions. However, these techniques cannot be identified only on beneficial grounds given the complexity, regulatory issues, limited materials, scalability, and, of course, the precision requirement during the manufacturing process. In general, the conflicting balance continues between the innovations and practicalities of these technologies.

2.2 MATERIAL ADVANCEMENTS IN 3D/4D PRINTING

Jung, Y.S. et al. [31] explored sustainable 4D printing using bio-based shape memory thermoplastic polyurethanes (SMTPU) that exhibit excellent shape recovery and mechanical properties. Their work highlights the potential of bio-derived SMPs for temperature-responsive applications through advanced structural and thermal analysis.

Zeng, S.Y. et al. [32] developed a single-material FDM-4D printing method enabling controlled deformation of bilayer actuators by optimizing area ratios and process parameters using the NSGA-II algorithm. Their approach demonstrated reliable shape transformation in complex structures, offering a foundation for future smart and transformable applications.

Yousefi, M.A. et al. [33] developed 3D/4D printable biodegradable nanocomposites using PLA-PBAT blends with Fe_3O_4 nanoparticles to enhance toughness, thermal resistance, and magneto-responsive shape memory behavior. The optimized 10 wt % Fe_3O_4 composition enabled rapid, contactless actuation, making the material suitable for smart and safe multifunctional applications.

Bodaghi, M. et al. [34] developed 3D/4D printable bio-composites by integrating PLA with bamboo charcoal and continuous flax fibers, achieving significant enhancements in mechanical strength, flame retardancy, and shape memory performance. The printed meta-bio-composites exhibited high recoverability, energy absorption, and sustainability, making them ideal for advanced multifunctional applications.

Rahmatabadi, D. et al. [35] enhanced 4D-printed shape-memory composites by incorporating PEG-functionalized CNTs into PVC-PCL matrices, improving CNT dispersion and interfacial bonding. The resulting biocompatible materials exhibited superior mechanical, thermal, and rapid shape-recovery properties, making them ideal for biomedical and adaptive engineering applications.

He, L. et al. [36] improved polypropylene's printability and shape memory behavior by blending it with PETG at varying ratios, achieving enhanced mechanical properties and rapid shape recovery. The 85% PETG blend showed the best performance, while the 55% blend offered high flexibility, making both suitable for diverse 4D printing applications.

Bouguermouh, K. et al. [37] developed thermo-sensitive SMP blends using FDM-compatible polymers like PLA, PMMA, PETG, and ABS to optimize mechanical strength and shape memory performance for 4D printing. The PLA/PMMA and PLA/PETG blends demonstrated excellent tensile properties and full shape recovery, showing promise for soft robotics and biomedical applications.

Tawk, C. et al. [38] introduced LSOVA—3D printed linear soft vacuum actuators—designed using low-cost FDM printing for safe and efficient soft robotic applications. These actuators deliver high force, fast response, scalability, and durability, making them ideal for tasks like gripping, locomotion, and prosthetic assistance.

Javaid, M. and Haleem, A. et al. [39] highlighted the transformative role of 4D printing in orthopaedics, enabling the development of smart, shape-changing implants tailored for personalized treatments. This technology supports innovations like self-assembling splints, adaptive stents, and customized joint replacements, enhancing surgical outcomes and patient care.

Pandey, A. et al. [40] investigated the shape memory behavior of 3D-printed porous PLA scaffolds reinforced with chitosan (CS), revealing up to 18.8% shape recovery under optimized conditions. The PLA/CS composites demonstrated favorable wettability and biocompatibility, highlighting their potential for self-healing bone implant applications.

Tu, H. et al. [41] highlighted that 3D concrete printing (3DCP) enables the rapid fabrication of complex, customized structures with minimal waste and faster construction times. They emphasized the importance of optimizing mix proportions and using waste materials to balance printability, strength, and sustainability in large-scale applications.

Zhu, Y. et al. [42] emphasized that additive manufacturing enables the fabrication of complex, multi-material optical devices that traditional methods cannot achieve. This advancement paves the way for next-generation functional optics in imaging, sensing, photonics, and metamaterials.

Mostafaei, A. et al. [43] highlighted binder jet 3D printing (BJ3DP) as a non-beam-based AM technique that enables rapid fabrication of complex, isotropic structures using powdered materials. The research underscores the importance of optimizing printing parameters and post-processing steps to enhance microstructural evolution and part performance.

Chen, G. et al. [44] demonstrated the integration of 3D-printed hydrogels with enzyme-induced biomineralization to create rigid, highly mineralized composites from soft materials. This approach enables precise control over mineral distribution and mechanical properties, paving the way for advanced functional materials with complex architectures.

Guddati, S. et al. [45] explained additive manufacturing techniques for fabricating porous structures, highlighting challenges in process control and its impact on final part quality. They emphasized the importance of lattice design and parameter tuning for applications in filtration, energy, and biomedical fields.

Table 2.1 Summary of Material Advancements in 3D/4D Printing: Advantages and Disadvantages.

Author Name	Technique	Advantage	Disadvantage
Jung, Y.S. et al. [31]	Bio-based SMTPU for 4D printing	Excellent shape recovery and mechanical properties; sustainable materials	Limited long-term stability under varying environmental conditions
Zeng, S.Y. et al. [32]	FDM-4D printing with NSGA-II optimization	Controlled deformation with high precision; reliable shape transformation	Complex parameter tuning; limited to single-material setups
Yousefi, M.A. et al. [33]	PLA-PBAT/Fe ₃ O ₄ nanocomposites for 3D/4D printing	Biodegradable; rapid, contactless actuation; enhanced toughness and thermal resistance	Potential nanoparticle agglomeration; process complexity
Bodaghi, M. et al. [34]	PLA with bamboo charcoal and flax fiber in 3D/4D printing	High mechanical strength, flame retardancy, sustainability	Fiber-matrix compatibility issues; fabrication challenges

Rahmatabadi, D. et al. [35]	PVC-PCL with PEG-functionalized CNTs	Superior thermal/mechanical properties; rapid shape recovery; biocompatible	CNT dispersion challenges; costly functionalization
He, L. et al. [36]	Polypropylene blended with PETG	Improved printability and rapid shape recovery	Trade-off between flexibility and mechanical strength at varying blend ratios
Bouguermouh, K. et al. [37]	Thermo-sensitive SMP blends (PLA, PMMA, PETG, ABS)	FDM-compatible; full shape recovery; suitable for soft robotics and biomedical	Thermal instability in certain blends
Tawk, C. et al. [38]	LSOVA (Linear Soft Vacuum Actuators) via FDM	Low-cost, scalable, high force and fast response for soft robotics	Limited material compatibility for FDM printing
Javaid, M. & Haleem, A. [39]	4D printing in orthopaedics	Smart implants, self-assembling splints, personalized treatment	High regulatory requirements; clinical validation needed
Pandey, A. et al. [40]	PLA/Chitosan porous scaffolds for 4D printing	Shape recovery up to 18.8%; biocompatibility; potential for self-healing implants	Limited mechanical strength
Tu, H. et al. [41]	3D Concrete Printing (3DCP)	Customizable, minimal waste, fast construction	Challenges in mix design and reinforcement integration
Zhu, Y. et al. [42]	Additive manufacturing for multi-material optical devices	Enables fabrication of complex optical structures unachievable by traditional methods	High precision required; material limitations
Mostafaei, A. et al. [43]	Binder Jet 3D Printing (BJ3DP)	Rapid production of isotropic, complex parts using powder metallurgy	Requires extensive post-processing to improve part performance

Chen, G. et al. [44]	3D-printed hydrogels with enzyme-induced biomineralization	Rigid, highly mineralized composites; precise control over structure	Limited material compatibility; slower processing time
Guddati, S. et al. [45]	AM for porous structures	Tailored porosity; useful in filtration, energy, and biomedical fields	Lack of process control; inconsistent part properties

Table 2.1 summarizes various advancements in materials used for 3D/4D printing, focusing on their techniques, advantages, and disadvantages. It highlights the development of bio-based materials like SMTPU and composites such as PLA-PBAT nanocomposites, which offer excellent shape recovery, mechanical strength, and sustainability. However, challenges such as limited thermal resistance, optimization complexity, and nanoparticle agglomeration were noted. Other materials, like CNT-reinforced composites and SMP blends, provide improved flexibility, rapid shape recovery, and biocompatibility but require complex functionalization processes or struggle with material compatibility. The table also emphasizes the potential for personalized implants in orthopedics, although regulatory and biocompatibility hurdles remain. These advancements demonstrate the potential for innovative applications in various fields but also reveal challenges that need addressing for broader adoption and consistency in results.

2.3 PROCESS OPTIMIZATION AND DESIGN STRATEGIES

Zeng, S.Y. et al. [46] explored the precise control of deformation in single-material 4D-printed bilayer actuators, using optimization algorithms to fine-tune design parameters for optimal shape transformation. Their work demonstrated the practical application of this approach to complex structures and proposed future enhancements for improving reliability in advanced fields like transformable vehicles.

Peng, X. et al. [47] developed a controllable deformation design framework for 4D-printed active composite structures, integrating material properties and optimization algorithms to achieve target deformations. Their approach demonstrated the accuracy of simulated and experimental results, offering a method for flexible design of complex structures with precise deformation capabilities.

Jian, B. et al. [48] explored the integration of 4D printing with origami-based design to create support-free 3D hollow structures. By using 2D printed origami precursor layouts and smart materials, they demonstrated that external stimuli could transform these layouts into functional 3D shapes without the need for support structures.

Sun, X. et al. [49] developed a machine learning and evolutionary algorithm-based approach to efficiently design active composites for 4D printing. By combining ML with finite element simulations and computer vision, they proposed a method to design structures that transform into target shapes under external stimuli, streamlining the design and printing process.

Benyahia, K. et al. [50] explained a computational design approach for multi-material 4D printing, focusing on converting digital material distributions into interlocking blocks. These blocks were printed separately using single-material AM and assembled to achieve the desired shape change, overcoming the challenges of multi-material deposition.

Saptaji, K. et al. [51] investigated the effect of cross-sectional shape design on the deformability of 4D printed gripper fingers, focusing on applications in soft robotics. By varying the cross-sectional shapes and dimensions, they found that the optimal design, using a rectangular cross-section, improved shape-memory performance and enabled the gripper to hold objects with diverse properties.

Saptaji, K. et al. [52] developed a thermos reversible composite gel (WPI-KC-KGM) for 3D food printing, exploring the impact of the κ -carrageenan to konjac gum ratio on the gel's rheological properties and printability. Their research identified the optimal formulations for print accuracy, with K5M5 achieving the best pore area and fidelity, and K7M3 providing the highest support similarity for temperature-controlled extrusion.

Ejeromedoghene, O. et al. [53] explained the integration of machine learning (ML) in the fabrication of responsive hydrogel composite materials for 3D/4D printing. Their work highlights the use of ML to optimize material selection, design, and manufacturing, enabling advanced applications in biosensors, wearable devices, and intelligent biomedical technologies with enhanced stimuli responsiveness.

Chen, J. et al. [54] developed a modified Computational Fluid Dynamics (CFD) model to enhance the simulation efficiency of surimi extrusion behavior, improving accuracy by replacing the traditional no-slip boundary condition with wall slip. They also proposed a machine learning model for rapid prediction of surimi printability, achieving high prediction accuracy with an $R^2 > 0.95$.

de Kergariou, C. et al. [55] developed a voxel-based technique to model 3D printed continuous yarns in fiber composites, using input variables from the printing path to define the part's design. The approach, coupled with an evolutionary algorithm, efficiently characterizes the mechanical and actuation properties of printed structures, demonstrated through flax fiber-reinforced PLA leaf-shaped case research.

Table 2.2 Process Optimization and Design Strategies in 3D/4D Printing

Author Name	Technique	Advantage	Disadvantage
Zeng, S.Y. et al. [46]	Optimization algorithm-based control of 4D-printed bilayer actuator deformation	High precision in shape transformation for complex structures	May require complex tuning and high computational cost
Peng, X. et al. [47]	Controllable deformation design integrating material properties and optimization algorithms	Accurate prediction and realization of target deformations	Computational intensity; limited scalability for large models
Jian, B. et al. [48]	Origami-based 4D printing for support-free hollow 3D structures	Eliminates need for support structures; efficient material usage	Limited material compatibility; complexity in folding path prediction
Sun, X. et al. [49]	ML and EA-based design of active composites	Fast and accurate design; streamlines simulation-to-print workflow	Dependence on training data; potential overfitting
Benyahia, K. et al. [50]	Computational design of interlocking blocks for multi-material 4D printing	Simplifies multi-material fabrication using single-material printers	Manual assembly required; less seamless integration
Saptaji, K. et al. [51]	Cross-sectional shape optimization for 4D-printed soft robotic gripper fingers	Enhanced deformability and grip adaptability	Limited to soft robotic applications; structural strength trade-offs
Saptaji, K. et al. [52]	Thermoreversible WPI-KC-KGM gel for 3D food printing	Improved print accuracy and pore fidelity in food structures	Temperature sensitivity; ingredient compatibility issues

Ejeromedoghene, O. et al. [53]	ML-assisted design of responsive hydrogel composites for 3D/4D printing	Efficient material and design optimization for biomedical applications	High data requirement; generalization challenges
Chen, J. et al. [54]	Modified CFD and ML model for surimi extrusion and printability prediction	Improved simulation speed and prediction accuracy ($R^2 > 0.95$)	Model specificity; limited to food/biomaterial applications
de Kergariou, C. et al. [55]	Voxel-based modeling of 3D-printed yarn paths in fiber composites	Detailed mechanical and actuation behavior prediction	Requires extensive printing path data; high processing demand

Table 2.2 presents the evaluation of several proposed techniques in respect of their process optimizations and design strategies associated with 3D/4D printing, indicating their advantages and disadvantages. The methods discussed in this overview include optimization algorithms for highly precise deformation control, origami-based design approaches for effective material utilization, and machine learning approaches in design of biomedical applications. While these methods assist in obtaining benefits such as high degrees of precision and swift design process and material efficiency, hurdles such as high computational cost, low scalability, and issues of material compatibility arise. The ongoing efforts of enhancing precision in printing design optimization techniques are demonstrated, while complexities and limitations associated with these approaches are acknowledged. Notably, the requirement of specific tuning and huge data sets for reliable predictions is also emphasized.

2.4 COST-EFFECTIVENESS AND ECONOMIC VIABILITY ANALYSIS

Raza, M.H. et al. [56] conducted a comparative economic analysis of offsite and onsite 3D construction printing (3DCP) techniques using Value Stream Mapping (VSM) and mathematical models. The research found that while offsite 3DCP incurs higher costs due to warehousing and assembly, onsite 3DCP was more cost-effective for larger projects, offering potential for cost reductions in small-scale projects through optimized transportation.

Sartini, M. et al. [57] conducted a techno-economic analysis of adopting additive manufacturing in investment casting, specifically rapid investment casting, to replace traditional wax injection. The research found that digital light processing (DLP) technology offers the best cost and time efficiency,

with significant advantages in scenarios involving low printer utilization rates, especially for small to medium-sized components.

Alzoubi, L. et al. [58] explained the advancements and applications of 3D printing in healthcare, focusing on personalized medicine, tissue engineering, and medical device production. They highlighted the potential for 3D printing to revolutionize healthcare by offering customized implants, prosthetics, and drug delivery systems while addressing economic, environmental, and ethical challenges.

Bahoria, B.V. et al. [59] developed an integrated model combining gaussian process regression, the firefly algorithm, and NSGA-III for optimizing 3D construction elements. Their approach, applied to concrete beams, achieved significant reductions in environmental and life cycle costs, setting a new benchmark for sustainable construction optimization.

Casucci, A. et al. [60] compared the clinical effectiveness and cost-efficiency of conventional and digital prosthodontic protocols for removable complete dentures. The research found that digital dentures, both milled and 3D-printed, reduced chairside time and laboratory costs, providing a practical alternative to conventional dentures without compromising bite force or masticatory performance.

Lin, C.W. and Chen, T. et al. [61] explored the application of 3D printing in aircraft manufacturing and MRO companies, identifying critical factors for enhancing sustainability. The research proposed a novel partial consensus FAHP approach to rank these factors, highlighting cost-effectiveness, the number of printable parts, and research advancements as key priorities.

Han, M. et al. [62] developed a techno-economic model for 4D printing using methacrylate-based thermo-responsive polymers, addressing the complexity of stimuli-responsive behavior and process parameters. Their optimization approach achieved a 22.25% cost reduction while maintaining shape memory performance, identifying material cost and labor rate as key cost drivers.

Weng, Y. et al. [63] explained a sustainable 3D printable cementitious material using magnesium potassium phosphate cement (MKPC) blended with fly ash and silica fume to enhance workability and strength. Their optimized formulation enabled rapid printing of a 20-layer, 180 mm structure in 5 minutes, showcasing feasibility for eco-friendly construction.

Shahar, F.S. et al. [64] examined the use of 3D-printed kenaf/PLA composites for ankle-foot orthoses (AFO), focusing on their density, fatigue, and impact strength. The research found that increasing kenaf content improved fatigue life while reducing density and impact resistance, indicating promising potential for sustainable AFO applications.

Yu, Q. et al. [65] explored the use of steel slag as a sustainable cement substitute in 3D printed concrete, highlighting its potential to reduce carbon emissions and costs. The research found that up

to 20% steel slag maintains later-stage performance while enhancing buildability and minimizing environmental impact.

Wang, Y.C. et al. [66] analysed the key concerns and benefits of 3D in the aircraft industry, emphasizing reduced costs, lighter parts, and faster production. Using a fuzzy systematic approach, five critical factors were identified and ranked to guide the industry's effective adoption of 3D printing technologies.

Table 2.3 Cost-Effectiveness and Economic Viability Analysis in 3D/4D Printing

Author Name	Technique	Advantage	Disadvantage
Raza, M.H. et al. [56]	Comparative economic analysis using VSM and mathematical models	Onsite 3DCP was more cost-effective for large projects	Offsite 3DCP incurs higher costs due to warehousing and assembly
Sartini, M. et al. [57]	Techno-economic analysis in investment casting using DLP	Best cost/time efficiency for small-medium components	Less effective for high printer utilization rates
Alzoubi, L. et al. [58]	Explanation of 3D printing in healthcare	Custom implants, prosthetics, and drug delivery	Economic, environmental, and ethical challenges
Bahoria, B.V. et al. [59]	Integrated GPR, Firefly Algorithm, NSGA-III for construction optimization	Reduced environmental and life cycle costs for concrete beams	Complex algorithm integration
Casucci, A. et al. [60]	Comparison of conventional and digital denture protocols	Reduced chairside/lab time with digital dentures	Initial setup cost for digital workflows
Lin, C.W. and Chen, T. [61]	FAHP-based sustainability ranking in aircraft 3D printing	Highlights cost-effectiveness, printable parts, and research	Subjectivity in consensus modeling
Han, M. et al. [62]	Techno-economic model for 4D printing with responsive polymers	22.25% cost reduction with shape memory maintained	High material cost and complex stimuli behavior

Weng, Y. et al. [63]	Sustainable MKPC-based cementitious 3D printing material	Eco-friendly, rapid printing, improved workability	Limited data on long-term durability
Shahar, F.S. et al. [64]	3D-printed kenaf/PLA composites for AFO	Improved fatigue life and reduced density	Reduced impact resistance at higher kenaf content
Yu, Q. et al. [65]	Steel slag as cement substitute in 3D printed concrete	Reduces emissions, maintains performance up to 20%	Performance may drop beyond 20% replacement
Wang, Y.C. et al. [66]	Fuzzy analysis for 3D printing in aircraft industry	Identifies/ranks key adoption factors like cost and speed	May overlook specific challenges in implementation

Table 2.3 provides a summary of various cost-effectiveness and economic viability analyses in the context of 3D/4D printing. It explores different applications such as construction, healthcare, and manufacturing, highlighting the advantages of cost reduction, efficiency, and sustainability. However, challenges include high initial setup costs, complex algorithms, and material-specific issues. The table also identifies trade-offs between environmental benefits and long-term durability, with some techniques like 3D printing in aircraft or construction facing limitations in terms of cost and scalability. This highlights the ongoing balance between cost efficiency, material use, and practical challenges in real-world applications.

2.4.1 Tabulated Cost Comparisons

Table 2.4 Comparative analysis of key cost factors between Additive Manufacturing (AM) and Traditional Manufacturing (TM).

Cost Factor	Additive Manufacturing (AM)	Traditional Manufacturing (TM)	Notes
Material Cost	✘	✔	AM materials, especially metals and specialized polymers, tend to be more expensive.
Equipment Investment	✔	✘	AM requires less initial capital investment compared to TM setups like injection molding.

Labor Cost	✓	✗	AM processes were more automated, reducing manual labor requirements.
Production Time	✓	✓	AM excels in rapid prototyping; TM was efficient for mass production.
Waste Generation	✓	✗	AM builds objects layer by layer, reducing material waste.
Customization Flexibility	✓	✗	AM allows for easy customization without additional tooling.
Economies of Scale	✗	✓	TM benefits from reduced per-unit costs at scale; AM does not scale as efficiently.
Tooling Requirements	✓	✗	AM doesn't require molds or dies, unlike many TM processes.
Energy Consumption	✗	✓	AM can consume more energy per part due to longer machine run times.
Lead Time	✓	✗	AM reduces lead times for design iterations; TM requires setup and tooling time.

Table 2.4 presents a comparative analysis of key cost factors between Additive Manufacturing (AM) and Traditional Manufacturing (TM). The evaluation reveals that AM offers clear advantages in areas such as equipment investment, labor cost, waste generation, customization flexibility, tooling requirements, and lead time, primarily due to its automated, tool-free, and layer-by-layer fabrication approach. AM also performs well in rapid prototyping, sharing an edge with TM in production time under different contexts. However, TM outperforms AM in material cost, economies of scale, and energy consumption, making it more suitable for high-volume production where per-unit costs were significantly reduced. Overall, the table highlights that while AM was advantageous for low-volume, highly customized, and prototype-driven applications, TM remains more cost-effective for mass manufacturing due to its scalability and lower material and energy costs.

2.4.2 Return on Investment for Additive Manufacturing

Return on Investment (ROI) for AM refers to the measure of the financial benefits a company or industry gains from implementing AM technologies relative to the costs involved in its adoption.

This metric was crucial for businesses to assess whether integrating AM solutions would yield sustainable profits, productivity improvements, and operational efficiencies. The ROI for AM was quantified in various ways, depending on the specific industry or application, but typically includes:

- ❖ **Cost Reduction:** AM offers significant cost savings through the reduction of material waste, lower energy consumption, and the ability to produce complex geometries without the need for expensive molds or tooling. For example, in the manufacturing of aerospace components, AM has been shown to reduce production costs by eliminating the need for traditional subtractive machining processes and reducing the weight of parts, leading to lower material costs.
- ❖ **Time Savings:** One of the main advantages of AM is that it can drastically reduce the lead time as compared to traditional production processes. With products designed and prototyped in-house and produced quickly, iterations could be done faster and time-to-market reduced. This kind of time was crucial especially in industries that are time sensitive in developing products the pharmaceutical industry and the automotive industry.
- ❖ **Customization and Personalization:** The production has generally been in situations such as the marketplace doing environment allowing AM to work at production costs lower than more established mass production techniques. Personalized production was very relevant to the healthcare context in that the application was generally made to manufacture personalized medical devices, implants, or drugs. The ability to manufacture products tailored to specific needs can lead to increased customer satisfaction and market differentiation.
- ❖ **Supply Chain Optimization:** AM enables decentralized production, thus avoiding dependency on centralized factories and distribution networks. This ensures a more flexible and agile adaptive supply chain, capable of producing on-demand and locally which reduces costs due to logistics and inventory management.
- ❖ **Waste Reduction:** Traditional manufacturing processes especially subtractive processes tend to cause a lot of material wastage. Unlike AM, an additive process on which materials are deposited layer by layer, waste is reduced and maximally utilized, leading to environmental and economic benefits.
- ❖ **Energy Efficiency:** AM sometimes proves to be energy efficient as compared to conventional processes of manufacturing. The main reason was that it used less material, and that since tools used were not so complicated, power consumption was less for the process.

2.5 MATERIAL EFFICIENCY AND SUSTAINABILITY FACTORS

Olawumi, M.A. et al. [67] explored the sustainability of recycling polymer composites using FDM, evaluating mechanical integrity and environmental impact across multiple recycling cycles. The research found that recycled polymers retained up to 80% tensile strength after three cycles, with a 30% reduction in energy use and 25% lower carbon emissions.

Nilimaa, J. et al. [68] presented comprehensive research of sustainable concrete construction, highlighting eco-friendly materials like green concrete and technologies such as 3D printing and carbon capture. The research emphasized interdisciplinary collaboration and emerging trends like digitalization and circular economy to overcome implementation barriers and enhance sustainability.

Cisneros-López, E.O. et al. [69] explored the use of recycled PLA blended with virgin PLA, chain extenders, and microcrystalline cellulose (MCC) to enhance FDM 3D printing performance. The research showed that additives like Joncryl and MCC improved mechanical strength and controlled melt flow, enabling higher recycled PLA usage with improved print quality.

Long, W.J. et al. [70] investigated MCC-reinforced cement-based composites for 3D printing, demonstrating enhanced rheological behavior, buildability, and mechanical strength. The research also showed a 6.82% reduction in CO₂ emissions, highlighting the material's potential for sustainable construction applications.

Javaid, M. et al. [71] highlighted the environmental advantages of additive manufacturing, including reduced material waste, energy usage, and emissions compared to conventional methods. The research emphasizes AM's growing role in achieving sustainable production through innovative material use and eco-efficient applications.

Javaid, M. et al. [72] explored 4D printing as an evolution of 3D printing, where smart materials enable printed structures to transform shape in response to external stimuli like heat, light, or electricity. The research emphasizes its transformative potential in manufacturing, medicine, and engineering by enabling self-assembly and programmable functionality.

Niazy, D. et al. [73] highlighted the role of four-dimensional printing in enhancing structural performance and material efficiency through stimulus-responsive materials. The research identifies key research areas in 4D printing for art, architecture, and construction (4DPAAC), promoting energy conservation, material reduction, and adaptability to climate change.

Fu, P. et al. [74] emphasized that 4D printing extends additive manufacturing by enabling printed structures to change shape or properties over time when exposed to external stimuli. The article

explains advancements in smart materials, printing methods, and polymer science, highlighting 4D printing's potential and future opportunities in dynamic manufacturing.

Hatami, H. et al. [75] explored the use of 3D and 4D printing technologies in manufacturing vascular stents, highlighting their potential to offer patient-specific designs with improved biocompatibility and reduced complications. These additive approaches enable complex geometries and minimally invasive solutions, addressing key challenges in conventional stent treatments for cardiovascular diseases.

Lalegani Dezaki, M. Et al. [76] investigated 3D/4D printing of PLA composites reinforced with natural mussel and wheat particles using FFF, showcasing improved mechanical properties, shape memory behavior, and reduced flammability. The research emphasizes sustainable fabrication through functionally graded and multi-material SMPCs for eco-friendly, reusable applications in engineering and daily use.

Rahmatabadi, D. et al. [77] explored the use of sustainable PLA-PBAT blends for 4D printing of shape memory polymers (SMPs), achieving rapid shape recovery and high elongation with excellent printability. The research demonstrates that blending PLA with PBAT improves thermal responsiveness, biodegradability, and mechanical properties, offering an eco-friendly solution for 4D printing applications.

Table 2.5 Material Efficiency and Sustainability Factors in 3D/4D Printing.

Author Name	Technique	Advantage	Disadvantage
Olawumi, M.A. et al. [67]	FDM (Recycling Polymer)	80% tensile strength retention after 3 cycles, 30% reduction in energy use, 25% lower carbon emissions	Mechanical degradation over multiple cycles
Nilimaa, J. et al. [68]	Sustainable Concrete	Use of eco-friendly materials, 3D printing, and carbon capture; emphasis on interdisciplinary collaboration	Implementation barriers due to economic and social factors
Cisneros-López, E.O. et al. [69]	FDM (Recycled PLA)	Improved mechanical strength, better melt flow, higher recycled PLA usage with better print quality	High melt flow of recycled PLA

Long, W.J. et al. [70]	Cement-Based Composites	Enhanced rheological behavior, improved buildability, 6.82% reduction in CO ₂ emissions	Limited to cement-based materials for 3D printing
Javaid, M. et al. [71]	Additive Manufacturing	Reduced material waste, lower energy use, and emissions; increased sustainability	Technological and cost barriers in implementation
Javaid, M. et al. [72]	4D Printing	Ability for structures to change shape based on external stimuli, self-assembly, programmable functionality	Limited to specific smart materials
Niazy, D. et al. [73]	4D Printing	Enhanced material efficiency, adaptability to climate change, energy conservation	Requires further research for widespread adoption
Fu, P. et al. [74]	4D Printing	Dynamic manufacturing through stimulus-responsive materials, potential in advanced applications	Emerging technology, further development needed
Hatami, H. et al. [75]	3D/4D Printing (Stents)	Patient-specific designs, improved biocompatibility, reduced complications, minimal invasiveness	High cost of 3D/4D printed stents
Lalegani Dezaki, M. Et al. [76]	3D/4D Printing (PLA)	Improved mechanical properties, shape memory behavior, eco-friendly applications	Limited to PLA composites, material constraints
Rahmatabadi, D. et al. [77]	4D Printing (PLA-PBAT)	Rapid shape recovery, high elongation, biodegradability, excellent printability	Limited to PLA-PBAT blends, may require specialized processes

Table 2.6 provides an overview of various material efficiency and sustainability factors in 3D/4D printing, highlighting techniques, advantages, and disadvantages. It covers a range of methods such as FDM using recycled polymers and PLA, cement-based composites, and advanced 4D printing technologies. These techniques were praised for their ability to reduce material waste, lower energy consumption, and contribute to environmental sustainability through eco-friendly materials and recycling. However, some challenges persist, such as mechanical degradation over multiple recycling cycles, limited material compatibility, and technological or cost barriers for widespread adoption. Additionally, certain techniques were confined to specific materials or require further research to achieve full potential in practical applications.

2.6 CHALLENGES IN LARGE-SCALE PRINTING

Shah, J. et al. [78] explored the advancement and challenges of upscaling polymer-based material extrusion 3D printing, focusing on the design and testing of a large-scale FFF printer. The research highlighted key design considerations and limitations, such as nozzle diameter effects, in achieving industrial-scale applications.

Ali, M.H. et al. [79] developed a novel large-dimensional multi-extrusion FDM printer capable of printing with five thermoplastic materials simultaneously. The research identified key large-scale printing challenges such as uneven bed temperature, thermal bending, and filament feed issues, while demonstrating enhanced flexibility and automation in AM.

Zhang, Y. et al. [80] explained the potential of screen printing as a scalable, low-cost method for fabricating printed microelectronics. They discussed ink formulation strategies, key applications in micro-energy devices and sensors, and outlined future challenges limiting broader industrial adoption.

Shen, H. et al. [81] proposed a large-scale additive manufacturing system utilizing multiple collaborating robots to overcome size limitations of conventional 3D printers. Their optimized task scheduling and interference avoidance strategies demonstrated over 73% improvement in printing efficiency during collaborative experiments.

Jafari, R. et al. [82] explained the use of high-precision 3D printing for fabricating superhydrophobic surfaces by tailoring surface chemistry and topography. The research highlights the advantages of additive manufacturing in creating complex, functional structures and discusses its potential across various scientific and industrial applications.

Quan, H. et al. [83] discussed the evolution of photo-curing 3D printing technologies such as SLA, DLP, LCD, CLIP, and MJP, highlighting their high precision and rapid fabrication capabilities. The research also explains their applications in the biomedical field and outlines existing challenges in material performance and printing mechanisms.

Zhang, Y. e al. [84] evaluated the mechanical properties and durability of large-scale 3D printed cement-based materials, revealing enhanced strength and sulfate resistance compared to mold-cast materials. However, due to interconnected voids aligned with the print direction, 3DPC exhibited anisotropic behavior and reduced resistance to frost and chloride penetration.

Chen, L. et al. [85] analysed the critical bioprocess technologies for scalable cell-based meat production, focusing on cell lines, culture media, scaffolds, and bioreactors. They emphasized the need for innovation to balance cost, quality, sustainability, and societal acceptance in future protein systems.

Anandakrishnan, N. et al. [86] introduced a rapid 3D bioprinting technique called FLOAT, enabling the fabrication of large, cell-laden hydrogel structures within minutes. This method minimizes deformation and cellular damage while supporting embedded vascular networks for improved cell viability and metabolic function.

Dörfler, K. et al. [87] highlighted Mobile Additive Manufacturing (MAM) as a scalable solution for in situ concrete construction, utilizing autonomous mobile robots for flexible, cooperative 3D printing tasks. The research emphasizes MAM's multidisciplinary nature, integrating architecture, materials, control, and sensing for enhanced on-site applicability.

Table 2.6 Challenges in Large-Scale Printing Techniques

Author Name	Technique	Advantage	Disadvantage
Shah, J. et al. [78]	Large-scale FFF (Fused Filament Fabrication)	Identified key design factors for industrial-scale printing	Challenges in nozzle diameter effects and system limitations
Ali, M.H. et al. [79]	Multi-extrusion FDM printing	Simultaneous printing with five thermoplastic materials; improved automation	Issues with uneven bed temperature, thermal bending, and filament feed
Zhang, Y. et al. [80]	Screen printing for microelectronics	Scalable, low-cost method for energy devices and sensors	Challenges in ink formulation and broader industrial adoption
Shen, H. et al. [81]	Multi-robot large-scale additive manufacturing	73% improvement in printing efficiency through optimized coordination	Complexity in task scheduling and robot interference management

Jafari, R. et al. [82]	High-precision 3D printing for superhydrophobic surfaces	Enables complex functional surfaces with tailored chemistry and topography	Material limitations and process scalability concerns
Quan, H. et al. [83]	Photocuring 3D printing (SLA, DLP, LCD, CLIP, MJP)	High precision, smooth surface, fast fabrication, biomedical applications	Material performance and printing mechanism limitations
Zhang, Y. et al. [84]	Large-scale 3D printed cement-based materials	Improved mechanical strength, shrinkage, and sulfate resistance	Anisotropic properties; low frost and chloride resistance due to interconnected voids
Chen, L. et al. [85]	Bioprocess technologies for cell-based meat production	Enables sustainable, scalable, and alternative protein production through advanced bioprocessing	High cost, scalability challenges, regulatory and social acceptance barriers
Anandakrishnan, N. et al. [86]	FLOAT (Fast hydrogel stereolithography)	Rapid printing, reduced deformation, embedded vascular networks	Technical complexity in controlling photopolymerization and vascular embedding
Dörfler, K. et al. [87]	Mobile Additive Manufacturing (MAM)	Scalable in situ printing using mobile robots with interdisciplinary design	Requires high integration of architecture, sensing, materials, and control systems

Table 2.7 outlines various challenges encountered in large-scale printing techniques. It explains methods such as FFF (Fused Filament Fabrication), multi-extrusion FDM, and photocuring 3D printing, emphasizing their advantages in terms of scalability, material diversity, and printing efficiency. However, significant challenges include issues like nozzle diameter effects, uneven bed temperatures, material limitations, and process scalability concerns. Additionally, more specialized techniques, such as mobile additive manufacturing and high-precision 3D printing, face hurdles like task coordination complexity, material performance constraints, and the need for high levels of system integration. These challenges hinder the broad adoption and optimization of large-scale printing technologies.

2.6.1 Space and Size Constraints

- ❖ **Limited Build Volume:** One of the main issues in large-scale 3D/4D was the restriction on the object size being printed. Most additive manufacturing equipment has a limited build volume, and for big structures, this becomes a very serious issue. The printer size restricts the maximum size of the part being printed in one go, resulting in multiple smaller parts that need to be assembled afterwards.
- ❖ **Structural Integrity:** Externally large parts typically demand unique design factors to preserve structural integrity when printed. For instance, extremely large parts tend to warp, buckle, or get deformed due to inhomogeneous cooling or material weight. Such effects might weaken or fail the strength and functionality of the final part.
- ❖ **Printer Capacity and Scalability:** With the increasing need for larger prints, there is a growing need for larger, more powerful machines that can support high material flow rates and ensure quality over larger surfaces. Scaling up the print size, however, also raises the machine setup and operation complexity, further complicating the process.

2.6.2 Post-Processing and Surface Finishing

- ❖ **Time and Cost:** It is imperative to carry out a post-processing event for major products so that they yield the quality and surface finish desired besides functionality. The greater the part, the more time and resources will be spent in support removal, smoothing, and surface treatment. For instance, removing supports off a large component requires manual labor or sophisticated automated systems which turns out quite costly and time consuming.
- ❖ **Surface Quality:** An industrial 3D print finish is often rough, while small parts have a finer finish. This difference is due to the layer deposition process itself. Making a large part look smooth and good has presented quite a challenge; advanced methods of surface finishing, such as sanding, polishing, and chemical smoothing, were necessary to use. Add to this the scale of the parts which makes these post-processing activities difficult to do uniformly.
- ❖ **Material Variation:** Larger printed parts often suffer from inconsistent material properties within different sections of the part due to variations in rates of cooling, flow of material, or print speed. This variability can affect the mechanical properties and even overall performance of the end product. Post-processing should be utilized to allow for consistency for large objects.

2.6.3 Machine Advancements and Precision Improvements

- ❖ **Precision Issues at Large Scales:** Precision is challenged when the size of printed parts increases. Very tight tolerances in large-scale prints have been found challenging, possibly due to material shrinkage, thermal distortion, and imperfections in the motion-system of the printer itself. Even minute inaccuracies on a very large print can lead to angular or linear errors in part geometry and functionality.
- ❖ **Machine Calibration and Control:** Large-scale AM machines necessitate calibrated and accurate control systems because such a system is dedicated to making the parts printed perfectly. Such phenomena, as thermal gradients or mechanical vibrations, can be detrimental to the excellence of prints. Thus, high-precision calibration systems and error-correction algorithms are necessary for consistent output provided that very large parts are to be printed.
- ❖ **Energy Consumption:** In general, bigger prints cost more in terms of energy used, increase the operational cost, and put the equipment under greater stress. As parts grow, energy efficiency in the process of printing becomes ever more crucial. Ways must be found by manufacturers to reduce the amount of energy consumed without sacrificing quality or speed of prints.
- ❖ **Material Deposition and Flow Control:** Deposition of materials becomes increasingly complicated as one goes larger with a part. It now becomes an exercise in flow control with new advanced techniques to deliver material throughout the larger scale while ensuring the part's thickness, density, and texture are uniform. This problem greatly increases with new or complex materials such as composites or functional inks in 3D/4D printing.

2.7 REAL-WORLD CASE STUDIES

Beer, N. et al. [88] investigated the use of 3D printing for customized medicines in the pharmaceutical system in Europe with differing scenarios applied, including industry, pharmacies, and the home of patients. They found that there were major challenges involved, such as regulatory, economic, ethical, and organizational ones, which would require cautious consideration before adopting this technology.

Seoane-Viano, I. et al. [89] investigated the viability of decentralized manufacturing (DM) of 3D printed pharmaceuticals, employing Efavirenz-loaded granulates to fabricate printlets through direct powder extrusion (DPE). The study showed the application of in-line near-infrared spectroscopy (NIR) for real-time analysis of drug load, with the potential for point-of-care quality control in 3D printing.

Alkhalidi, A. and Hatuqay, D. [90] analysed the construction of energy-efficient, low-cost dwelling units through additive manufacturing in buildings. The authors aimed to improve printable wall systems and materials that minimize thermal transmittance under climatic zone legislations and for annual energy requirements in various locations.

Brion, D.A. and Pattinson, S.W. [91] developed a system that uses 3D printing process metadata and video footage to predict and correct printing material flow errors in real time. This approach leverages regression models for fast, data-driven error correction, enabling more autonomous and accurate 3D printing, even with complex materials.

Yi, Q. et al. [92] developed a self-powered, MXene-based, 3D-printed wearable system for continuous real-time monitoring of physiological biosignals. The system integrates power-efficient triboelectric nanogenerators and pressure sensors, demonstrating wireless, on-demand monitoring without external power sources.

Strandhagen, J.W. et al. [93] emphasized that the shipbuilding industry faces economic, social, and environmental sustainability challenges, necessitating digital transformation. They proposed nine Industry 4.0-based solutions to enhance sustainable operations within shipbuilding supply chains.

Guerra-Zubiaga, D. et al. [94] proposed the use of Digital Twin technology integrated with Digital Manufacturing Tools to enhance production planning and commissioning. Their approach enables real-time interaction between virtual and physical systems, improving flexibility, efficiency, and error detection in manufacturing processes.

Table 2.7 Real-World Case Studies Demonstrating Additive Manufacturing Techniques, Advantages, and Limitations

Author Name	Technique	Advantage	Disadvantage
Beer, N. et al. [88]	3D printing for personalized medicines	Enables tailored drug production across various settings	Faces regulatory, ethical, economic, and organizational challenges
Seoane-Viano, I. et al. [89]	Decentralized Manufacturing using DPE and in-line NIR spectroscopy	Real-time quality control and potential for point-of-care drug production	Implementation complexity and potential regulatory hurdles
Alkhalidi, A. and Hatuqay, D. [90]	Additive manufacturing for residential units	Energy-efficient, low-cost housing with optimized thermal performance	Dependent on climatic zones and complex material optimization

Brion, D.A. and Pattinson, S.W. [91]	Real-time error correction using metadata and video in 3D printing	Improves accuracy and autonomy in complex 3D printing	Requires extensive data and modeling, possibly increasing system complexity
Yi, Q. et al. [92]	MXene-based, self-powered 3D-printed wearable biosensor	Wireless, real-time physiological monitoring without external power	Material and integration challenges, especially in mass production
Strandhagen, J.W. et al. [93]	Industry 4.0 digital solutions in shipbuilding supply chains	Addresses sustainability across economic, environmental, and social dimensions	High implementation cost and technological adaptation issues
Guerra-Zubiaga, D. et al. [94]	Digital Twin with Digital Manufacturing Tools	Enhances production planning, flexibility, and error detection	May require significant initial setup and integration with existing systems

Table 2.7 outlines various techniques researchers explore in innovative manufacturing and technology applications. Beer et al. studied 3D printing for personalized medicine, highlighting regulatory challenges. Seoane-Viano et al. focused on decentralized pharmaceutical production with real-time quality control using NIR spectroscopy. Alkhalidi and Hatuqay worked on additive manufacturing for energy-efficient housing but encountered climatic zone limitations. Brion and Pattinson developed a system for real-time 3D printing error correction, improving accuracy but adding system complexity.

2.7.1 House Building and Construction

Additive manufacturing has revolutionized the construction sector by enabling automated, layer-by-layer fabrication of housing components and even entire structures. Technologies such as concrete 3D printing (e.g., Contour Crafting, D-Shape) have demonstrated the ability to print walls, beams, and facades with complex geometries and significantly reduced construction times.

Case Study: Apis Cor's 3D-printed house in Russia was completed within 24 hours using a mobile printer, demonstrating affordability and portability.

Advantages: Reduced labour cost, minimized waste, customization flexibility, and potential for on-site printing in remote or disaster-prone areas.

Challenges: Scaling up, structural integrity, building code compliance, and integration with traditional building materials.

2.7.2 Shipbuilding and Heavy Machinery

In the marine and heavy machinery sectors, 3D printing was adopted primarily for tooling, spare parts, and complex components that were traditionally expensive or time-consuming to produce. Large-format metal additive manufacturing systems have been used to fabricate high-strength components with optimized design, reducing material usage and production lead time.

Case Study: The U.S. Navy utilized additive manufacturing to develop a 30-foot-long 3D-printed hull mold using carbon-reinforced plastic, cutting the process from months to weeks.

Material: High-performance alloys like titanium, Inconel, and stainless steel for corrosion resistance and load-bearing capabilities.

Benefits: Supply chain resilience, reduced inventory, localized production, and maintenance readiness.

Limitations: Certification hurdles, post-processing requirements, and consistency in mechanical properties.

2.7.3 Robotics and Automated Production Lines

In the field of robotics and automation, 3D/4D printing facilitates rapid prototyping, ergonomic design, and component customization. Printed robotic arms, end effectors, and smart materials with shape-memory functionality (4D printing) were being integrated into intelligent automation systems.

Case Study: MIT's CSAIL lab successfully developed 3D-printed hydraulic robots that required no assembly, enabling direct application in manufacturing environments.

Applications: Soft robotics, grippers, wearable exoskeletons, and bioinspired actuators.

Impact: Rapid iterations during the design cycle, lightweight structures, cost-effectiveness, and higher adaptability in Industry 4.0 frameworks.

Challenges: Motion precision, durability of printed joints, and compatibility with control systems.

The literature reviewed suggests that additive manufacturing has matured from prototyping to full-scale production in various sectors. Advancements in materials and design strategies, combined with economic advantages, are driving widespread adoption. However, large-scale implementation faces hurdles related to print size, post-processing, and precision. Emerging trends in 4D printing and smart material integration indicate a shift toward dynamic, self-functional systems, redefining future manufacturing paradigms.

CHAPTER- 3

CHAPTER 3: OPTIMIZING 3D/4D PRINTING TECHNOLOGY FOR LARGE-SCALE PROTOTYPING: ADDRESSING SPEED, COST, AND QUALITY CONTROL CHALLENGES

3.1 INTRODUCTION

3-Dimensional and 4-Dimensional printing technologies are latest adapted technologies in additive manufacturing that provide the enhanced capabilities in terms of design, customization of the products, and functionality. Whereas 3D printing allows for the very accurate production of intricate, layer-by-layer geometries directly from digital models using a broad spectrum of materials ranging from polymers to metals and biomaterials 4D printing boosts the additional element of time in that printed items are able to modify their shapes or function in reaction to environmental stimuli like heat, light, water, or magnetic fields. This dynamic development has enormous implications across sectors, ranging from aerospace and automotive to biomedical and wearable technologies, facilitating the creation of smart materials, adaptive components, and personalized health devices. A review of these technologies is important as it not only records the current state-of-the-art technologies but also delineates present challenges, like material constraints, scalability, and long-term performance, and outlines future directions and multidisciplinary applications that potentially will transform manufacturing, healthcare, and more. The expansion of 3D/4D printing in the production business with customized novel designs is gaining importance since it allows people to create the structures in a realistic representation. This vital technology has seen numerous amazing developments since the late 20th and early 21st centuries, satisfying the demands of designers, engineers, and manufacturers to produce high-quality, personalized goods. The origins of 3D/4D printing have been found in Chuck Hull's invention of Stereolithography (SLA) in the 1980s. Skyler Tibbits, the creator and codirector of MIT's Self-Assembly Lab, coined the phrase "4D printing" in 2013 as a result of the advancement. Since then, breakthroughs in materials science, software engineering, and hardware innovation have propelled the technology's fast progress. This layer-by-layer production approach is dubbed "additive manufacturing" to set it apart from subtractive manufacturing techniques such as machining or milling. However, because of the challenges with deformation strategies such as material waste, long deformation times, and inability to fabricate complex geometric shapes with traditional Computerised Numerical Control (CNC) machines; designers are

now turning to additive manufacturing processes, which lessen or eliminate these limitations [95-96]. Figure 3.1 illustrates the design and structure of the 3D/4D printing products.

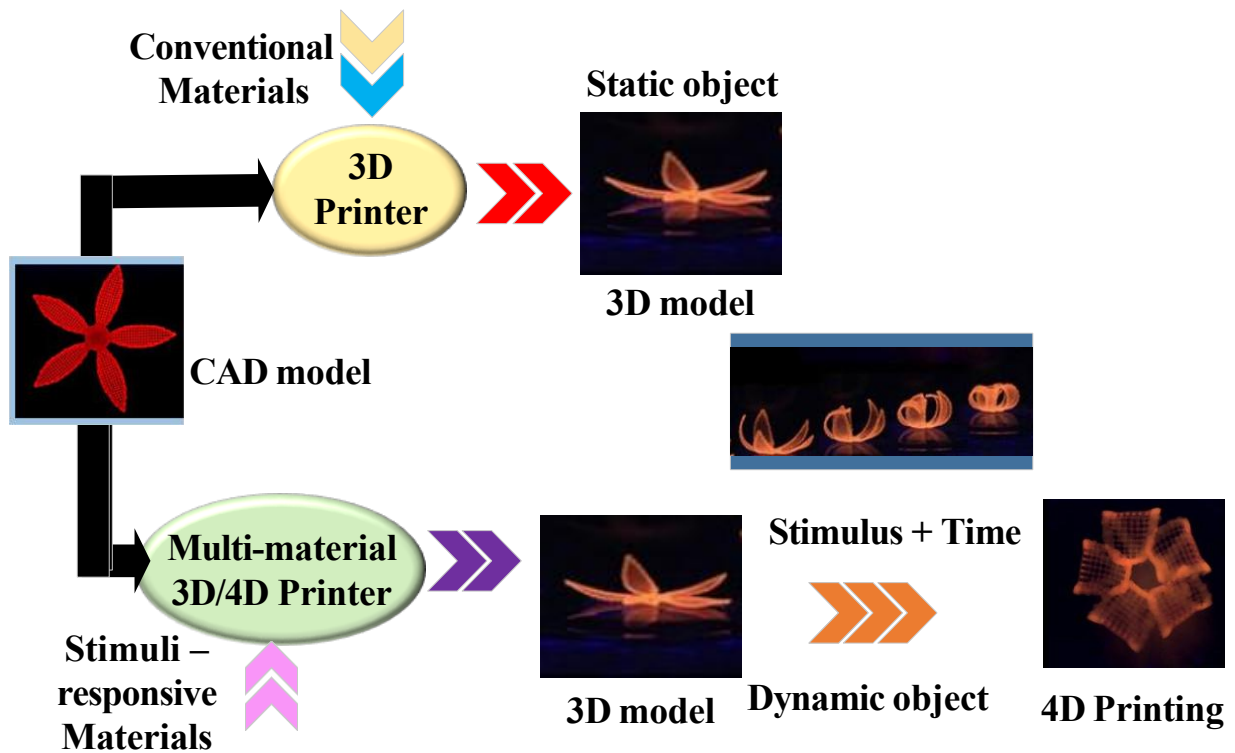


Figure 3.1 3D/4D printing design and structure of products

Additionally, the 3D/4D printing sector has been trying to make use of current technological breakthroughs like cloud integration in order to maximize production capacities in light of the growing need for the manufacture of customized products [97-98]. According to a market analysis by Global Additive Manufacturing, the market share of 3D/4D printed items has climbed to 51% in areas such as aerospace, automobile manufacturing, and healthcare as shown in Figure 3.2 (a). Additionally, the growth of industries-based 3D/4D printing product manufacturing is expected to be close to 31% as illustrated in Figure 3.2 (b). In 2023, this technology market size is reached at 352.2 billion USD and growth is expected to reach 867.5 billion USD in 2029, with a Compound Annual Growth Rate (CAGR) of 16.7 % as depicted in Figure 3.2 (c).

Despite significant progress in 3D/4D printing, manufacturing still faces challenges with material selection, post-processing, and quality-related limitations. Furthermore, the 3D/4D structure's mechanical strength is closely correlated with the physiological and mechanical characteristics of the base material that is applied [99-100]. With the help of newly developed cloud technologies, desk top 3D/4D printer manufacturing on a modest scale has been substantially optimized. In Additive Manufacturing (AM), the base material, controllability, and production cost determine the printer's capabilities in relation to the industry's ultimate use. Furthermore, small and medium-sized businesses find that the AM method takes too long to implement for 3D/4D printing.

In addition, these small-scale printers are not helpful for the industry's prototype production since it is unable to overcome print volume limits [101]. Extrusion-based 3D/4D printing has increasing potential in the industrial sectors, along with other fabrication methodologies because it promotes low-cost functionality and enhances the feasibility of printing full-scale structures which gradually eliminates production challenges such as the time and expense associated with creating large moulds and machine rigs, and limit problems with scaling sizes [102].

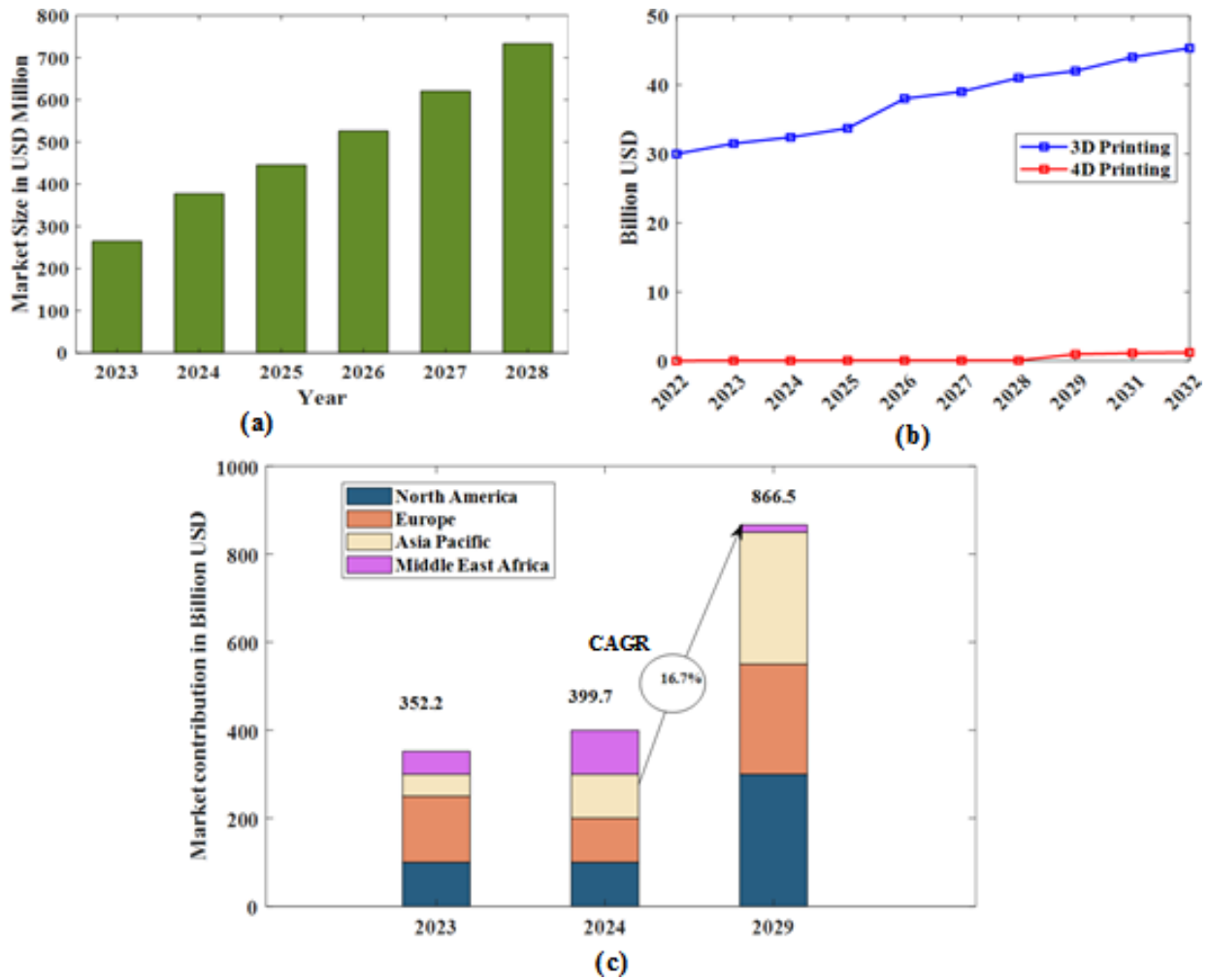


Figure 3.2 Worldwide Market Scenario forecasts in 3D/4D printing (a) Market size (b) Market growth of 3D/4D printing in industry (c) Market growth contribution based on regions

This research analyses the difficulties encountered in transitioning from small-scale to large-scale fabrication, including the design parameters of the nozzle size, layer height, temperature control, and cost-effective options for large-scale prototyping [103]. It also offers several strategies for optimizing high-potential quality control design, such as the use of Computed Tomography (CT) scanning for printed part analysis.

3.1.1 Process of 3D/4D printing

A remarkable range of technology and processes are used in 3D/4D printing, which has transformed production in a number of different sectors. This novel technique offers unmatched flexibility, adaptability, and efficiency over conventional manufacturing techniques by enabling the production of three-dimensional items from digital models [104]. Figure 3.3 depicts the process of 3D/4D printing.

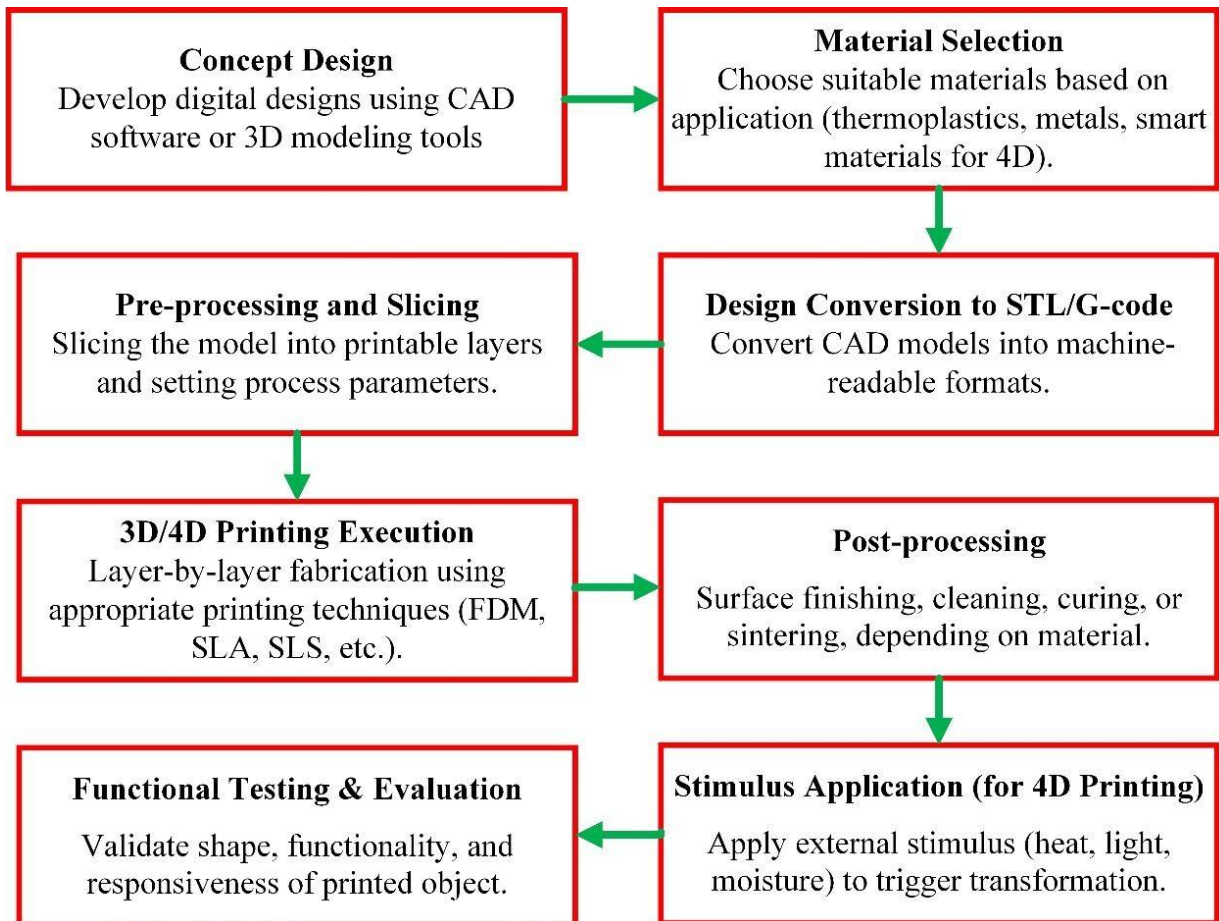


Figure 3.3 Process of 3D/4D Printing

In-depth analysis of the 3D/4D printing processes with its additive manufacturing techniques fundamental ideas, essential elements, uses, and potential is provided in this thorough investigation.

3.1.2 3D/4D Technology Methods of printing

The addition of dynamic, time-variable features into objects 3D/4D printed in response to environmental stimulants such as temperature, humidity, light, and magnetic fields brings into concept the aspect of self-assembly or time-dependent self-transformation. Industry in 3D/4D printing enables new applications to programmable matter, shape-changing materials, and adaptive structures [105]. Digital cutting, layer-by-layer printing, and Computer-Aided Design (CAD) are the fundamental principles behind 3D/4D printing. CAD software analysis to create a digital model or

3D scanners to digitize an existing object is the initial step in the process. An Industry-based 3D/4D printing architecture with the system integrated design modelling is demonstrated in Figure 3.4.

Liquid photopolymer resins are selectively cured by UV lasers in SLA printers' layer by layer, causing the materials to transform into accurate structures. Material Jetting (MJ) printers employ several print heads to jet liquid photopolymer droplets onto a build platform. The droplets are then cured using UV light to create solid layers. This process enables the creation of complex, multi-coloured prototypes and functional parts due to its high resolution and multi-material capabilities [106-107]. In order to further expand the capability of AM, researchers are considering novel materials, techniques, and hybrid techniques as the technology continues to evolve.

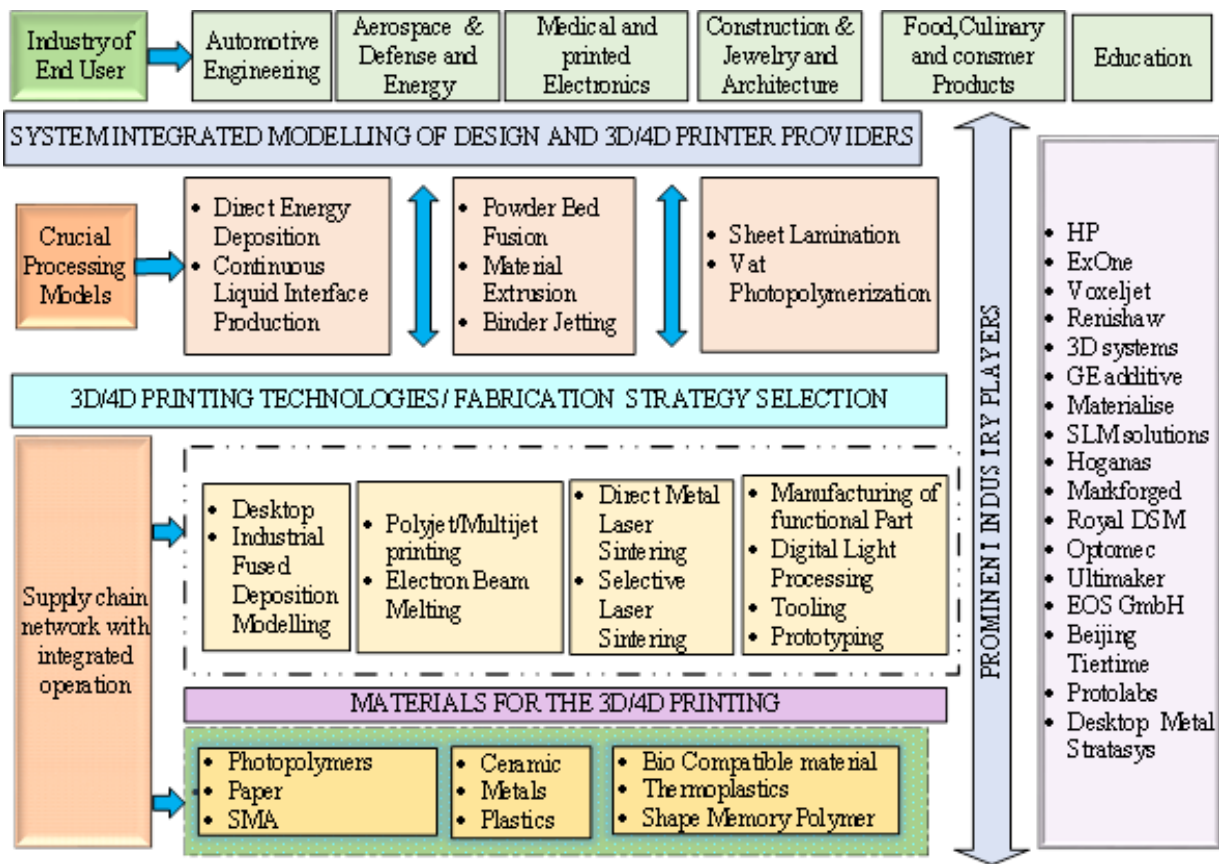


Figure 3.4 Architecture for 3D/4D printing processes based on industry design modeling

3.1.3 Key Components For 3D/4D fabrication

A standard 3D/4D printing system is made up of a number of vital parts, each of which is important to the printing process. Depending on the specific innovation and application, these components may differ, but generally 3D/4D printer is the key element in the process of turning digital models into tangible objects bilayer-by-layer depositing or solidifying print materials such as thermoplastics, photopolymers, metals, ceramics, composites, Shape Memory Alloy (SMA), Shape Memory Polymer (SMP), and biocompatible materials [108].

Aside from the build platform, print head/nozzle, and control system, other essential parts that govern the printing process are motor drivers, sensors, actuators, firmware, slicing software, and other hardware and software components that guarantee accurate movement, temperature control, layer alignment, and high-quality prints. Tools and equipment's required to enhance appearance, usefulness, or mechanical qualities make up post-processing equipment [109-110]. Safety interlocks, ventilation systems, enclosure panels, material handling procedures, and personal protective equipment (PPE) are among the measures being looked to ensure the protection of 3D/4D printed equipment and materials. Callipers, micrometres, CT scanners, surface profilometers, and tensile tests are examples of quality assurance instruments used in 3D/4D printing which verify dimensional correctness, surface finish, material qualities, and structural integrity. Figure 3.5 depicts the architecture of key components for 3D/4D fabrication.

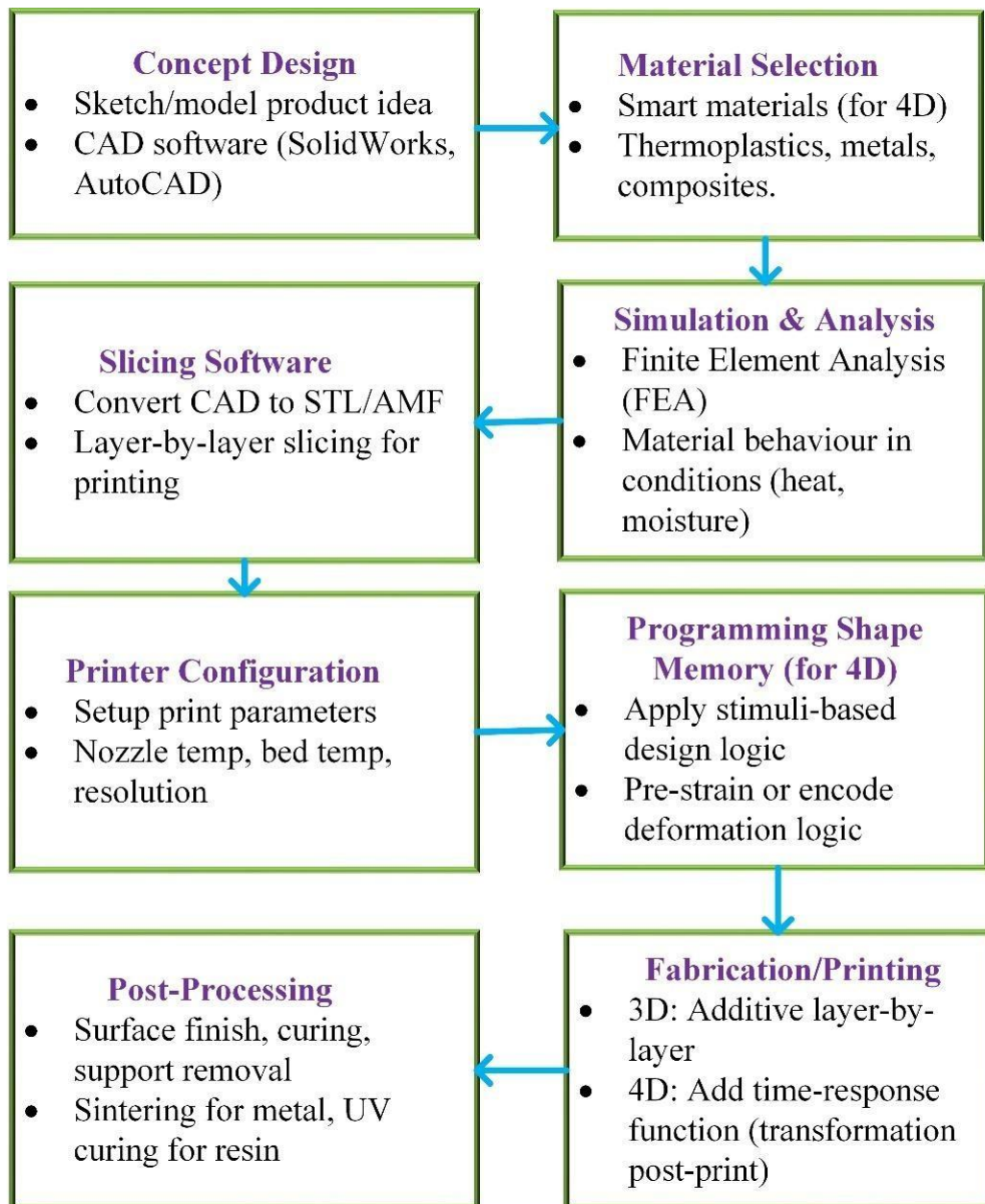


Figure 3.5 Architecture of key components for 3D/4D fabrication

Overall, these elements and printing technologies enable the smooth transformation of computer designs into physical constructions. 3D/4D printing's adaptability, speed, and customizability have revolutionized traditional manufacturing processes and opened up new avenues for creativity and innovation in a wide range of industries, including consumer goods, architecture, healthcare, automotive, aerospace, and education [111]. It expands the significance of endorses in the large-scale prototyping of 3D/4D structures, which is covered in the next section.

3.2 LARGE SCALE-BASED PROTOTYPING

Over the past few years there has been a notable upsurge in invention and utilization of AM manufacturing in a number of sectors. Though the technique gained traction initially in small-scale applications and prototyping, it is becoming evident that it has the potential to revolutionize large-scale production [112]. Rapid advancements in extrusion-based 3D/4D printing offer a practical means of getting beyond the limitations of traditional manufacturing techniques. FDM is a strong challenger with great potential for the industrial sector. Table 3.1 depicts the analysis of the large scale-based prototyping.

Table 3.1 Analysis of the large scale-based prototyping

Category	Details	Examples	Material Used	Challenges
Prototyping Technique	Additive Manufacturing (Large-format 3D printing)	Big Area Additive Manufacturing (BAAM)	Thermoplastics, carbon-fiber composites	High energy consumption, warping
Design Tools	CAD/CAE tools for scaling & structural testing	SolidWorks, Fusion 360	Digital designs	Limited support for massive models
Fabrication Platform	Robotic Arm-Based Extrusion or CNC Hybrid Machines	KUKA-based robotic 3D printers	Metal powder, concrete	Vibration damping, resolution issues
Application Domain	Aerospace, Automotive, Construction	Car frames, UAV shells, housing	PLA, ABS, metals, concrete blends	Transport logistics, part handling

Testing & Validation	Structural testing, simulation under load, wind tunnel testing	Finite Element Analysis (FEA), Physical drop test	Depends on prototype	Cost of failure, test space constraints
----------------------	--	---	----------------------	---

Larger and more complex structures produced because it employs a continuous flow of material instead of the layer-by-layer material deposition used in conventional 3D/ 4D printing procedures [113]. It has attracted attention because, in comparison to conventional production processes, it produces designed components with enhanced functionality at a significantly lower cost.

3.2.1 Working principle

The thermoplastic extrusion principles, which include heating a solid material to its melting point, pushing it through a nozzle or die, and then cooling it to produce a solidified structure, are the foundation of the material extrusion process. With 3D/4D printing, material is precisely deposited in accordance with a pre-defined digital model because the process is mechanized and digitally controlled.

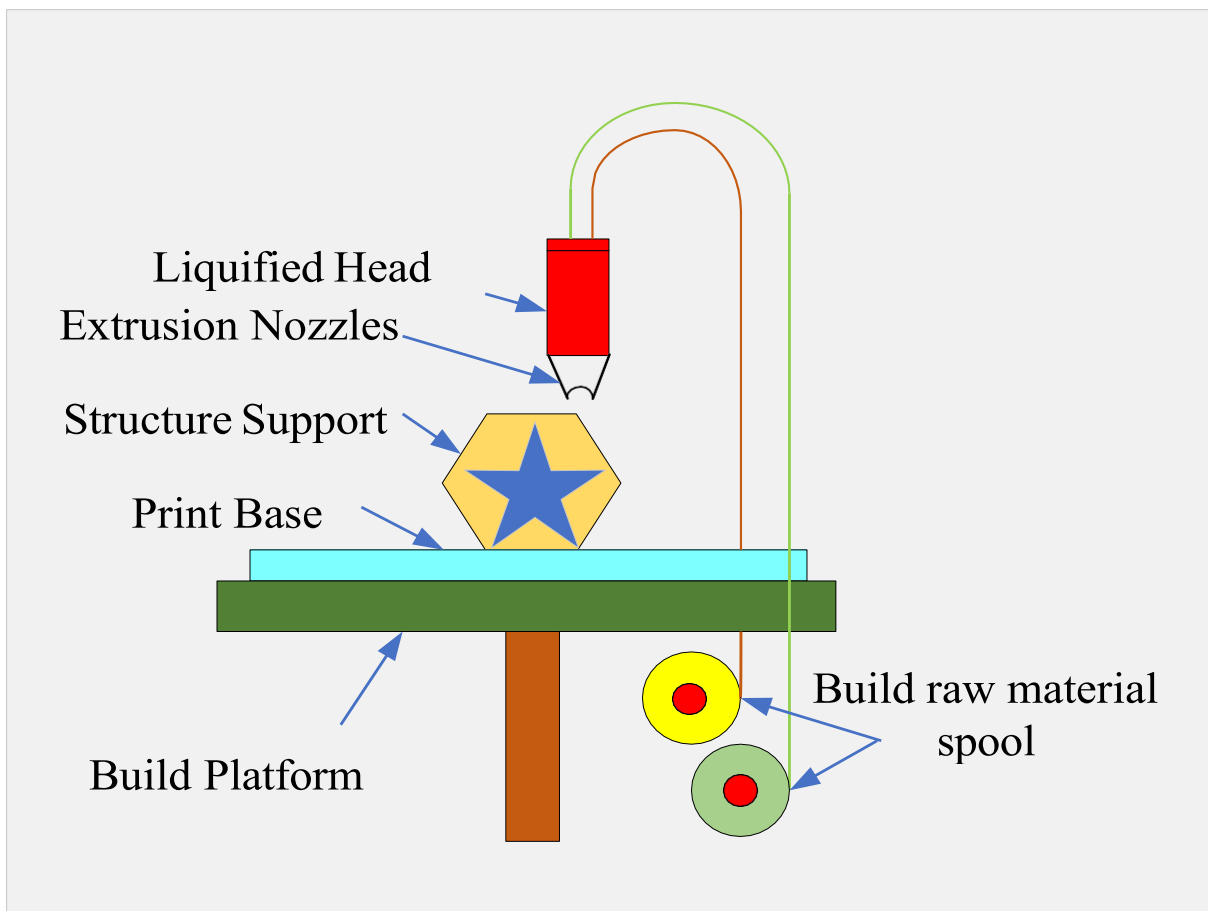


Figure 3.6 Device structure of FDM

An extruder with a motorized feeding mechanism that forces thermoplastic filament into a heated chamber where it melts and becomes viscous is one of the main parts of a material extrusion 3D/4D printer as illustrated in Figure 3.6. The diameter of the material deposited is determined by the extruder nozzle, which is also a major factor in defining the printed object's resolution and surface polish. There are two main purposes for the heated nozzle. The first step involves heating the thermoplastic filament to the point of melting, which facilitates extrusion. The second involves regulating the deposition temperature to guarantee appropriate layer adhesion and ideal material characteristics. The material being utilized and its particular processing needs are taken into consideration while regulating the nozzle's temperature [114-116].

The build platform holds the expanding object during printing and offers a steady surface for material deposit. If the material is prone to shrinkage or distortion after cooling, heating it helps to avoid warping and increase adhesion between layers. Motion controllers, temperature controllers, motor drivers, and slicing software are some of the hardware and software elements that make up the control system and regulate the printing process. Slicing software creates the tool path instructions that the printer must follow by converting the digital model into a sequence of tiny horizontal layers, or slices.

3.2.2 Materials Used

A wide range of thermoplastic materials used in large scale material extrusion 3D/4D printing, each offering unique properties and characteristics suited to different applications. Common thermoplastics used in FDM printing include Polylactic Acid (PLA) which is an eco-friendly thermoplastic made from renewable materials that decomposes naturally [117]. Acrylonitrile Butadiene Styrene (ABS) which is a durable and impact-resistant thermoplastic commonly used in automotive parts, electronics housings, and consumer goods.

It is commonly used in food packaging, medical devices, and industrial applications where clarity and durability are essential. Nylon (Polyamide) is a strong and flexible thermoplastic known for its low friction coefficient, strong tensile strength, and resistance to abrasion. It is used in applications requiring high impact resistance, such as mechanical parts, gears, and bearings. Polycarbonate (PC) is a tough and heat-resistant thermoplastic with excellent optical clarity and electrical insulation properties [118]. It is used in aerospace, automotive, and electronics applications where high strength and temperature resistance are critical. Table 3.2 list a few widely accessible thermoplastic composite materials that are utilized as filament in the FDM process.

Table 3.2 Thermoplastic composite filaments that are commercially available

Company	Product
PolyTech Materials Inc.	CarbonX CF-Nylon, GlassX GF-ABS, PolyBlend PC-CF, HeatShield PEI-GF
AddiForm Technologies	AddiStrong PLA-CF, AddiTough ABS-KF, AddiFlex PETG-CF, AddiResist PA-GF
ThermoFab Industries	ThermoWeave PETG-GF, ThermoForce Nylon-CF, ThermoShield PC-GF
FilaMatrix Corp.	MatrixBlend ABS-Kevlar, MatrixMax Nylon-CF, MatrixFlex TPU-GF
CompFil Solutions	CFlex PLA + CF, GFlex ABS + GF, DuraComp PETG + CF, ResiComp PC + KF
NexaFil Composites	NexaTough PC-CF, NexaShield PEEK-GF, NexaFlex PA-KF, NexaCore PPS-CF
FiberForge Materials	ForgeFil Nylon-Kevlar, ForgeX PEEK-CF, ForgeTuff ABS-CF, ForgeLite PC-GF
StratoPolymers Ltd.	StratoComp PEI-CF, StratoFlex PLA-GF, StratoDur PC-KF, StratoTech PEEK-CF

3.2.3 Current State of the Art in Large-Scale Prototypes Extrusion Machines

The most recent breakthroughs in large-scale prototype extrusion machines include a variety of improvements targeted at improving printing speed, scale, accuracy, and material flexibility [119]. Large-scale printing is the focus of certain 3D/4D printers, although these machines are far more costly and slower than smaller counterparts for many smaller enterprises.

These days, large-scale prototype extrusion machines are outfitted with sophisticated automation and clever features that improve dependability, expedite printing, and maximize resource use. The concept of the large-scale manufacturing sector employing Big Area Additive Manufacturing-Cincinnati Incorporated (BAAM-CI) FDM based car chassis printing is shown in Figure 3.7. It incorporates temperature sensor monitored operation to control the material flow via the extrusion nozzle.

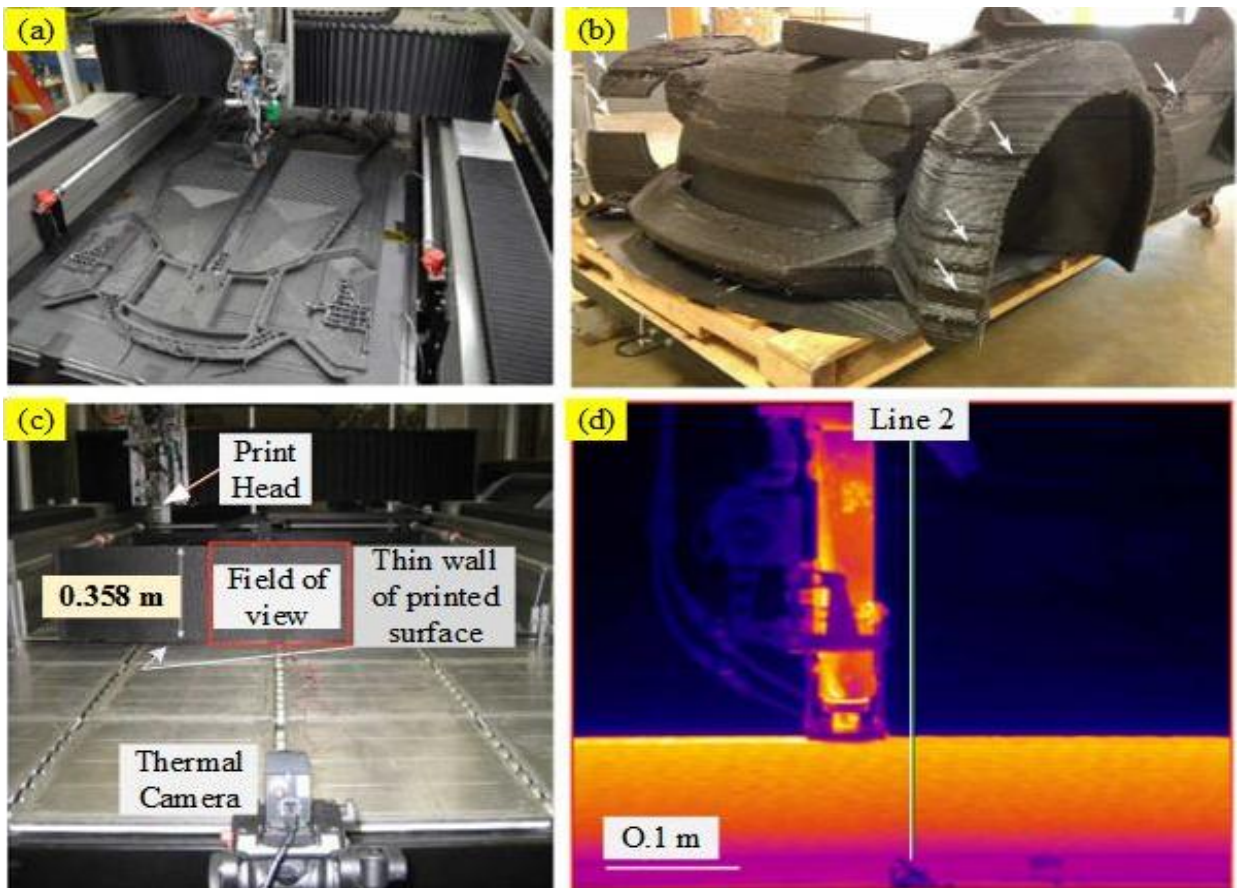


Figure 3.7 Large scale manufacturing industry framework (a) Using the BAAM-CI method large size automobile chassis are 3D/4D manufactured (b) A printed automobile chassis that has several cracks which are shown by white arrow (c) Using a thermal camera with FDM to print and check the surface temperature (d) Thermal camera picture displaying blue cooling zones and orange hot areas

These devices use cloud computing, Internet-of-Things (IoT), and data analytics technologies to enable remote monitoring and control, improve workflows, and gather, analyse, and share real-time production data. This connectivity facilitates customization, just-in-time production techniques, on-demand manufacturing, and enhanced traceability, quality assurance, and agility.

The integration of large-scale prototype extrusion machines with Industry 4.0 technology allows manufacturers, designers, and engineers to realize vision and bring innovative products to market more quickly and efficiently than ever before, even though these machines offer formerly unprecedented capabilities in terms of printing volume, speed, precision, material versatility, and automation.

Table 3.3 Recent extrusion-based 3D/4D printer application in large scale manufacturing

Printer size	Extruder type	Material used	Temperature at extruder	Controller software used	Printer used
6096 mm × 3186 mm × 1829 mm	Pellet-based extruder	PLA	80 °c	Slicing software with G-code	Big Area Additive Manufacturing (BAAM) printer by Cincinnati Lab
1270 × 1120 × 1730 mm	Single screw extruder	PLA-INGEO 3052D	153 °c	WYKO VISION32®	MEX 3DP
3.56 m × 1.65 m × 0.86 m	Melt-extruded pellets with single screw extruder	ABS	200°c	EXAMINIR software (FLIR)	BAAM by OAK RIDGE
6 m × 4 m × 2 m	Equal sized drier equipment type	Wood-Fiber (WF) - PLA	240 °c	ARAMIS- DIC software	INGERSOLL Master print
6096 mm × 3186 mm × 1829 mm	Pellet-based extruder	ABS	323 °c	TGA 55'S TRIOS software	BAAM-CI
1850 mm × 2250 mm × 1725 mm	Polymer pellet -2 x modular extrusion heads	PLA	60°c	Slicing software with G-code	BIGREP ONE

3.3 CHALLENGES OF UPSIZING THE 3D/4D PROTOTYPING

The industrialization of 3D/4D printing brings with it a host of opportunities as well as a multitude of obstacles [120]. A comprehensive strategy that incorporates technological developments, legal frameworks, and business alliances is essential to realizing the full potential of 3D/4D printing in many sectors and transforming the design, production, and distribution of goods worldwide.

3.3.1 Speed Control Challenges

Optimizing 3D/4D printing is essential to meeting large production needs without sacrificing efficiency and quality. This means improving material durability, printing speed, and accuracy to compete with conventional production techniques. After analysing the issues surrounding printing speed, including scaling-up and rate optimization issues for polymer extrusion, it is determined that there aren't many studies on optimization for counter rotating twin screw extrusion [121]. It is also recommended that process modifications be made while keeping scaling parameters as near to the reference process parameters as feasible in order to guarantee quality for scaled up printing process. Table 3.4 depicts the summary of challenges and optimization approaches for scaling 3D/4D printing.

Additionally, parallelly connected Multi nozzle print head which features an extrusion nozzle array of 26 cylindrical nozzles with an inner diameter of 250 μm is increased printing speeds. Fine features were also preserved using 11 twin-screw parallel extruders but in big scale it has difficulties [122-123]. Also, advanced methods of printing in small scale such as acoustic liners, scissor style deployable structures, and huge area AM coupled with hardware looping have practical challenges in the designing and modelling. Moreover, Continuous Liquid Interface Production (CLIP) which is a resin-based hybrid 3D/4D fabrication method derived from the classic SLA/Digital Light Processing (DLP) process, it constantly cures a liquid resin into solid pieces with the application of light and oxygen which create items with smooth surface finishes and prints at quick rates have succeeded in the medium scale but lags behind for large scale industry. Common firmware, controllers, and electronic systems enable quick 3D/4D printing with high-quality printing finishes and to create precise 3D/4D printing by incorporating slicing software is also beneficial but not for big sized one and it is quite challenging.

Table 3.4 Summary of challenges and optimization approaches for scaling 3D/4D printing

Category	Key Focus	Insights/Challenges	Remarks
Material & Process Optimization	Durability, speed, accuracy	Limited studies on optimization for counter-rotating twin screw extrusion	Requires more research and development
Scaling-Up Printing	Matching scaled parameters to reference	Quality assurance is difficult when scaling up without process modification	Maintain original process fidelity during scale-up
Multi-Nozzle Systems	26-nozzle array (250 μ m diameter)	Boosts speed, but preserving precision is challenging at large scale	Suitable for moderate-scale use
Parallel Extruders	11 twin-screw parallel extruders	Fine features preserved, but not scalable for large production	High complexity in control and consistency
Advanced Printing Methods	Acoustic liners, scissor-deployable structures, large area AM	Design and modeling complexity increase drastically with scale	Effective in lab scale, not yet industry-ready
CLIP (Continuous Liquid Interface Production)	Resin-based hybrid method	Fast and smooth printing at medium scale, not yet viable for large-scale production	Limited by resin behavior and hardware
Firmware & Electronics	Controllers, slicing software	Enhances quality and speed for small/medium prints, struggles with big-sized models	Needs advanced hardware upgrades for scalability

3.3.2 Quality of the Product Challenges

Establishing standard operating procedures and guaranteeing adherence to safety and quality standards need close cooperation between academic institutions, industrial players, and regulatory agencies. Due to its poor resolution, most 3D/4D printing methods compromise the overall accuracy and quality of the produced parts. Every technology used in additive manufacturing creates the 3D component layer by layer. Because it depends on the adhesion between layers, this presents a problem to the printed part's overall mechanical qualities. Methods to enhance the interlayer adhesion should be the subject of further investigation. Better mechanical qualities result from increased layer adhesion, and this is advantageous for the widespread advancement of 3D and 4D printing technologies. Figure 3.8 depicts the analysis for 3D/4D printing challenges and considerations.

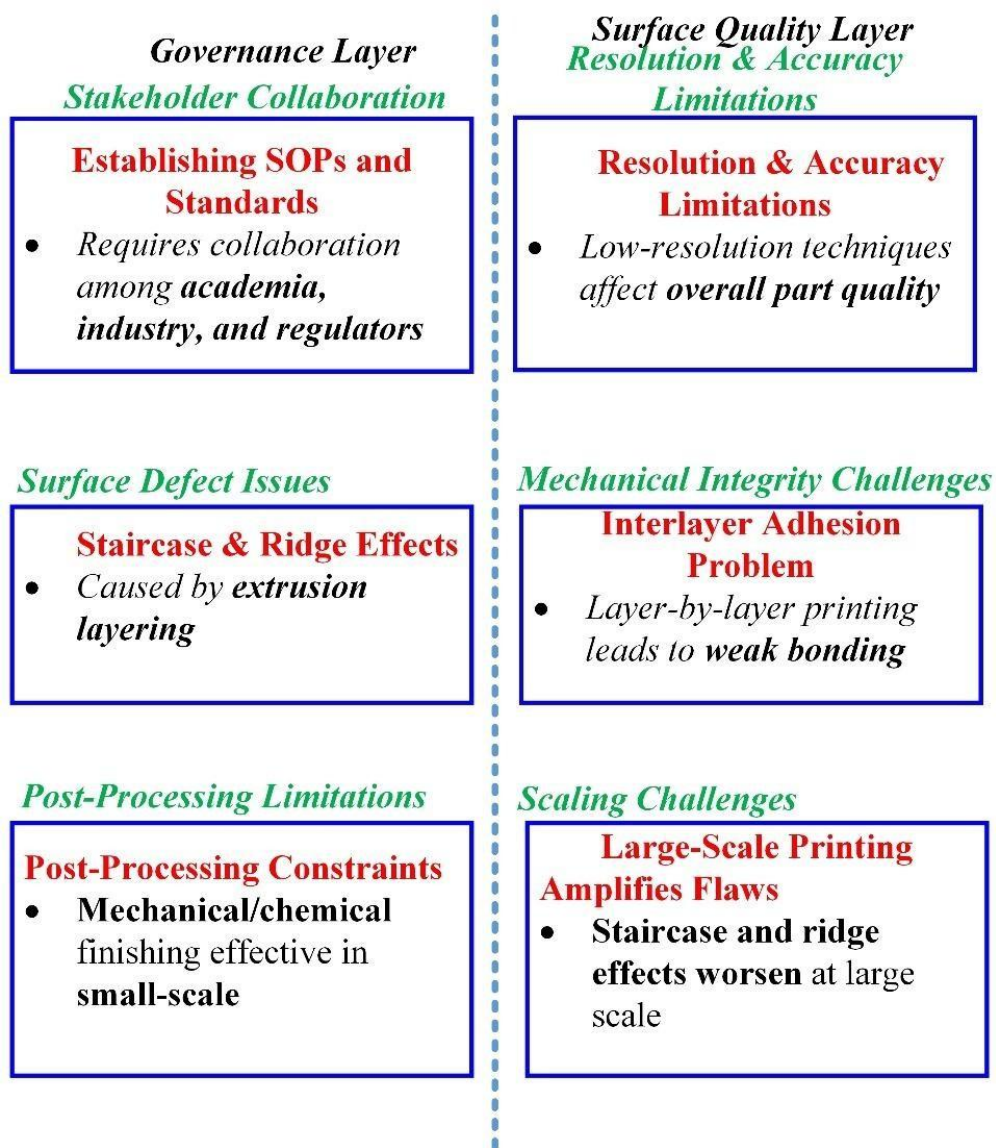


Figure 3.8 Analysis for 3D/4D printing challenges and considerations

Because of the underlying idea behind the extrusion process, surface flaws like the staircase effect and ridge impact are unavoidable. Because each layer is layered on top of the one before it, there is

a minimum vertical increase equal to the height of the printing layer. When generating an inclined surface, the staircase effect happens, with each subsequent layer producing a tier-based sloping surface. On level surfaces, the ridging effect produces a beaded surface finish as a result of each layer producing a little swell. The impacts of the ridge and staircase are often amplified in large-scale 3D/4D printing. Mechanical or chemical post-processing techniques have been shown to be a viable solution in small-scale extrusion components. It is possible to target and treat certain component surfaces or characteristics with abrasive machining [124]. These techniques work well for smaller-scale components but are ineffective when applied to larger-scale ones.

3.3.3 Process Standardizing Challenges

Since there are no regulations certifying and qualifying AM products, it is challenging to examine AM. Moreover, differences in AM machine types and processing parameters lead to gaps in process certification and qualification. Table 3.5 depicts the analysis of key focus areas in additive manufacturing standardization.

Table 3.5 Analysis of key focus areas in additive manufacturing standardization

Focus Area	Challenge	Standard Body	Status	Standard Code
Process Control	Inconsistent layer bonding	ASTM	Under Development	ASTM-AMX101
Material Traceability	Lack of material source tracking	ISO	Active	ISO-AMTR5001
Machine Calibration	Printer misalignment	NIST	Draft Stage	NIST-AMCAL-2025
Post-Processing QA	Heat treatment variability	ISO/ASTM Joint	Published	ISO/ASTM-AMQA-7100
NDE Methods	Difficulty detecting microdefects	ASTM	Pilot Testing	ASTM-NDE-AM92

The major organizations that are important in creating AM standards were ASTM and ISO. Non-destructive evaluation (NDE) permits the investigation of quantities of interest without impairing a component's functionality. Certain NDE technology standards, such ASTM WK47031 and ASTM 52908, are being developed with the intention of helping choose NDE techniques and providing precise metrology criteria.

3.3.4 Cost Challenges

Encouraging wider adoption requires resolving the cost-effectiveness issue. To make 3D/4D printing competitive with traditional manufacturing, production costs may be reduced by utilizing automation, optimizing supply chains, and implementing economies of scale. The manufacturing sector, particularly the large-scale, strives to reduce costs by cutting tooling and maintenance expenses as well as outsourcing design costs, which improves the coherence between part production and implementation as shown in Figure 3.9. Additionally, labour costs decreased by automating post-processing processes like surface polishing and support removal through careful design considerations.

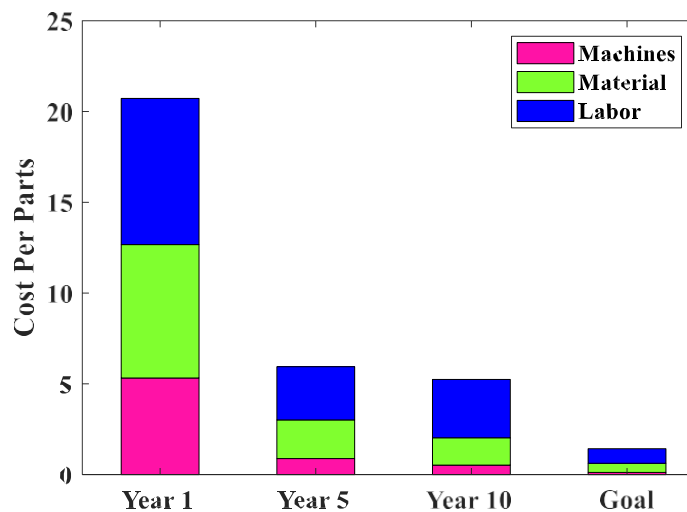


Figure 3.9 Cost forecasting for the large-scale 3D/4D printing sector

Likewise, a decrease in subcomponents and assemblies is made possible by the addition of more complicated components. Reducing the number of stages required to complete the part through the use of a digital to completed product approach significantly streamlines the supply chain hierarchy. The whole structure as well as later qualifying procedures were subjected to simulation, testing, and validation. Many of these manuals rely on significant project expenses and time commitments. In certain situations, where the cost of producing several smaller samples is nearly equivalent to that of producing whole components, the certification process optimized by demonstrating the integrity of the design using statistical analysis of multiple full-scale parts.

3.4 EXISTING SOLUTIONS AND OPPORTUNITIES

Adding supply chain optimized design at the early stages of product development assist differentiate between design choices and provide an early edge in AM optimization. More practically, FEA may reduce the need for expensive mechanical testing by simulating production outcomes. The computing cost of simulation might frequently be unmanageable without model reduction. The zone-based technique is implemented to lower the amount of computing intensity for full-scale AM simulation

in order to assess exceedance of parameter. By breaking down AM components into its most crucial geometries, simulations be made more accurate in areas of most relevance. This enables large-scale industry in economically viable printing of 3D/4D structure. Moreover, several innovations in printing speed enhancement are achieved in industries like food, construction and using CLIP interface.

This chapter discusses the problems associated with the industrial-based 3D/4D printer's scaling-up operation is examined, along with its implications for product quality and total cost. These include design and simulation-related concerns. Moreover, interpretation is essential to efficiently and successfully accomplishing design goals in large-scale 3D/4D production. To make sure that the manufactured goods fulfil the required criteria, designers must properly comprehend the design specifications. When dealing with large volumes of data such as CAD models, modelling outcomes, sensor data etc. Interpretation is critical for making educated decisions over the process of manufacturing, from choice of materials to process optimization in supply chain management. Designing goods that provide value and satisfaction requires a thorough understanding of end consumer's need and preferences. When it comes to material characteristics, purpose of design, sustainability consideration, and future trends, interpretation aids in translating the findings of feedback from consumers, market patterns, and accessibility research into practical design improvements that support the overall design goals in the application fields of 3D/4D printing such as soft robotics, tissue engineering, drug delivery, mechanical industry, transparent glass, construction are now being produced on a smaller scale which is required to scale up using sophisticated optimization techniques without compromising the product's quality, that is the most important factor in this industry.

As these technologies are employed in more sectors, the market for additive manufacturing and 3D/4D printing is growing quickly. The primary forces for market expansion have been product development and prototyping applications, as end-use production becomes more prevalent. However, the majority of the advancements in 3D/4D printing and AM have been made with small-scale equipment up to this point. It is discovered that a few challenges must be addressed in larger-scale 3D/4D printers to become feasible one. For large-scale 3D/4D printers, more accurate environmental controls are needed to prevent warping caused by temperature variations. To overcome these obstacles, significant research and development expenditures are required to create novel printing processes and material compositions. In the future, we intend to develop a framework for a new product design process aimed at improvising design for manufacturing using 3D/4D printing technology.

CHAPTER- 4

CHAPTER 4: LASER METAL WIRE DEPOSITION FOR ADDITIVE MANUFACTURING OF COMPLEX SOLID STRUCTURES

4.1 INTRODUCTION

Additive Manufacturing (AM), also recognized as 3D printing, has developed into one of the most disruptive technologies in the manufacturing industry [125]. The value of AM is no longer in doubt as it introduces a manufacturing process model that produces intricate customized products with precision and low waste. AM has transformed prototyping, allowing manufacturing organizations to reduce time and costs associated with development by permitting rapid iterations and design changes [126]. By democratizing innovation, AM allows designers and engineers autonomy to develop intricate geometries that would be very difficult to produce, if not impossible, with traditional means [127]. In addition, AM allows for localized manufacturing, minimizing dependency on long supply chains, making it a more sustainable practice [128].

As a major driver of Industry 4.0, AM is prepared to disrupt as many industries as possible, from aerospace and automotive sectors to healthcare and consumer goods, through scalable, efficient, and more cost-effective manufacturing [129]. Laser Metal Weld Deposition (LMWD) is arguably the most important form of AM because this technology will radically change the way that metal parts are made and could be repaired. LMWD utilizes the precision and energy efficiency of laser technology to deposit metal in a very controlled manner, giving a high level of accuracy in creating complex geometries and repairing very high value components. The most important aspect of LMWD is this: it is capable of creating parts with better mechanical properties, less wasted material, and reduced production time compared to previous manufacturing methods [130].

Also, LMWD's ability to repair and remanufacture parts gives expensive machines far longer life, making it invaluable for valuable machine parts in industries such as aerospace, automotive, and energy. This process can enhance the performance and life of metal parts and, therefore, support sustainable manufacturing by lowering material and energy consumption [131]. AM in LMWD represents an enormous technological leap in industrial manufacturing processes, combining the cut precision of laser piece by piece deposition with the nature of AM additive manufacturing. This combination yields more complex and customizable metal parts that conventional subtractive modules cannot perform. The potential of AM in LMWD stands with the ability to manufacture parts

with complex geometries, internal architecture, and customized properties, increasing design complexity and innovative ability [132].

4.1.1 Key Components of Laser Metal Weld Deposition

The key components of LMWD are displayed in Figure 4.1. Initially, the laser source provides the stable thermal energy to make the melt pool on the substrate and ultimately add the material. Secondly, the wire feeding system, which is often automated, continuously delivers the metal wire into the melt pool where it is fused layer by layer to construct the part. Thirdly, the motion control system, which is based on a robotic system or CNC (Computerized Numerical Control) system, is responsible for the position of the deposited wire to ensure precision and coordination between the laser source mechanical system and the feedstock delivering system, the wire feeding system. Shielding gas is typically added to protect from oxidation and contaminants, as a spray stabilizer for melt pool properties, to provide a stable ambient condition around the melt pool. All these components and systems are integrated for a seamless operation to allow high-quality near net shape production for 3D/4D metal printing.

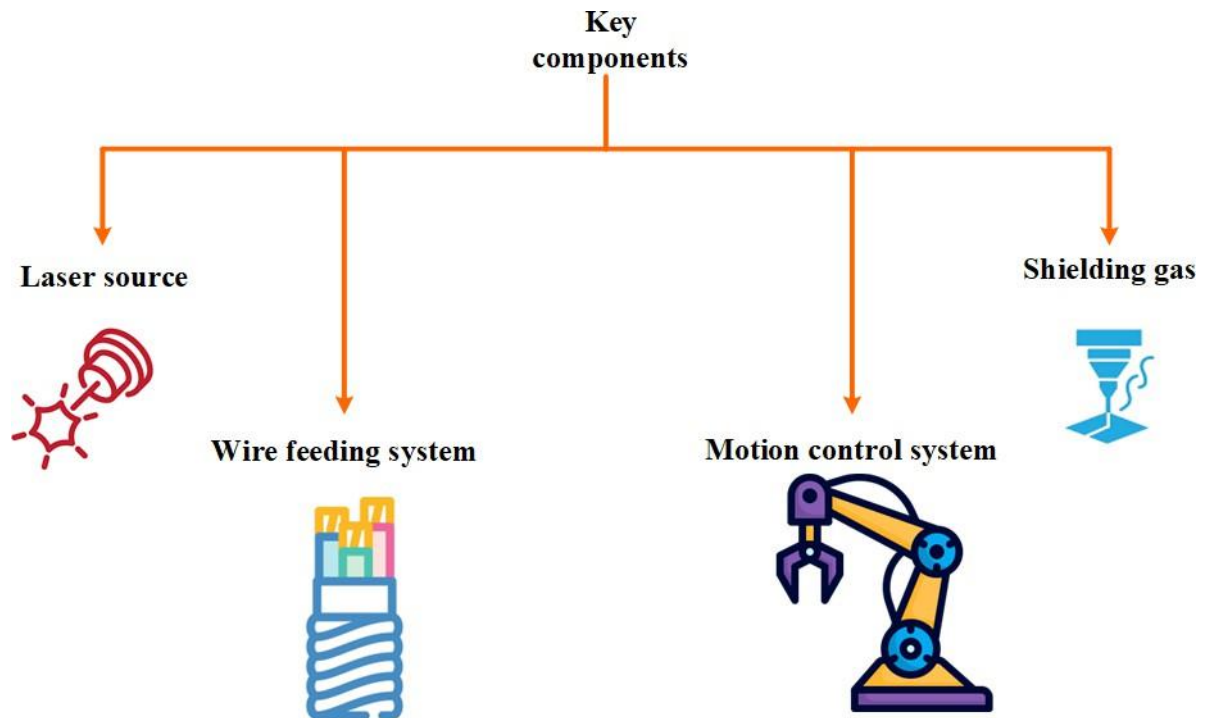


Figure 4.1 Key components of LMWD

4.1.2 Printing Process

The workflow of the printing process is illustrated in Figure 4.2. It is a simple workflow progressing from file development to completed objects. Initially, files are created. The files then undergo model slicing and path generation using software tools, in which the model is transformed from a model

into layer-by-layer toolpaths. In the material processing and layering stage, the machine reads the toolpath profile to deposit the material or transform the material according to the deposition or transformation. Finally, the desired moving and performing final product is obtained.

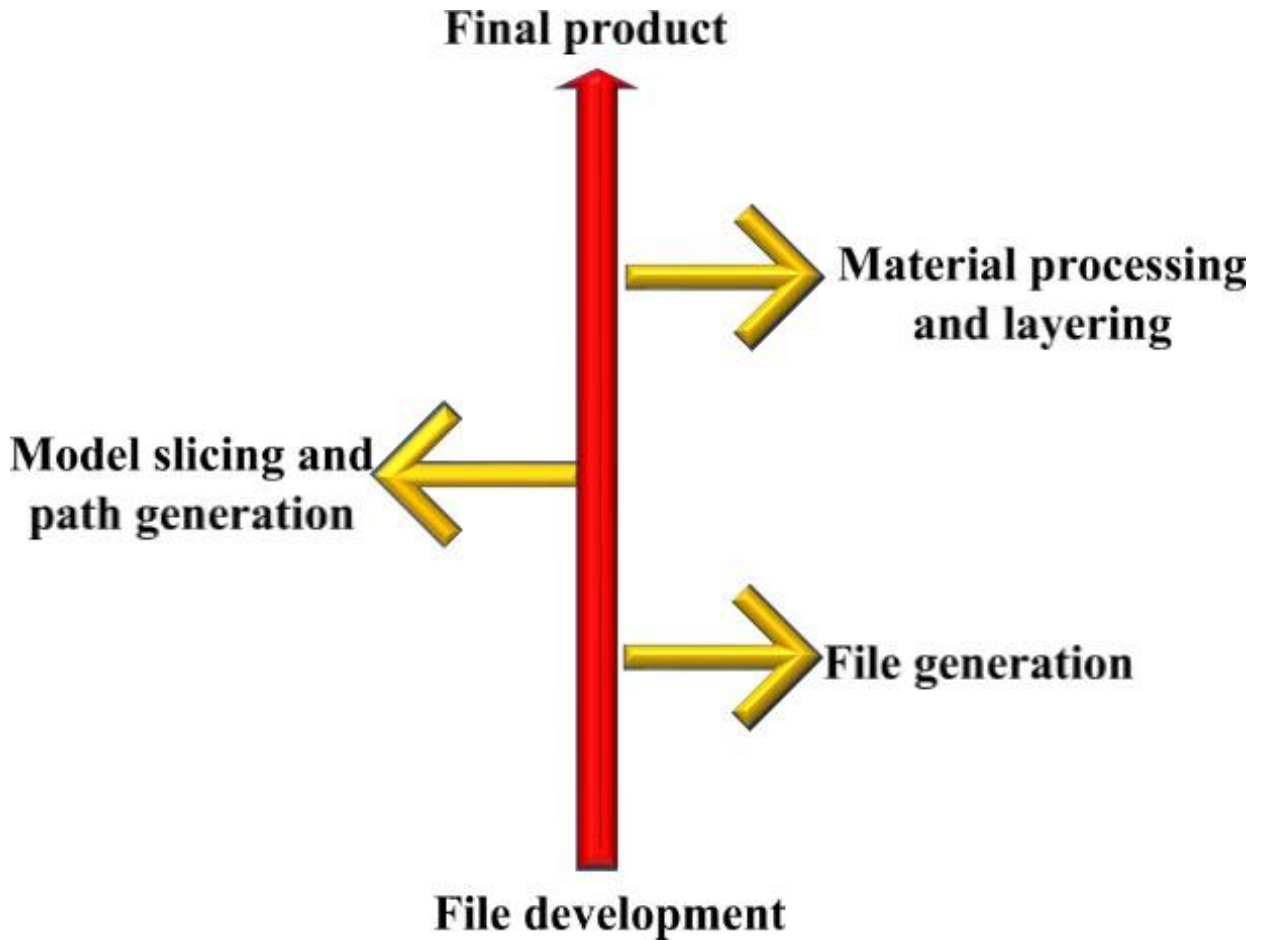


Figure 4.2 The workflow of the printing process

4.1.3 Systematic Protocol to Fabricate a Metal Structure

Figure 4.3 exhibits a schematic of the systematic procedure for AM of 3D/4D metal structures. Initially, the melt pool is generated, wherein the laser energy balance perspective creates a localized molten region on the substrate. In Step 2, the deposition of metal material into the melt pool begins, usually in the form of wire. Step 3 signifies the formation of the first solidified layer as solidification of the deposited melt occurs on its melt side in clear contact with the molten pool. This first layer becomes the base over which further building is carried out on. The fourth step continues to build up the layers; thin layers of material are deposited and consolidated layer by layer to become a 3-D structure. Step five is the end stage of printing wherein the finished 3-D metal object is formed; if embedded smart materials or responsive mechanisms can change shape or function over time in response to external stimuli, then it is called a 4D structure.

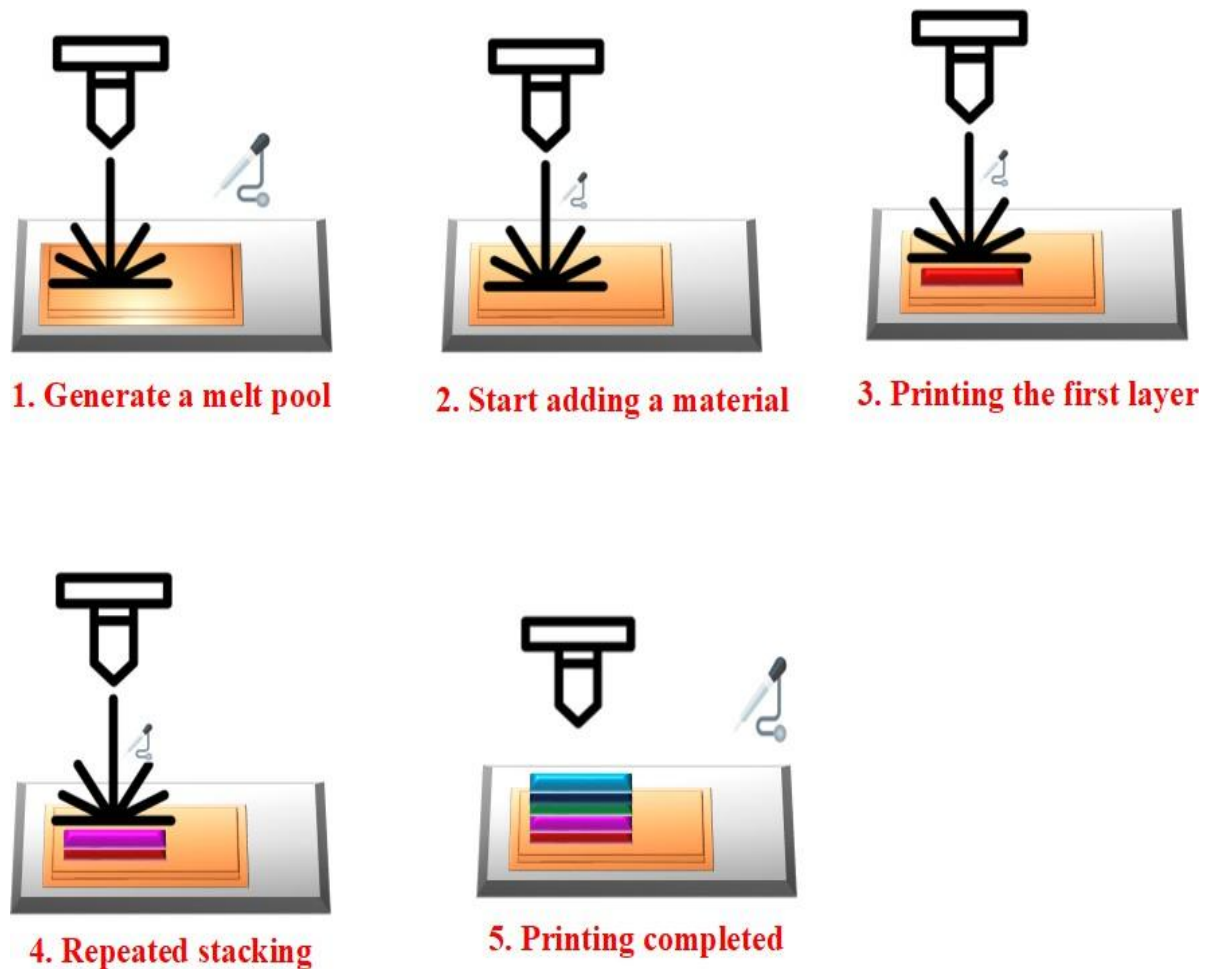


Figure 4.3 Systematic Protocol to Fabricate a Metal Structure

4.2 SYSTEM UNDER CONSIDERATION FOR INVESTIGATING LASER METAL WELD DEPOSITION

Figure 4.4 depicts a process flow for investigating and applying LMWD in AM. The first step involves exploring the LMWD technique for creating high aspect ratio thin-walled structures by depositing layers on a substrate in the scanning direction.

Next, a 200W direct diode laser source and a wire feeding system are integrated, with laser parameters and wire feed rates calibrated for optimal performance. Aspect ratios and layer widths are measured to determine correlations with processing parameters. Material usage efficiency is calculated by converting different forms of material into the final product efficiently. The implications on design flexibility and innovation potential in AM are analyzed, emphasizing the impact of the LMWD process. Finally, the developed process is applied in a practical scenario, showcasing the final application with a space-oriented application. The overall flow illustrates the LMWD technique to its final application, emphasizing calibration, parameter variation, efficiency analysis, and design implications.

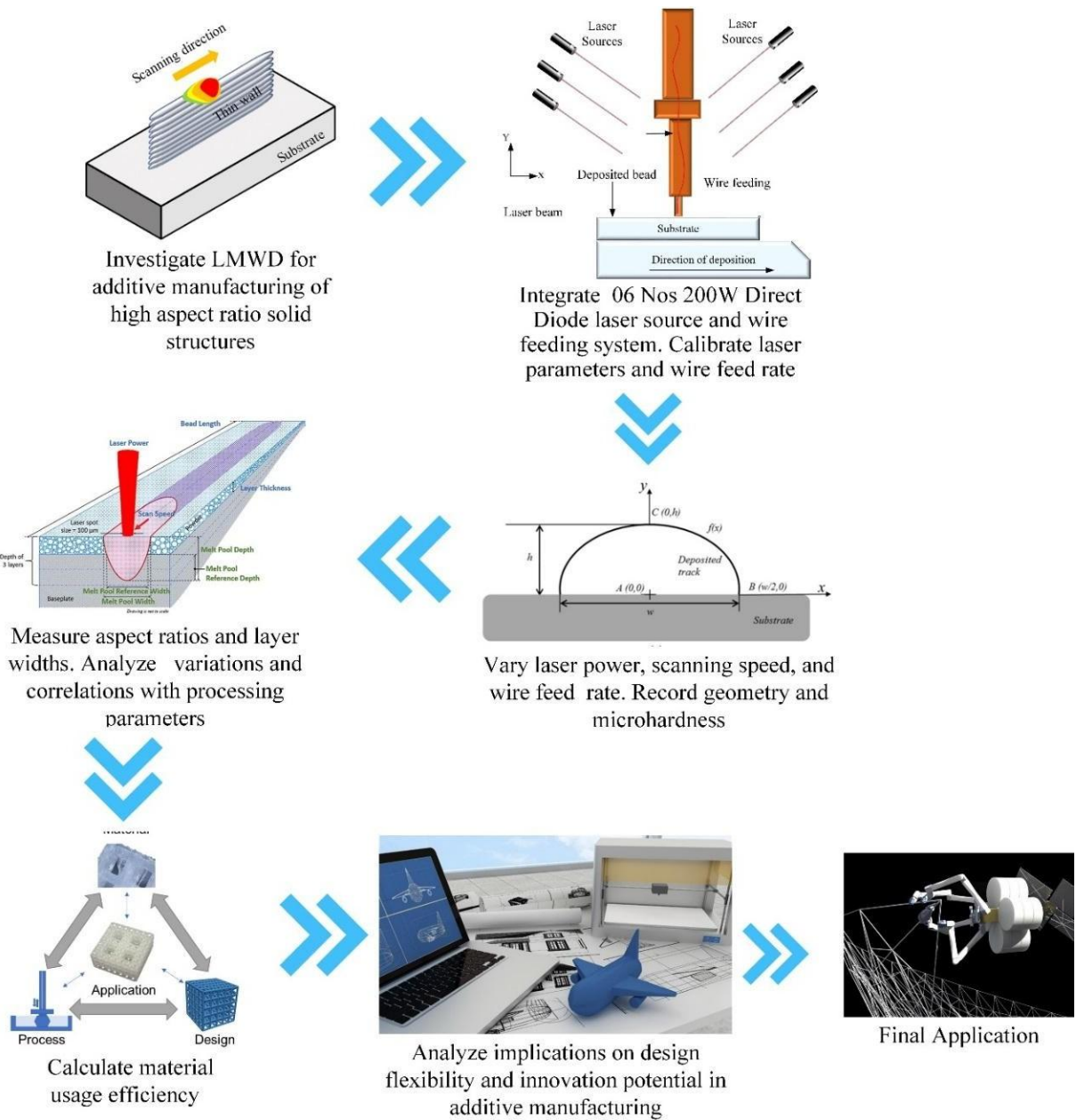


Figure 4.4 Proposed architecture for additive manufacturing of complex solid structures

4.2.1 Laser Metal Wire Deposition System

The LMWD system comprises a welding station (Meltio 3D printer) and an in-built wire feeder, is shown in Figure 4.5. The welding station features a Neodymium-doped Yttrium Aluminium Garnet (Nd:YAG) source that generates pulses ranging from microseconds to milliseconds at Pulse Repetition Rates (PRR) in the frequency range.

The maximum peak power (P_{peak}) of the pulses reaches 10 kW, resulting in maximum average power of 140 W and pulse energy (E) of 60 J. Rate of speed of fibre delivery is utilized for transporting the laser beams from the sources to the upper heads, employing a 0.6 mm fibre, 400 mm collimating

lens, and 250 mm focal lens. This setup achieves a very fine spot of 0.35 mm diameter, with the capability to adjust the maximum spot diameter between 0.4 mm and 0.6 mm automatically.

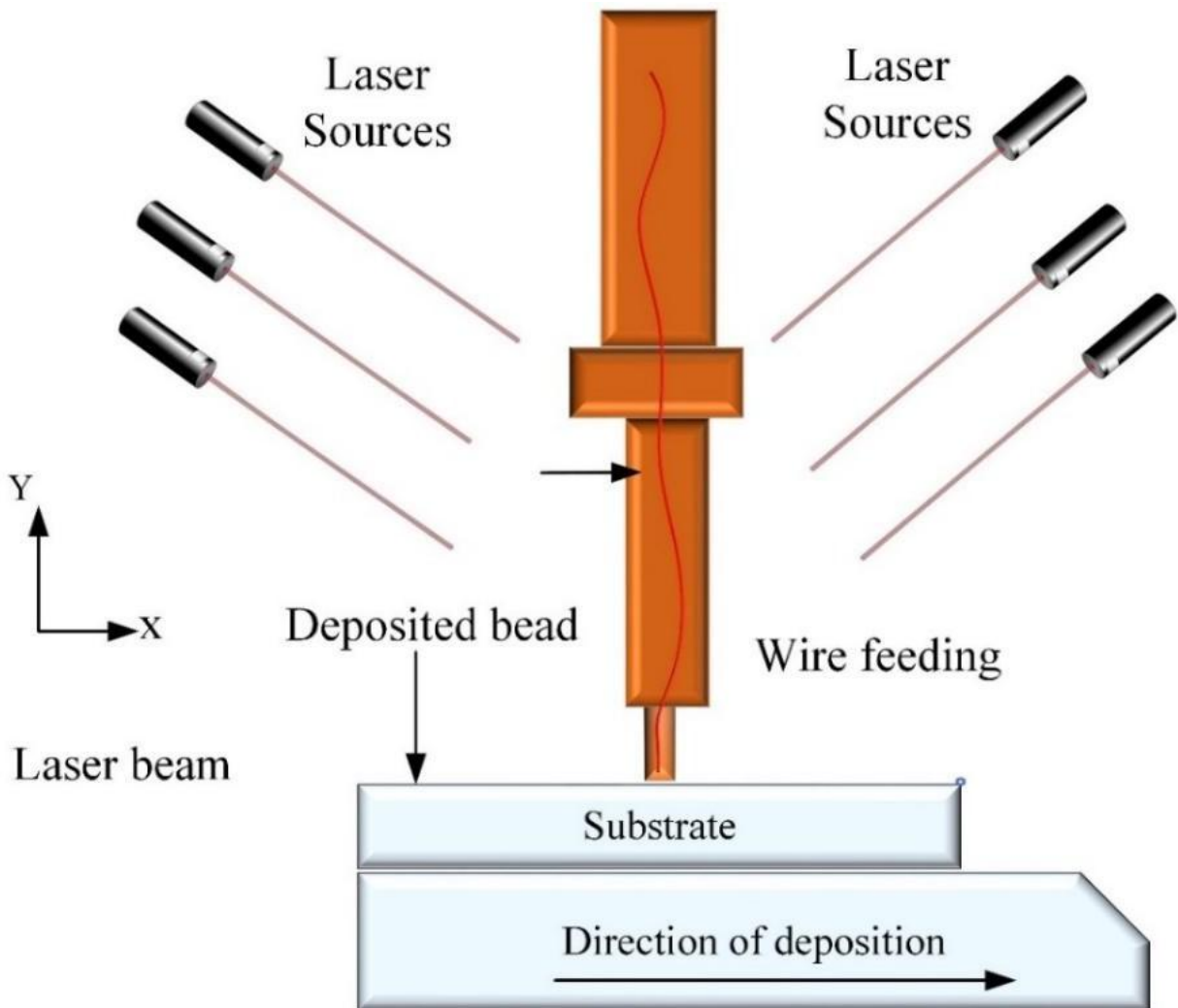


Figure 4.5 Working principle of LMWD technique

4.2.2 Control Software Architecture

Figure 4.6 illustrates the control software system architecture, which comprises a servo control module and a laser control module connected by a common interface. The control software also functions as a suite of software packages that manage all operational factors. This software is developed from and extended using contemporary open-source software, Ultimaker Cura for 3D printing, and augmented with programmable control features for 4D printing, using the advanced platform Fusion 360 with simulation plugins. All of these platforms allow active parameter changes through the programming functionality, and managing time-dependent transformations is viable using 3D/4D printed materials.

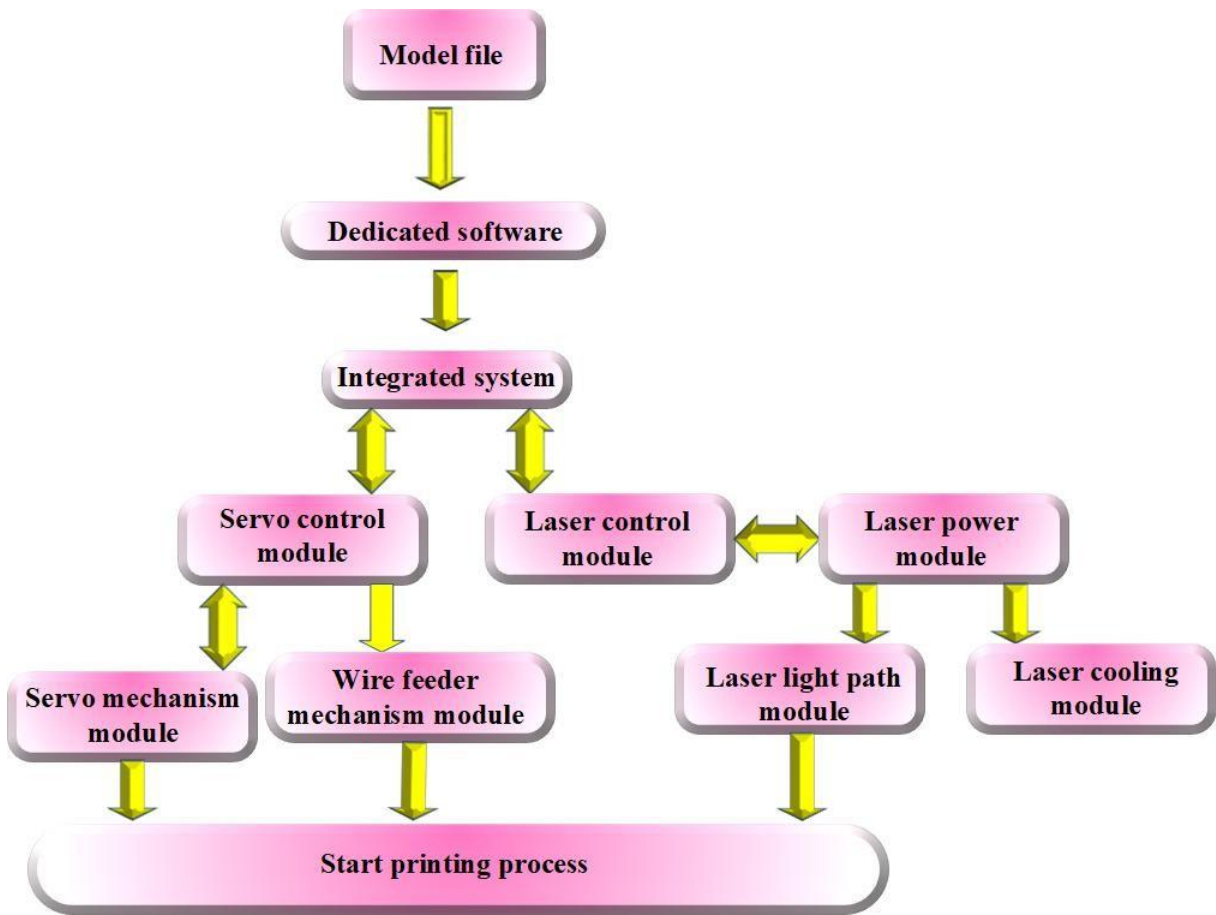


Figure 4.6 Control software architecture

4.2.3 Mathematical Formulation for Printing Solid 3D/4D Structures

LMWD serves as a tool for selecting a printing architecture by using the following approach. Equation (4.1) is used to stochastically choose printing patterns to initialize an array with ‘A’ amount of product to be fabricated in the 3D/4D techniques.

$$A = STO(1, A(Print_Surface)) \quad (4.1)$$

where, A and $A(Print_Surface)$ denotes the overall number of printing surface accessible, and STO specifies stochastic technique utilized to generate numeric groups. Equation (4.2) estimates the fitness factor associated with this LMWD according to printing approaches.

$$Print_{fit} = \frac{1}{A} \sum_{j=1}^A PE_j * \left(\frac{D_j}{Maxi(D)} + \frac{Maxi(THRP)}{THR_i} \right) \quad (4.2)$$

where, D_j specifies constitute temporal assessment indicators associated with the provided printing schemes, PE_j specifies print efficiency, $Maxi(D)$ denotes the maximum energy consumption, ‘A’ represents advancement ratio for the printed product, THR_i represents throughput delay, and $THRP$ denotes throughput rate of printing. Also, $Print_{fit}$ corresponds to quality of the printed materials, and Equation (4.3) is used to predict the PDR rates.

$$PDR = \frac{1}{TC} \sum_{j=1}^{TC} \frac{Q_{ryj}}{Q_{tyj}} \quad (4.3)$$

where, PDR specifies print deposition rate, Q_{ry} and Q_{ty} stand for the single and multiple deposition layer that are sent and obtained over TC temporal contacts.

4.2.4 Material Usage Efficiency

Evaluating material use efficiency in LWMD is crucial for optimizing resource utilization, reducing waste, and minimizing costs in manufacturing processes. This assessment helps in achieving precise control over material deposition, enhancing the structural integrity and performance of the final product. Efficient material usage also contributes to sustainability by decreasing the environmental impact of production. Ultimately, this evaluation supports the development of more advanced and economical manufacturing techniques. Material use efficacy is also indicative of process stabilities, which is vital for which maintains a geometrical tolerance. Efficiency of material use (η) is measured as the ratio of the deposit volume (K_d) to the wire volume (K_w).

$$\eta = \frac{K_d}{K_w} \quad (4.4)$$

$$V_w = \frac{\pi}{4} \cdot d_w^2 \cdot VTJ \cdot i \cdot M = \frac{\pi}{4} \cdot d_w^2 \cdot VTJ \cdot \frac{e}{\gamma} \cdot M \quad (4.5)$$

where volume of wire (V_w) delivered is contingent upon certain process parameters which include wire diameter (d_w), rate of wire feed ratio (VTJ) maximum number of layers (M) and the duration of a single layer (i). For a minimum-walled structures on a constant length (e) and normal constant transverse variable speed (γ) deposits of the wire volume is measured as:

Regarding a constant deposited section within the amount of deposit length, A_d specifies the position of the material use efficiency is derived as follows:

$$\eta = \frac{A_d}{\frac{\pi}{4} \cdot d_w^2 \cdot VTJ \cdot \frac{e}{\gamma} \cdot M} \quad (4.6)$$

To assess the material utilization and the area of deposited material, measurements are taken for both single-layer and multi-layer deposits.

4.2.5 Deposition Efficiency Calculation

In the field of manufacturing processes, Deposition Efficiency Calculation (DEC) is an approach that has found extensive application in multi-objective optimization. It involves changing a multi objective problem to its single objective counterpart [133].

Normalize the kth objective using the following criteria:

$$r_i^{(n)}(k) = \frac{\max_i(r_i^{(0)}(k)) - r_i^{(0)}(k)}{\max_i(r_i^{(0)}(k)) - \min_i(r_i^{(0)}(k))} \quad (4.7)$$

If the objectives adhere to the smallest-best criterion, the evaluation focuses on minimizing the values of interest. This means that lower values are preferred and considered optimal. For example, in the context of material utilization and deposition area, a smaller amount of wasted material and a more compact deposition area would be ideal.

$$r_i^{(n)}(k) = \frac{r_i^{(0)}(k) - \min_i(r_i^{(0)}(k))}{\max_i(r_i^{(0)}(k)) - \min_i(r_i^{(0)}(k))} \quad (4.8)$$

where, $r_i^{(0)}(k)$ specifies the value of the kth nominal objectives measured at the ith trial, $\max_i(r_i^{(0)}(k))$ and $\min_i(r_i^{(0)}(k))$ denotes the maximum and the minimum value of the kth objectives measuring at the ith trial. In this research, the objective function (w and p) are formulated according to the given Eqn. (4.7) and k is formulated according to Eqn. (4.8). Calculating DEC_i for the normalized data using Eqn. (4.9):

$$DEC_i = \frac{\theta_{\min}(k) + \Phi * \theta_{\max}(k)}{\theta_{oi}(k) - \theta_{\min}(k)} \quad (4.9)$$

where, $0 \leq DEC_i \leq 1, \theta_{oi}, \theta_{\min}, \theta_{\max}$ are calculated in the Eqns. (4.10), (4.11) and (4.12):

$$\theta_{oi}(k) = |r_0^{(n)}(k) - r_i^{(n)}(k)| \quad (4.10)$$

$$\theta_{\min}(k) = \min_i \left(\min_k \left(|r_0^{(n)}(k) - r_i^{(n)}(k)| \right) \right) \quad (4.11)$$

$$\theta_{\max}(k) = \max_i \left(\max_k \left(|r_0^{(n)}(k) - r_i^{(n)}(k)| \right) \right) \quad (4.12)$$

$$r_0^{(n)}(k) = \max_i(r_i^{(n)}(k))$$

where, $r_i^{(0)}(k)$ are the reference sequences, for example $\max_i(r_i^{(0)}(k))$ is a coefficient in the range of (0, 1).

$$DEC_i = \sum \omega_j * DEC_j \quad (4.13)$$

where, ω_j is the computed weight of the jth objective with $\sum \omega_j = 1$ and $0 < DEC_j$. Finally, the maximum optimized solution relates to the peak value of DEC_i. This peak value represents the most efficient configuration, leading to the highest performance outcomes and minimal waste. By

targeting this peak value, the process achieves enhanced material utilization and process efficiency, ultimately contributing to more effective and sustainable manufacturing practices.

4.3 RESULTS AND DISCUSSIONS

This section provides a comprehensive evaluation of experimental findings, including a detailed examination through SEM and other characterization techniques. This section elucidates the impact of various deposition parameters on material efficiency, structural integrity, and overall performance, providing critical insights into the effectiveness of the optimized process.

4.3.1 Testing Configuration

Figure 4.7 illustrates the analytical specimen setup for LMWD of Meltio M2000-DLX 3D printer is a high-performance AM system featuring a 200W diode laser surrounded by six additional laser units, ensuring uniform energy distribution for precise material deposition. It boasts a dual-extrusion system capable of handling high-strength carbon fibre composites and versatile thermoplastics, with a generous build volume of 600 mm × 600 mm × 600 mm. An AI-driven slicer optimizes material usage and print times, while a closed-loop cooling system maintains optimal temperatures to prevent overheating. Main parameters of the prototype of LMWD system are shown in Table 4.1.

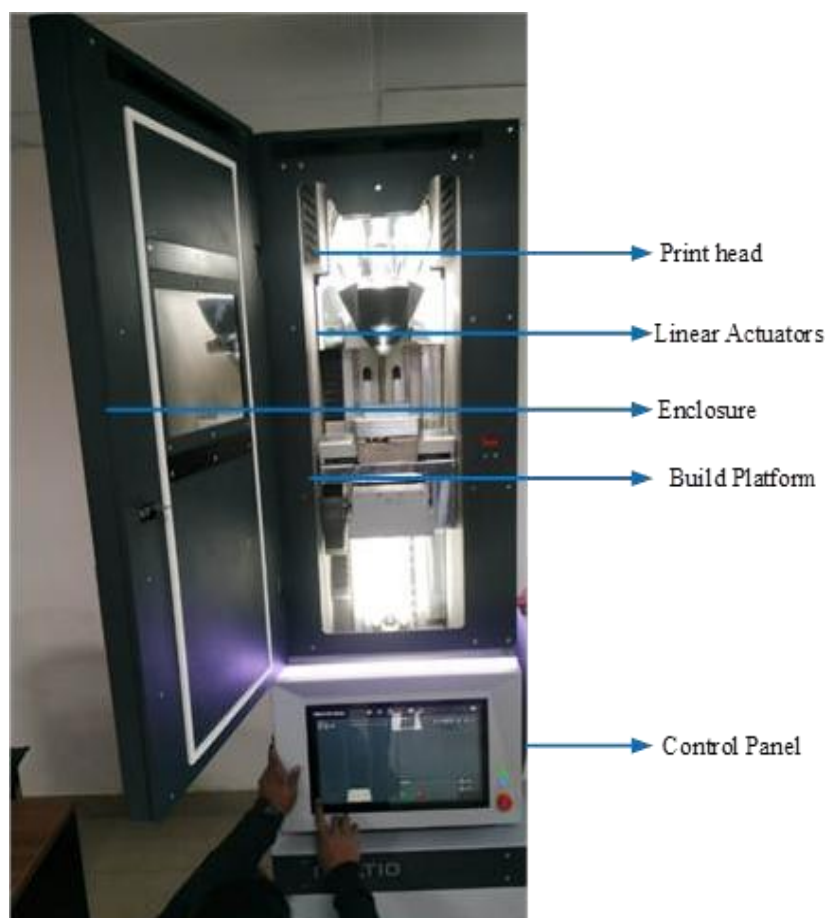


Figure 4.7 Specimen setup in the Meltio 3D Printer

The welding stations consist of 4 linear and 2 rotation axes, enabling precise control of speed (v) via numerical control. The wire feeder systems, named Lach, is controlling through a LabVIEW interfaces, which regulates the Wire Feed Rates (WFR) and synchronizes laser emissions at the beginning of each new layers. Various nozzle dimensions are employed to accommodate different wire sizes.

The printer robust aluminium frame and heated build platform ensure durability and excellent first-layer adhesion. High-precision stepper motors and linear guides provide smooth, accurate movements for high-resolution prints. Additional features include a touchscreen interface for intuitive control, an enclosed build chamber for safety, and a filtration system to manage fumes and particulates, making the Meltio M2000-DLX ideal for industrial applications requiring precision and reliability.

Table 4.1 Main parameters of the prototype of LMWD system

Feature	Value
Dimension (W×D×H)	570×700×1200 mm
Envelope ratio of print	146×170×380 mm
Total Weight	260 kg
Power Source	1300 W
Type of laser	06 Nos 200 W direct diode lasers
Wavelength of laser	978 nm
Type of Wire Feed	Up to 3 × K400 spools
Wire Feedstocks	0.9-1.3 mm wire diameter
Cooling Chamber	Water-cooled chiller
Control Chamber	Closed-loop chamber
Input Power	209/240 V single phase
Power Consumption ratio	3-6 kW peak depending on selected option

Figure 4.8 (a) and (b) depict components printed using a Meltio 3D printer. Figure 4.8 (a) shows a circular insert with internal features, characterized by a cylindrical shape with internal threaded or grooved elements. This part potentially serves as an insert for a larger assembly or as a custom connector piece. Figure 4.8 (b) showcases a rectangular block with distinct angled channels or grooves, which could function as a guide or alignment block in a mechanical assembly.

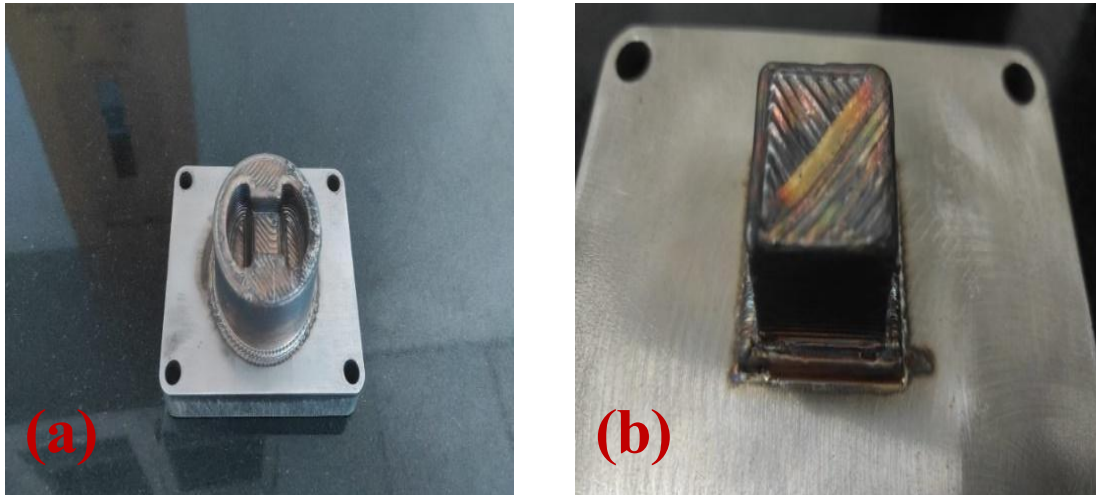


Figure 4.8 Pictorial representation of (a) Circular insert with internal features (b) Rectangular block with angled channels

Both components demonstrate the precision and versatility of metal 3D printing in creating intricate and functional parts. The research utilized austenitic stainless steels for both substrate and wire materials. AISI 301 wires, 0.5 mm in diameter and employed alongside AISI 316 substrates which is 10 mm thick. Table 4.2 presents the nominal chemical composition of these alloys.

Table 4.2 Chemical constitution of the specimen

AISI 316	Wt. %
C	0.09
Si	0.75
Mn	2
P	0.046
S	0.04
Cr	17-19
Mo	3-4
Ni	11-15
Fe	Bal

4.3.2 Single-Layer Deposition

Figure 4.9 depicts the relationship between increased E and height increment (Δz) at various scanning speeds (v) for a laser-based manufacturing process. Subfigures (a), (b), and (c) illustrate this at scanning speeds of 6.5 ms, 8.1 ms, and 9.2 ms, respectively. In each subfigure, the height increment (Δz) is plotted against increased E , with colour bands representing different height ranges.

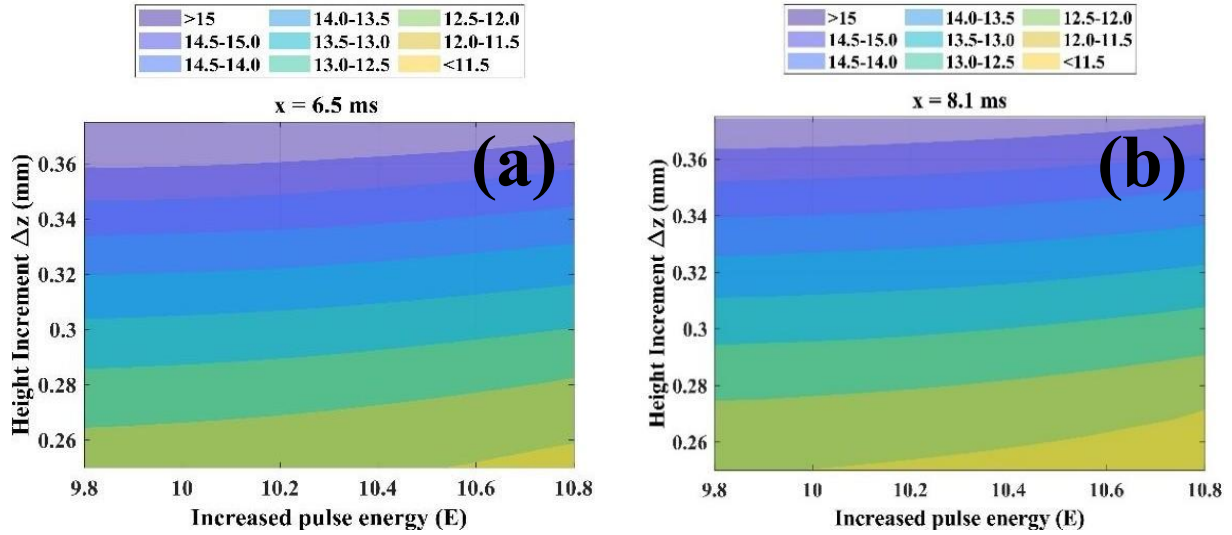


Figure 4.9 Contour plots for three variable pulse duration (a) speed, $x = 6.5$ ms (b) $x = 8.1$ ms and (c) $x = 9.2$ ms

As E increases from 9.8 to 10.8, the height increment also rises, with noticeable differences in the bands indicating various achieved heights. Each subfigure shows a consistent trend of increasing height with higher E , adjusted for the different scanning speeds, and provides a clear visualization of scanning speed influences the height increment under varying pulse energies.

4.3.3 Calculation of Deposition Efficiency

Figure 4.10 illustrates deposition efficiency with the fitted curves which highlights key finding that, LMWD exhibits exceptionally high material use efficiency under stable deposition conditions. The observed decline in material use capacity with higher fluence is attributed to increased fume and vapor production, along with the generation of sparks and dross under these varying experimental conditions. Overall, single-layer deposition demonstrates greater efficiency, supported by a higher coefficient of the single point regressors.

To determine material efficiency, the finished product volume of 1000 cm^3 , k_w of 1200 cm^3 and rejection volume (k_r) of 30 cm^3 are taken into account and total product volume k_w calculated as follows,

$$K_w = K_w - K_r = 1200 - 30 = 1170 \text{ cm}^3 \quad (4.14)$$

By using the Equation (4.4),

$$\% \eta = 1000 / 1170 \approx 0.85 (85\%) \quad (4.15)$$

It is important that single-layer depositions maintain stability in regions of reduced varying E and pulse durations, resulting in a limited overall fluence range (30.25-32.46 J/mm²), and the material efficiency is 90 % shows effective contribution of the wire material to the final product creation.

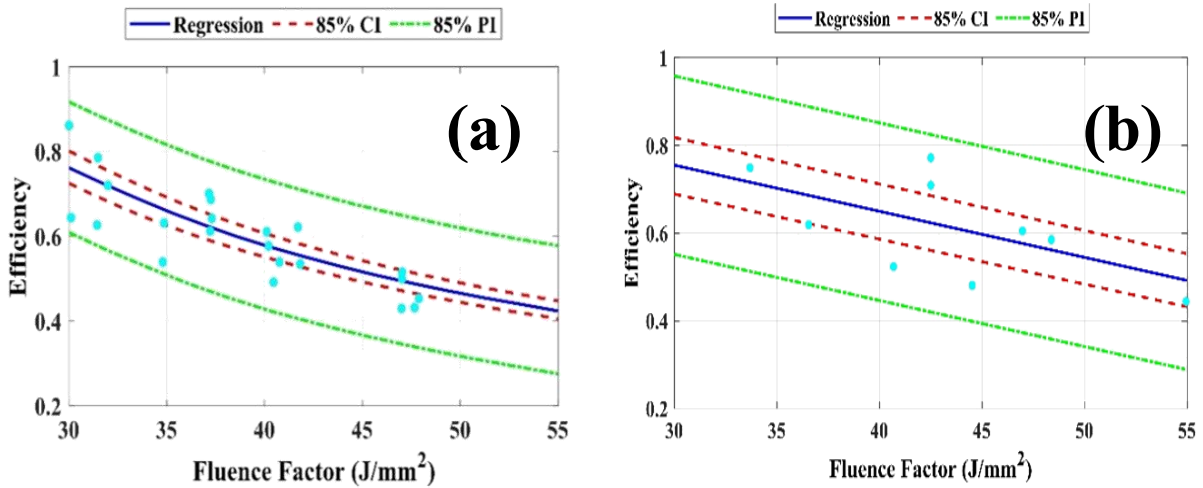


Figure 4.10 Deposition efficiency of (a) Single layer deposition (b) multi-layer deposition

4.3.4 Effect of Coefficient of Friction at Diverse Loading Scenarios

Figure 4.11 illustrates the variation of coefficient of friction at different normal loads with the relationship between scanning speed and the coefficient of friction for three sliding velocities: 0.5 m/sec, 0.75 m/sec, and 1 m/sec. For a sliding velocity of 0.5 m/sec, the coefficient of friction increases steadily from approximately 0.7 at 0.4 m/min to about 0.74 at 0.6 m/min. At a sliding velocity of 0.75 m/sec, the coefficient of friction shows a slight rise, starting around 0.69 at 0.4 m/min and ending at about 0.705 at 0.6 m/min. For a sliding velocity of 1 m/sec, the coefficient of friction remains almost constant initially, with a slight increase from around 0.68 at 0.4 m/min to approximately 0.685 at 0.6 m/min.

The observed minimal deviation in the coefficient of friction at a 40N load across different scanning speeds and sliding velocities, as shown in Figure 4.7, is attributed to optimized deposition parameters that ensure stable material consistency and thermal management. At this load, the balance between laser power, wire feed rate, and scanning speed appears to produce a uniform deposition layer, resulting in consistent microstructural characteristics that stabilize hardness and frictional behavior.

This equilibrium minimizes fluctuations in the coefficient of friction, even at varying speeds, indicating an optimized parameter range that supports predictable, reliable frictional performance throughout the tested conditions. Overall, the graph indicates that the coefficient of friction tends to

increase with higher scanning speeds for all sliding velocities, with a more pronounced impact at the lower sliding velocity of 0.5 m/sec and a less significant effect at the higher sliding velocity of 1 m/sec.

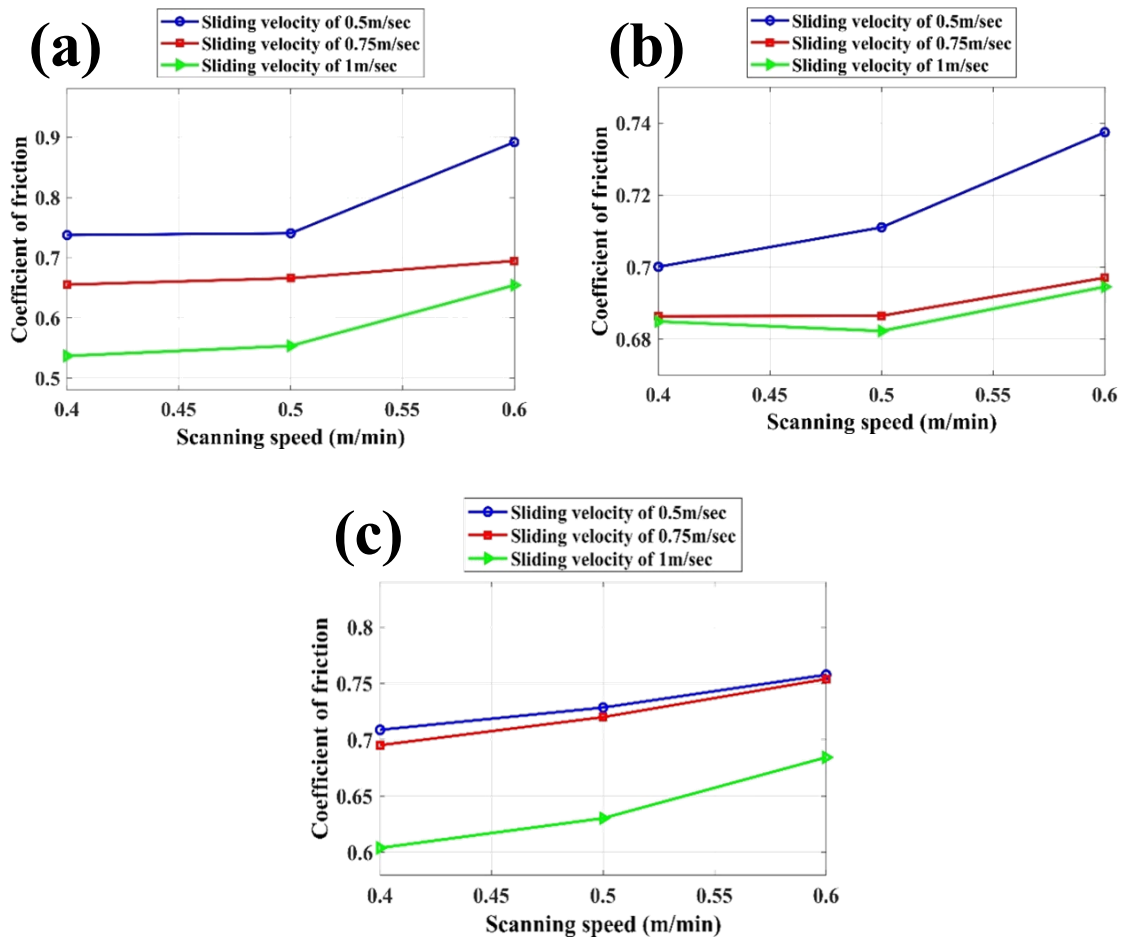


Figure 4.11 Variation of coefficient of friction at diverse normal loads of (a) 20 N, (b) 40 N, and (c) 60 N with different scanning speeds and sliding velocity

4.3.5 Analysis on Deposition Rate and Hardness of the Printed Solid Structures

Figure 4.12 illustrates the effect on deposition rate on the solid structures at variable speeds by exploring the relationship between power (in watts) and deposition rate (in mm^3/min) for three different scanning speeds: 0.4 m/min, 0.5 m/min, and 0.6 m/min. At a scanning speed of 0.4 m/min, the deposition rate increases significantly from around $500 \text{ mm}^3/\text{min}$ at 1000 W to about $900 \text{ mm}^3/\text{min}$ at 1400 W.

For the scanning speed of 0.5 m/min, the deposition rate steadily rises from approximately $500 \text{ mm}^3/\text{min}$ at 1000 W to around $800 \text{ mm}^3/\text{min}$ at 1400 W. At 0.6 m/min, the deposition rate increases more gradually, starting at roughly $500 \text{ mm}^3/\text{min}$ at 1000 W and reaching about $700 \text{ mm}^3/\text{min}$ at 1400 W. Overall, the deposition rate increases with higher power for all scanning speeds, with the increase at the minimum scanning speed of 0.4 m/min and the least significant at the highest scanning speed of 0.6 m/min.

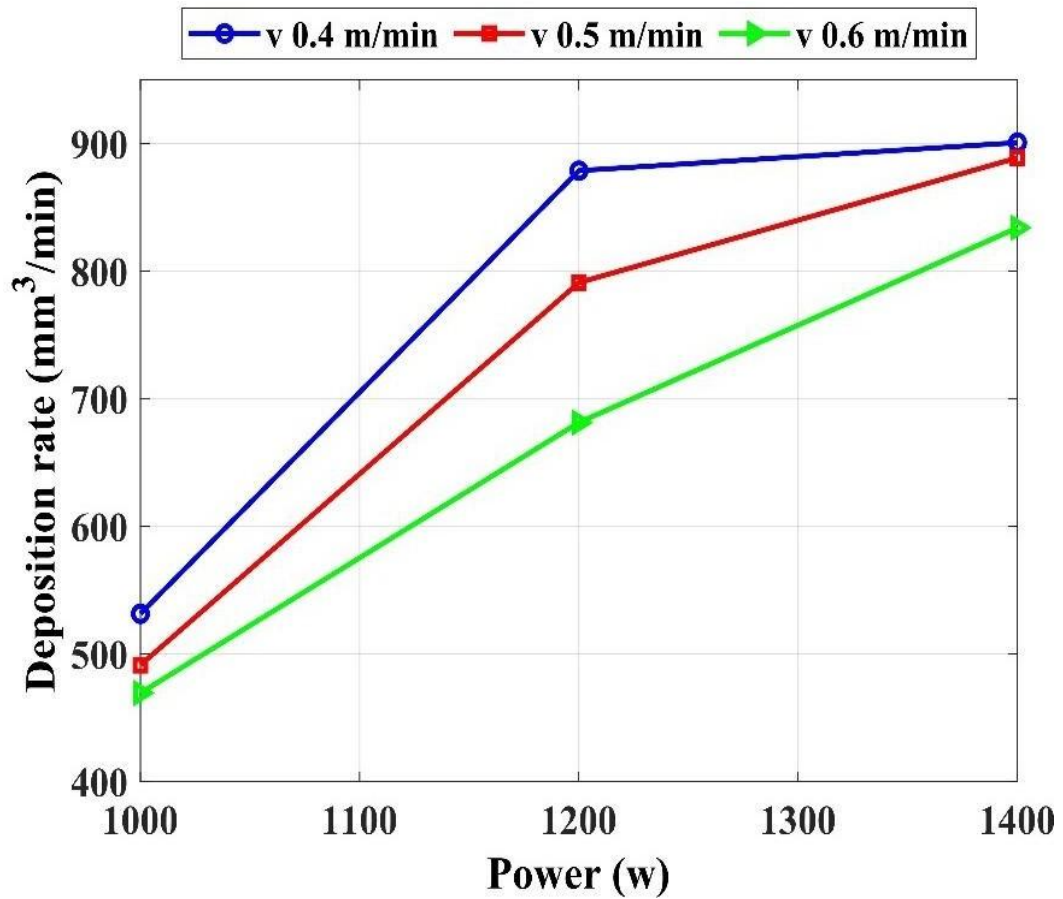


Figure 4.12 Impact of deposition rate on the solid structures at variable speeds

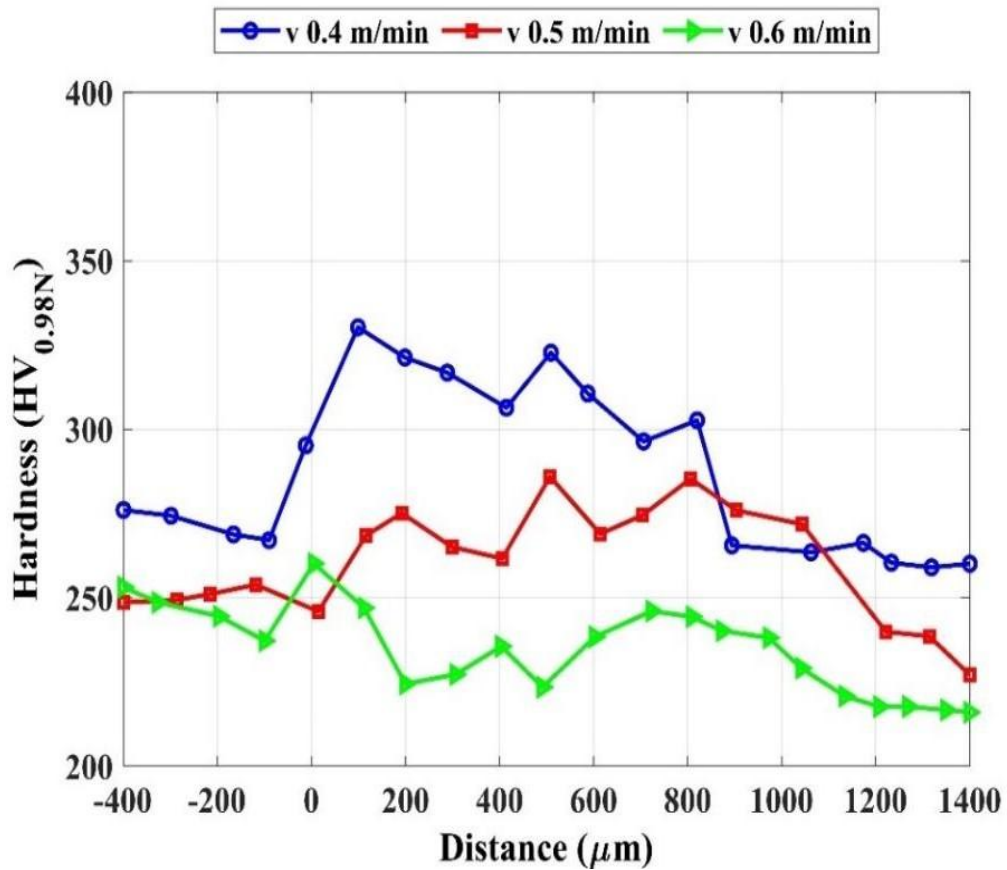


Figure 4.13 Effect of hardness on the solid structures at variable speeds

Figure 4.13 depicts the effect of hardness on the solid structures with the relationship between hardness (measured in HV 0.98N) and distance for three variable scanning speeds, such as 0.4 m/min, 0.5 m/min, and 0.6 m/min. At 0.4 m/min, hardness exhibits significant fluctuations, beginning around 270 HV, peaking near 350 HV at approximately 200 μm , and then showing periodic variations with a general downward trend to about 250 HV by 1400 μm . The 0.5 m/min speed shows moderate fluctuations, starting at 250 HV, reaching about 310 HV near 200 μm , and gradually decreasing with some variability to around 230 HV by 1400 μm . Conversely, at 0.6 m/min, hardness remains relatively stable with minor fluctuations, starting near 240 HV, increasing slightly to about 260 HV around 200 μm , and maintaining a gentle decline to approximately 220 HV by 1400 μm . Overall, higher scanning speeds result in lower and more stable hardness values, while lower speeds lead to higher and more variable hardness, with intermediate speeds showing a moderate trend between these extremes.

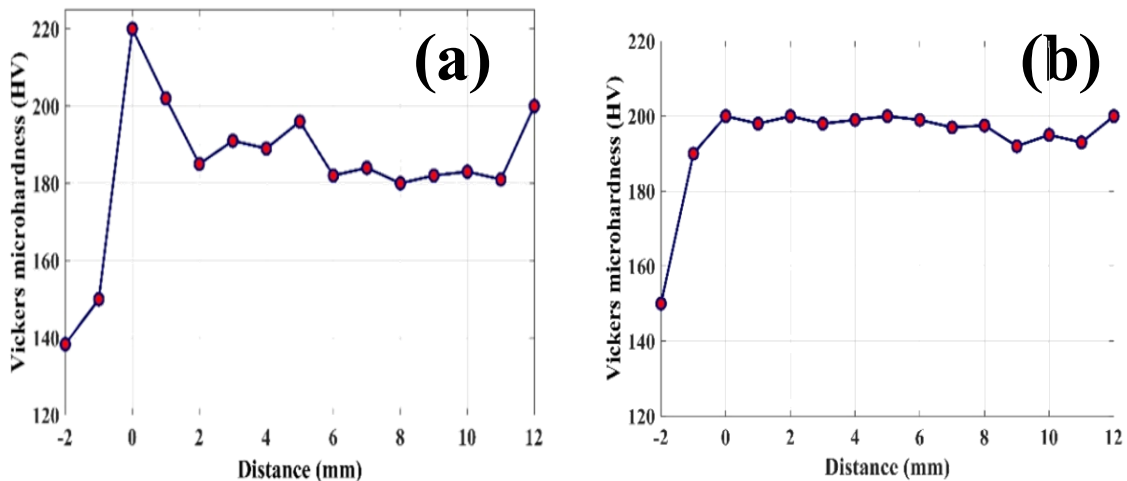


Figure 4.14 Analysis of Vickers Microhardness test (a) Single layer deposition (b) Multilayer deposition

Figure 4.14 illustrates the outcomes of the Vickers Microhardness test. Figure 4.14 (a) and (b) respectively depicts the relationship between distance (mm) and Vickers microhardness (HV) for single layer and multi-layer deposits. The single layer deposit shows an initial Vickers microhardness of approximately 220 HV, decreasing steadily to around 140 HV as the distance increases up to 12 mm. At 50 mm, there is a data point showing 120 HV. The variation in Vickers microhardness within multi-layer deposits is generally lower than that observed in single-layer deposits, attributed to a more uniform thermal distribution and diminished residual stresses in multi-layer configurations.

During single-layer deposition, the material undergoes swift cooling and steep thermal gradients, potentially resulting in microstructural inconsistencies, including irregular grain sizes or phase variations, which can lead to notable hardness variations within the layer. In contrast, the multi-layer deposit begins with a Vickers microhardness of about 130 HV, fluctuating within the range of 100

HV to 120 HV as the distance extends to 10 mm. It allows heat to accumulate from subsequent layers, enabling improved thermal stability and homogeneous cooling, which aids in the reduction of residual stresses and refinement of the microstructure. This leads to a more uniform hardness profile across the deposit, with less fluctuations than single-layer deposits.

4.3.6 Scanning Electron Microscope Analysis

Based on the provided SEM image of the single-layer deposition analysis of 3D printed SS316 material, the following observations are made from Figure 4.15.

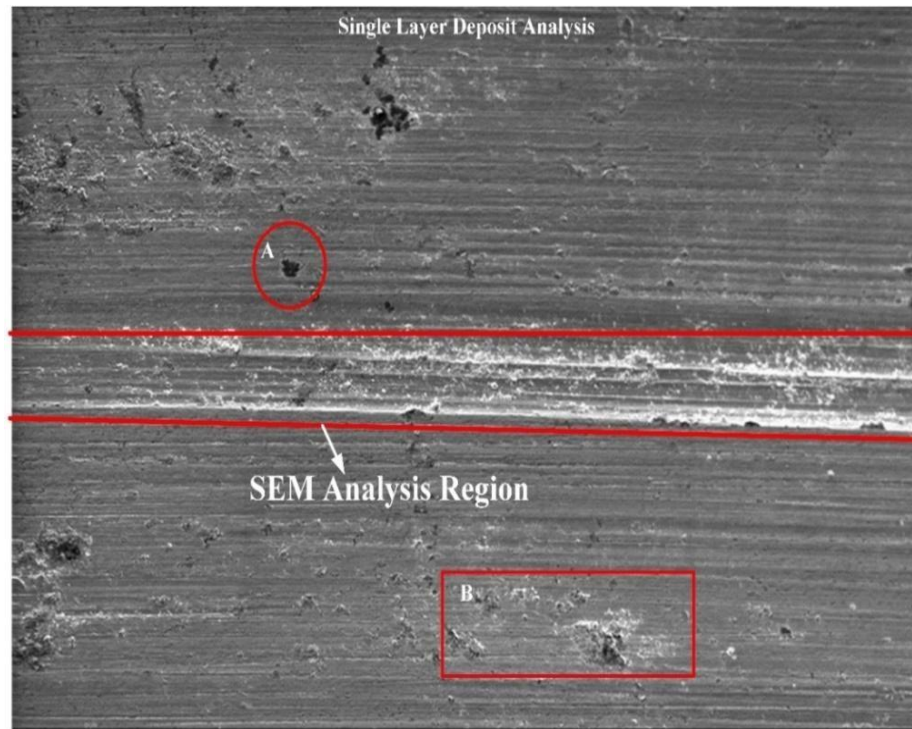


Figure 4.15 Single layer deposited 3D Material of SS316

- **Region A (circled area):** This area appears to have a defect or inclusion, which could be due to contamination or an anomaly during the printing process. Such defects affect the performance characteristics and integrity of the material.
- **Region B (boxed area):** This area shows surface irregularities and possibly un-melted powder particles. These surface defects might result from improper layer adhesion or insufficient melting during the 3D printing process.
- **General Surface Analysis:** The SEM analysis region indicates some degree of roughness and layering, which is typical in additively manufactured materials. The surface quality and uniformity are crucial for the final mechanical properties and performance of the printed component.

Overall, the findings suggest that while the single-layer deposition of SS316 generally follows expected patterns, there are noticeable defects and irregularities that could impact the performance

and reliability of the printed part. Further optimization of the printing parameters may be required to enhance the quality and consistency of the deposition.

4.3.7 X-Ray Diffraction Assessment

The X-ray diffraction (XRD) assessment provided depicts a spectrum for a single layer deposited material, specifically SS316, fabricated through a 3D printing process. The material analysed is Stainless Steel 316 (SS316), which is deposited using a 3D printing method, focusing on a single layer deposition. The XRD pattern reveals distinct peaks corresponding to different phases within the SS316 alloy.

Peaks marked with ‘#’ indicate the presence of iron (Fe) phases, while a peak marked with ‘@’ at around 40° confirms the presence of nickel (Ni). Additionally, peaks denoted by ‘S’ represent the remaining phases, including elements like chromium (Cr) and molybdenum (Mo), which are integral to SS316 properties. The sharpness and intensity of these peaks suggest a high degree of crystallinity and a well-preserved crystalline structure post-3D printing, indicating that the process maintains the material's integrity and phase composition effectively. Figure 4.16 shows the XRD Analysis of the single deposited layer of SS316. Outcomes of XRD Analysis are shown in Table 4.3.

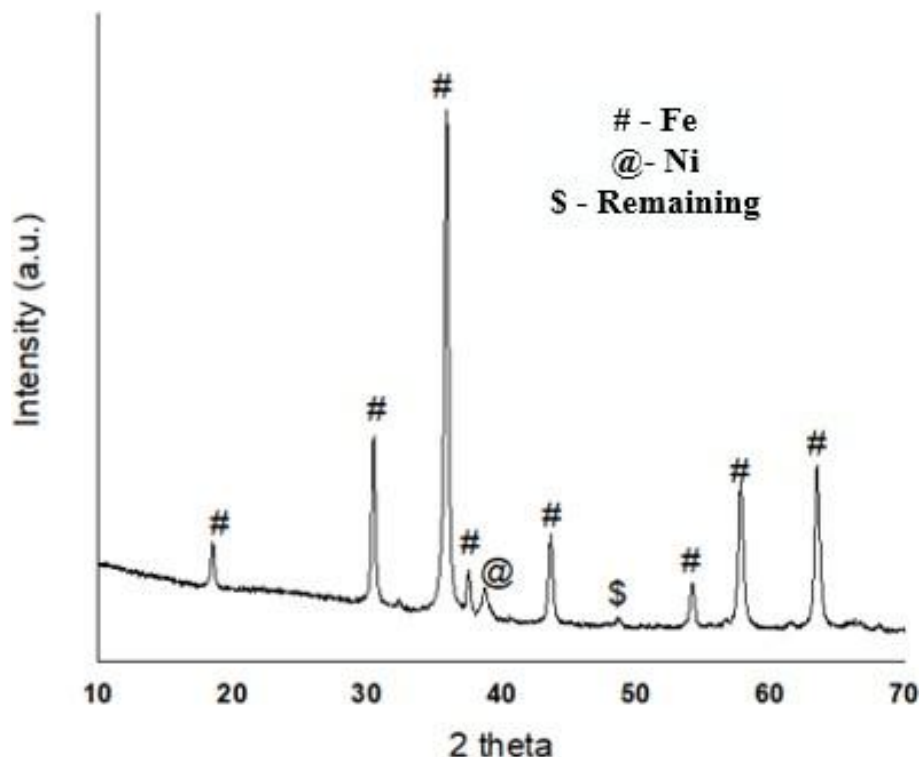


Figure 4.16 XRD Analysis of the single deposited layer of SS316

The XRD pattern indicates high crystallinity in the single-layer deposited SS316, maintaining its structural integrity and crystalline phases during the 3D printing process. Dominant peaks confirm the presence of Fe as the primary element, Ni at around 40° , and other alloying elements like Cr and

Mo, which contribute to the alloy's overall properties. The analysis confirms that the 3D printing process preserves the essential phases and crystallinity of SS316, ensuring its mechanical and chemical properties remain intact.

Table 4.3 Outcomes of XRD Analysis

2theta Range	Symbol	Element	Interpretation
20-30°	#	Fe	Sharp and intense peaks indicate the presence of iron phases, suggesting that the SS316 retains a strong crystalline structure of iron after the 3D printing process.
40°	@	Ni	The peak indicates the presence of nickel, a significant alloying element in SS316, contributing to its corrosion resistance and mechanical properties. The intensity suggests a well-integrated Ni phase within the iron matrix.
50-70°	S	Remaining Phases	Peaks in this region represent the remaining phases of the SS316 alloy, including minor elements such as Cr, Mo, and other alloying elements. These contribute to the overall performance of SS316, providing additional strength and resistance to corrosion and oxidation.

4.3.8 Discussions

The research is organized and systematically examines the LMWD in the manufacturing process for 3D/4D metal construction. The research addressed many of the pressing challenges surrounding the efficiency of material use, control of deposition, and mechanical performance through vibrant tuning of deposition conditions and process parameters. One of the key factors is that for high efficiency of use of metal, stable fluence values should be maintained. Research showed that when deposition conditions are controlled and stable, high efficiency of material usage is obtained, but when fluence levels reach and exceed a level of 59 J/mm², there is a marked decline in the efficiency of the process because of added fume and dross fume that contribute to lost material from surface discrepancies, with the fluence of the problem.

Additionally, in a multi-layer deposition situation, the efficiencies observed are from a more refined fluence range of 30.25–32.46 J/mm². This indicates fine control of the laser energy input is required to achieve layer uniformity and avoid thermal stress between layers. There is also some influence of

scanning speed on mechanical performance, as the coefficient of friction elevates from 0.7 to 0.74 as the scanning speed increases. The coefficient of friction massively increases, especially at lower sliding velocities of 0.5 m/s, indicating increased surface roughness or increased surface oxidation. Higher power levels significantly boost deposition rates, with the rate increasing from 500 mm³/min at 1000 W to 900 mm³/min at 1400 W.

In addition, deposition rate performance is closely related to the power input; for example, we have improved deposition rate performance from a rate of 500 mm³/min at 1000 W to a rate of 900 mm³/min at 1400 W; we have improved manufacturing throughput and not degraded quality or effectiveness of the printing process. Microhardness testing shows variability across the different scanning speeds, but when taken together, they show generally stable and acceptable hardness values, thus supporting that the parts fabricated are mechanically robust. Finally, XRD shows processed material is highly crystalline and phase stable, thus there is an assurance of structural and functional properties of the respective printed materials throughout the deposition process.

This chapter highlights the significant potential of LMWD as an advanced AM technique for creating complex solid structures with high precision and material efficiency. By focusing on the single deposition technique within LMWD, we evaluated material usage and calculated DEC, considering critical factors such as wire feed rate, laser power, and deposition speed. Detailed analysis revealed that the coefficient of friction increases with higher scanning speeds, with a more pronounced impact at lower sliding velocities. Additionally, notable fluctuations in deposition rate and hardness are observed, particularly at the lowest scanning speed.

The COF increased slightly with scanning speed, rising from 0.7 at 0.4 m/min to 0.74 at 0.6 m/min, and showed a smaller increase from 0.68 to 0.685 at 1 m/sec. Higher power levels significantly boosted deposition rates, particularly at 0.4 m/min, where it rose from 500 mm³/min at 1000 W to 900 mm³/min at 1400 W. Hardness measurements varied with scanning speed, showing higher and more variable values at lower speeds. XRD analysis confirmed distinct peaks for Fe, Ni, Cr, and Mo phases in SS316, indicating high crystallinity and maintained material integrity post-3D printing. These findings emphasize the necessity of optimizing deposition parameters to enhance DEC, leading to more efficient production processes with minimal material wastage.

CHAPTER-5

CHAPTER 5: TRANSFORMATIVE IMPACT OF 3D/4D PRINTING ON SUPPLY CHAIN DYNAMICS THROUGH HIGH-VALUE DESIGN CONCEPTS

5.1 INTRODUCTION

The advent of 3D and 4D printing technologies has greatly destabilized the traditional model of manufacturing and supply chain models, providing levels of customization, efficiency, and flexibility that is not possible previously [134]. 3D printing AM refers to the construction of 3 spatial dimensions by adding material in layers until a required form is built [135]. 4D printing is similar to 3D printing, but adds time as a variable, making changes to the object's material or structure when a stimulus occurs. These changes bring production closer to the point of use in space and time, resulting in dramatically reduced lead time, storage, and decentralized production systems [136,137].

Supply chain dynamics involve the ever-changing, interdependent forces of goods, information, and finance that determine the flow of products through global networks. Supply chains are no longer linear models as they once were; rather, they are adaptive systems, which must evolve to the volatility created by both internal and external factors, such as changes in demand, supply shortages or delays, geopolitical risk, as well as constant technological advancements, and still retain an efficient and resilient supply chain. Some drivers for change include demand forecasting, supplier relationship construction, inventory efficiency, and agile logistics, which are facilitated by supporting technologies including artificial intelligence, internet-of-things, or blockchain. The overview of supply chain dynamics is depicted in Figure 5.1.

In the context of the supply chain management function, flexibility resulting from 3D/4D printing means reliance is decreased relative to mass production and long-distance transport, allowing companies to produce just-in-time, reducing waste and decreasing or eliminating inventory while also improving responsiveness to market shifts. Further, these technologies allow for rapid prototyping and faster innovation cycles, which allow companies to take advantage of high-value design concepts like light-weighting, biomimicry, and multi-material assemblies [138]. Ultimately, this means they can deliver a product that is more personalized and sustainable, but with enhanced functionality and performance.

High-value design today addresses not just aesthetics and usability, but also optimization, adaptability, and lifecycle effectiveness. 3D/4D printing supports all of these aims by facilitating the

production of parts that are lighter, stronger, and smarter. For example, aerospace and medical industries embrace 3D/4D printing for parts that are structurally efficient and take into account specific functions. Therefore, 3D/4D printing's disruptive potential to supply chain dynamics is realized through its capability to align design innovation with manufacturing knowledge to create more resilient, agile, and value-centric supply networks.



Figure 5.1 Overview of supply chain management

5.1.1 Methods of 3D/4D Printing

All 3D/4D printing methods follow the same five-step process chain: 3D/4D modeling, data translation and transfer, testing and preparation, construction, and post-processing [139] as illustrated in Figure 5.2. It begins with the 3D CAD model, which is converted into a .STL file format, which is a standard file type for 3D printing that contains the geometry of the model. It is then unlayered using slicing software, which takes the model and slices it into thin horizontal layers and addresses the tool paths and directions for printing. The AM operation begins, and material is laid down layer by layer in the X, Y, and Z directions for the build process to create the product. The object exhibits

behavior to stimuli over time and may change shape and functionality-leading to distinctions between shapes and functionality, consistent with 4D printing. The result is a functional 3D product and, commonly, exhibits dynamic behavior based on the smart materials that may have been used. Uniquely, the flowchart represents the complete digital-to-physical conversion in advanced manufacturing systems.

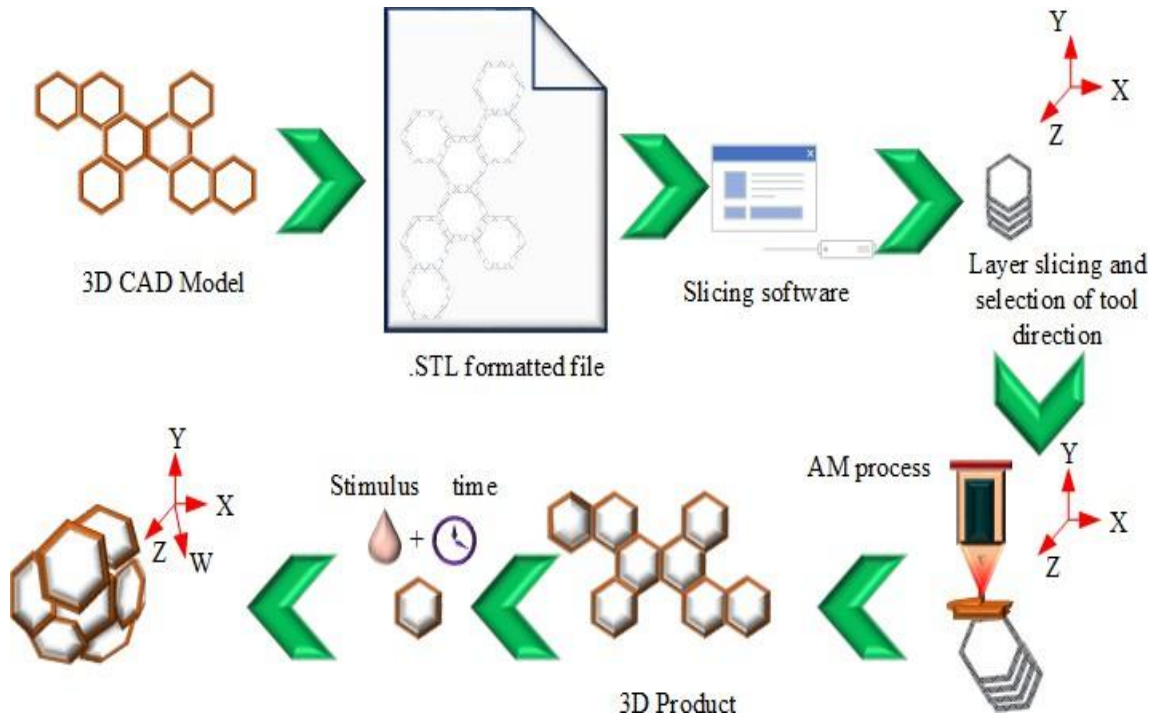


Figure 5.2 3D/4D printed additive manufacturing process strategy.

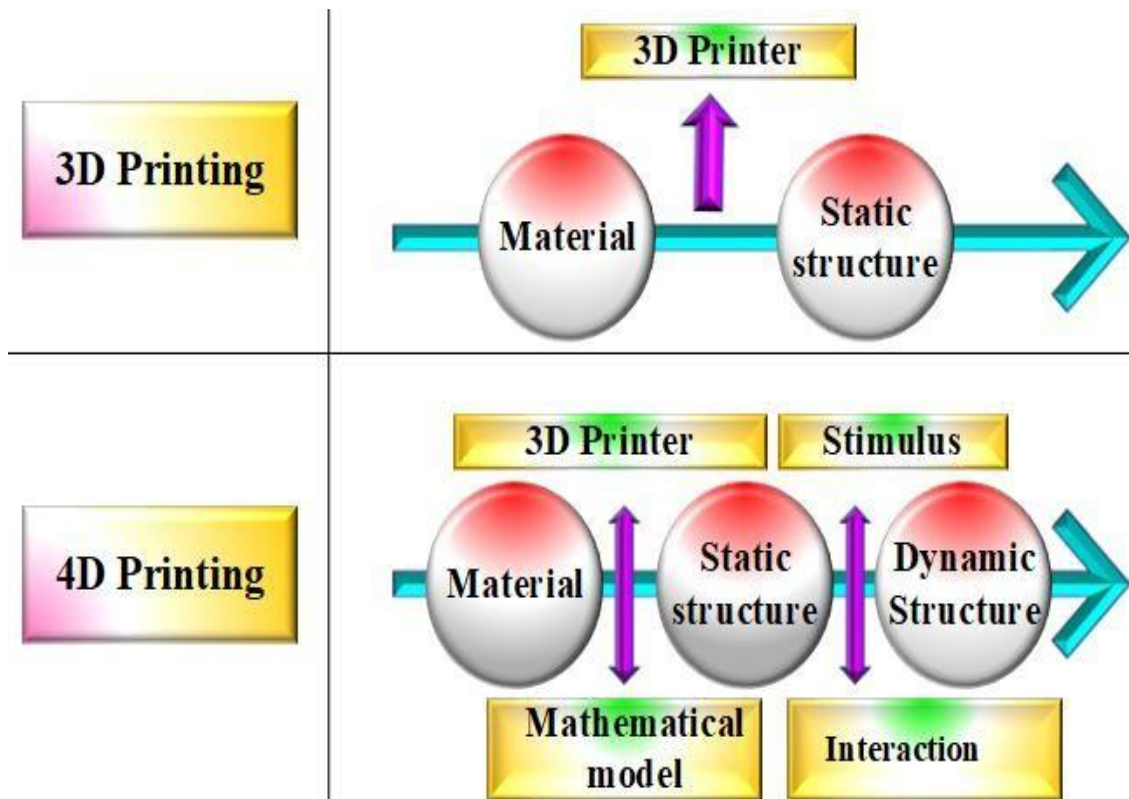


Figure 5.3 Differences between 3D and 4D printing

Figure 5.3 illustrates the differences between 3D and 4D printing. The fundamentals of 4D printing are divided into five categories: 3D printing systems, stimuli, smart materials, interaction methods, and mathematical modeling. These categories are essential for ensuring the object is created with the appropriate tools and materials based on its intended use. Although 4D printing can sometimes be a completely different endeavour due to its responsive nature, the techniques for producing the object are quite similar to those of traditional 3D printing.

5.1.2 Contribution of the Proposed Framework

The proposed research investigates the transformative potential of 3D/4D printing technologies in disrupting traditional supply chains through localized production and customized product offerings, with a strong emphasis on High Value Design Principle (HVDP) concepts. The proposed research work process is illustrated in Figure 5.4. By enabling on-demand manufacturing of complex 3D/4D components, these advanced integrated design technologies reduce reliance on centralized mass production and global logistics networks, thereby enhancing supply chain efficiency and responsiveness.

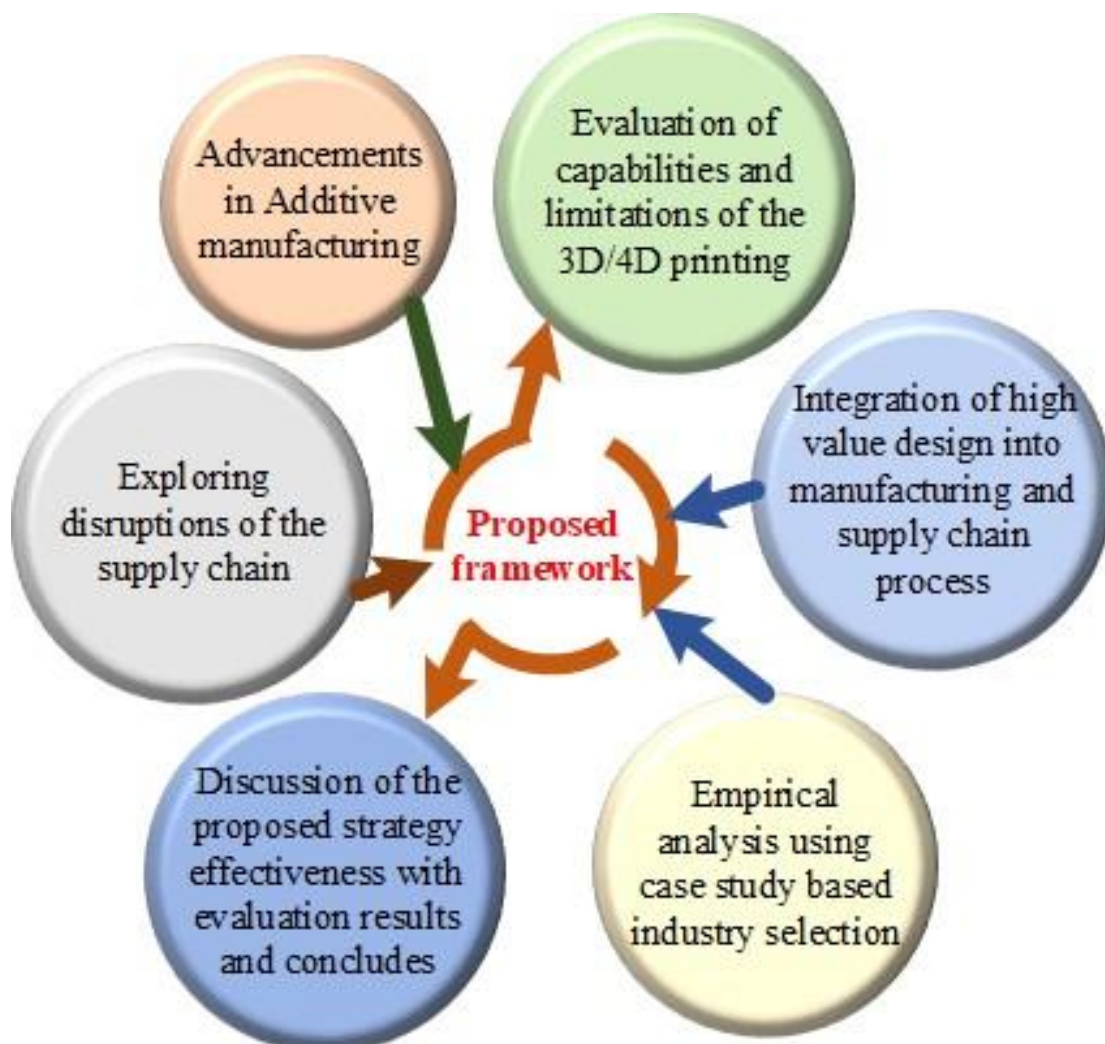


Figure 5.4 Proposed research analysis process workflow

5.2 PROPOSED SUPPLY CHAIN DYNAMICS THROUGH HIGH-VALUE DESIGN FRAMEWORK

The proposed research methodology presents a new model of performance evaluation to examine ongoing interruptions in the supply chain and identify breakthroughs in AM, as discussed in previous sections. This portion of the research focuses on exploring the effects of merging HVDP with recent technologies behind 3D and 4D manufacturers to potentially support supply chain controllability. The performance discussion, in terms of efficiency, provides insight into the potential, combined with HVDP, with the flexibility and adaptability offered via 3D/4D manufacturing, improves the responsiveness to fulfil orders faster and efficiently, lowers lead times and inefficiencies, and links to decision systems throughout the broader supply chain. A set of research hypotheses are developed to track the impact to operationalization of these dynamics, focusing on performance indicators of customization, inventory, and risk mitigation; The set of research hypotheses will provide empirical evidence as a basis and is intended to provide further understanding of the strategic effectiveness for industry to employ advanced manufacturing technologies and developed operational innovation for supply chain performance.

5.2.1 Hypothesis Development

A flexible supply chain allows for the rapid introduction of new and old items to the market in the needed quantities, as well as flexibility in the delivery process. AM manufacturing control with HVDP adoption greatly improves supply chain dynamics management competitiveness. The correlation between supply chain dynamics control, HVDP dimensions, company performance, supply chain efficiency, and supply chain resilience is considered for the developed hypothesis.

By considering all aspects of the 3D/4D adoption and supply chain dynamic control, the following hypothesis H_1 to H_4 are developed, and implications of these hypotheses are also depicted in Figure 5.5.

By considering all aspects of the 3D/4D adoption and supply chain dynamic control, the following hypothesis H_1 to H_4 are developed, and implications of these hypotheses are also depicted in the Figure 5.5.

H₁: 3D/4D Printing adoption is positively related to the Supply chain dynamics of AM.

H₂: HVDP integration is positively impacting with transformative changes in the supply chain dynamics with AM adoption.

H₃: HVDP adoption is possibly impact the supply chain efficiency.

H₄: HVDP adoption is possibly impact the supply chain resilience.

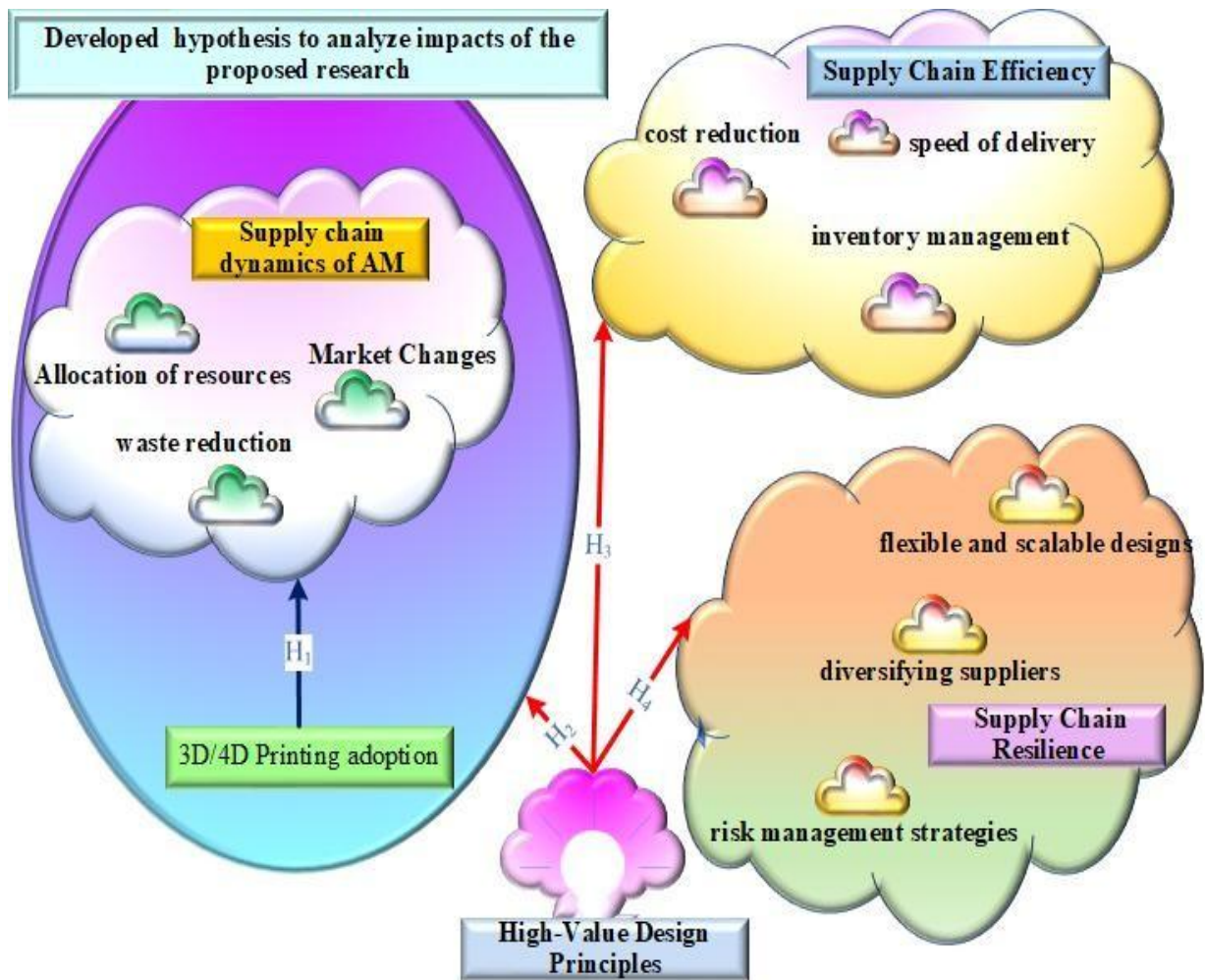


Figure 5.5 Developed research hypothesis for the proposed empirical analysis

5.2.2 Technical Assessment

3D/4D printing technology used widely in industries, including healthcare, aircraft, construction, and fashion. 3D/4D printing has received substantial interest in biomedical engineering because to its ability to solve the limits of existing therapy [140]. AM based production in medical and pharmaceutical technology has grown potential popularity in recent years [28]. Table 5.1 summarizes the technical assessments of the supply chain integrated with 3D/4D printing adoption [141-145].

Researchers and manufacturers have significant issues as a result of the 3D/4D printing industry appetite impact on supply chain management during disruptive conditions. Many important factors prevent 3D/4D printing from being widely used, such as the expensive cost of purchasing printers, inexperience with technology, and the limits of 3D/4D printers. In order to realize its vision, clients use a specific combination of manufacturing and design-related service components that a typical 3D/4D printing provider offers. Managers of supply chains produce any portion at any time in various places and batch sizes without worrying about huge tooling costs with the advances of digital

manufacturing technologies, which helps to overcome the major challenge of supplying the required components at a cheap cost with a high fulfilment rate.

Table 5.1 Assessment of technical feasibility with AM integrated supply chain

Benefits	Challenges	Implementation Strategies
Customization and Responsiveness, reduced Lead Times. Revolutionize manufacturing	Material Limitations, Quality Control,	Start with small-scale trial projects to evaluate the impact of 3D/4D printing on the supply chain practices.
Decentralized Production, Enhanced resilience against disruptions	Initial Investment	Work closely with material suppliers to develop compatible materials and processes.
Combining environmental sustainability with cost effectiveness	Affecting performance and durability	Utilizing advanced tools like IoT and AI for real-time monitoring and analytics to optimize operations of the supply chain.

Furthermore, with the availability of highly customizable parts, customers may take ideas from 3D/4D printing websites to develop own items. When used in low volume markets, 3D/4D is less expensive and produces products with fewer inputs and outputs. It also offers customized high-value production for the manufacture of aerospace and biomedical components. For example, supply chains are getting localized and digitalized while becoming simultaneously less energy and resource-intensive in the whole life cycle of a product. The service control strategy with process and information flow in the management of AM products supply chain dynamics is depicted in Figure 5.6.

Compared to 3D/4D printing, 5D/6D printing possibly produces more intricate structures that are stronger and need less material [146]. The prospect of 3D/4D printing utilization in the upcoming organ industry, including temporal aspects of the bioprinting process [147] and polymer-based fused deposition modelling technologies in the construction business [148] is essential for developing innovation, increasing effectiveness, and resolving present issues in both disciplines.

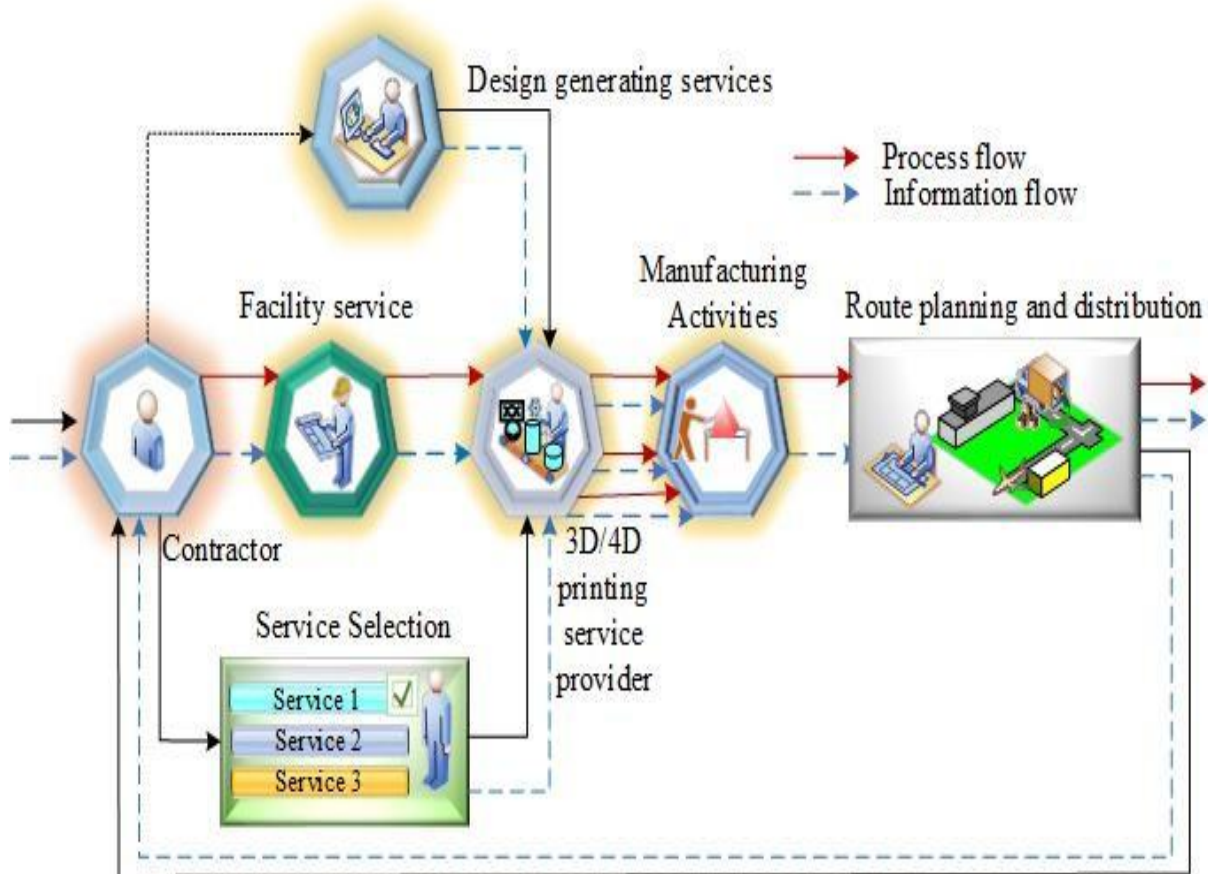


Figure 5.6 Service of 3D/4D printing integrated supply chain dynamics control strategy

5.2.3 Proposed 3D/4D Printing Adoption in Supply Chain Dynamics Control

In the automotive spare parts industry, AM-enabled trucks improve agility and resilience by enabling a shift from make-to-stock to make-to-order models [149]. In the construction industry, proposed HVDP-AM technology help to offset supply chain disruptions, with manufacturers playing a critical role in building resilience [150]. Findings shows that some barriers to AM adoption leave the supply chain open to reliance on capacity of suppliers and production, use of restricted materials, significance purity of the product, availability of raw materials, unpredictable demand of customer, equipment reliability, unanticipated technological failures, dependence on the availability of utilities, industrial surveillance, and data flow. Figure 5.7 depicts the various possible beneficial directions of the supply chain dynamics management.

To solve the aforementioned supply chain challenges, examine the possible position of AM in a Traditional Manufacturing (TM) network of supply chain, where facilities of AM may serve as a resource for TMs as well as a committed supplier of quick and affordable sourcing solutions.

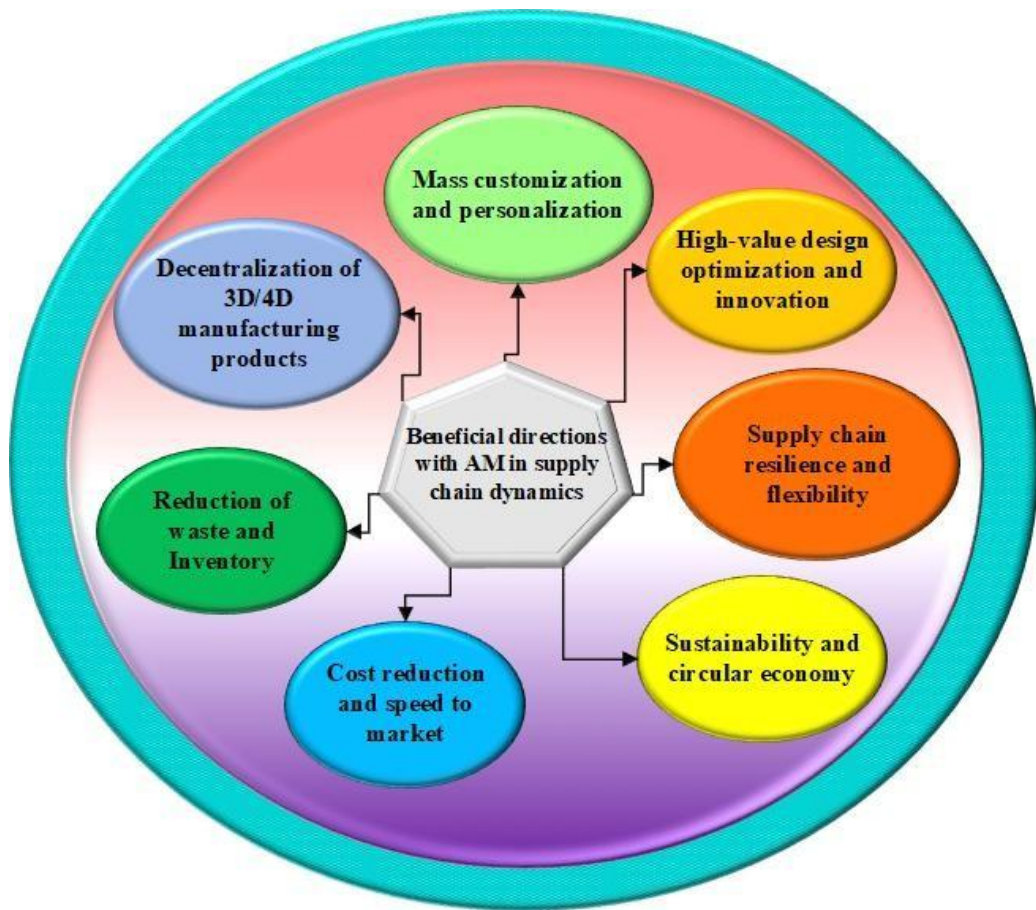


Figure 5.7 Benefits of supply chain dynamics with 3D/4D printed additive manufacturing

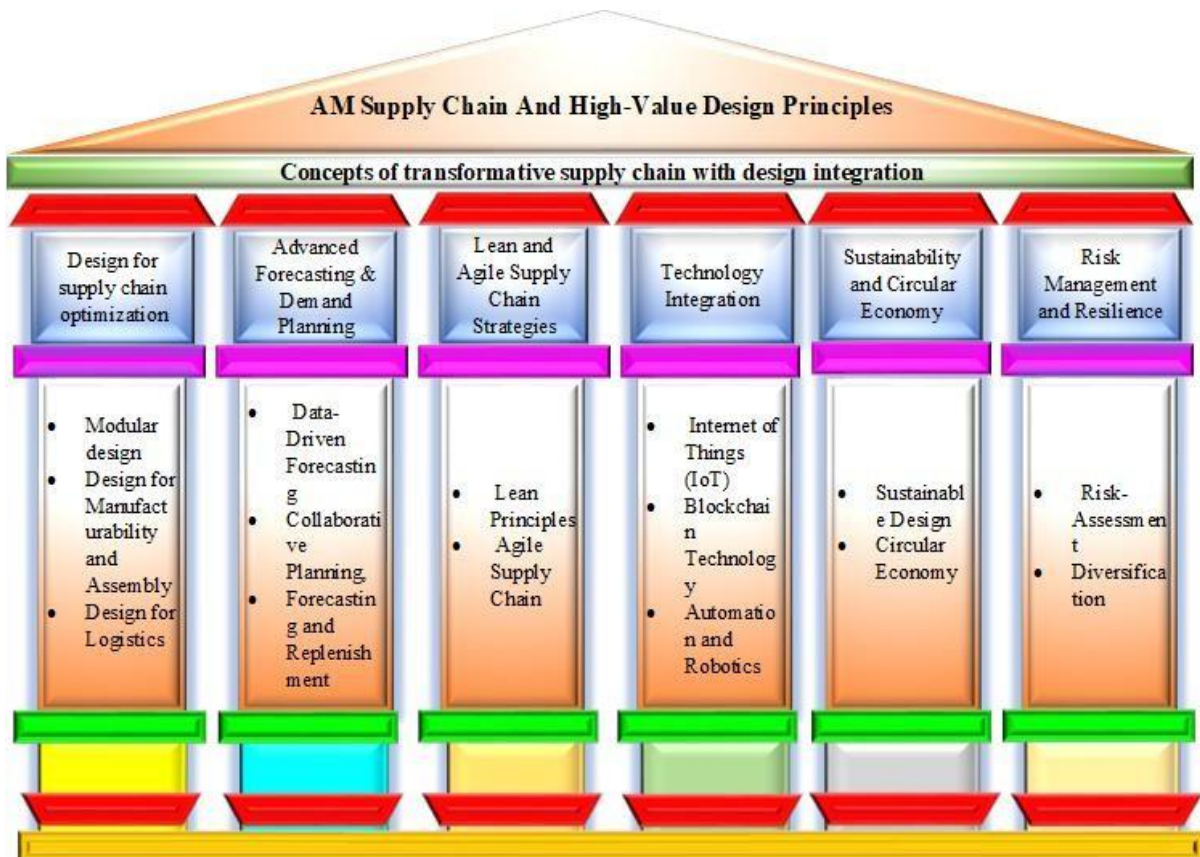


Figure 5.8 Proposed AM supply chain control with high value design principles

5.2.4 High Value Design Principles Integration with Supply Chain Analysis

The integration of the HVDP practices with the Supply Chain Dynamics Control (SCDC) and AM adoption is focused on this research and performance improvements by the proposed integration are analysed for each principle in this section. The proposed important HVDP integration with 3D/4D printing supply chain dynamics management are depicted in Figure 5.8.

5.3 PROPOSED DESIGN FOR SUPPLY CHAIN OPTIMIZATION

Decentralized supply chain configurations generally outperform centralized ones in logistics performance, particularly under variable demand conditions [151]. It has been demonstrated that employing a stochastic optimization model that incorporates AM capabilities for responsive sourcing may significantly reduce the uncertainties in demand within TM networks [152]. Design focuses on delivery route in an AM-enabled supply chain, showcases feasibility of same-day delivery through optimized routing strategies [153]. AM-enabled trucks to enhance resilience in the automotive spare parts supply chain and it ensures feasible supply chain framework [154].

In construction, Design for Manufacture and Assembly (DfMA) is gaining attention, with digital fabrication and AM practices [155]. The integration of DfMA with advanced technologies and practical application of DfMA tools [156] have the potential to transform design and manufacturing processes across multiple sectors. Additionally, possible directions in improving efficiency, sustainability, lower production costs, lead times, and error rates are addressed. The integration of AM with design principles has led to improvements in fabrication, generation, and assessment phases, driving the designs creation for high-performance [157].

Impact of AM on the supply chain, specifically reduces costs related to transportation and warehousing, as well as reducing waste production [158]. It also offers direction to academics, managers, and product designers to further enhance the circular economy movement at the supply chain level in order to manage the complexities. The integration of advanced HVDP for logistics including packaging, transportation, and warehousing improves the supply chain dynamics control and provides beneficial optimization in space utilization, transportation cost reduction, and improved supply chain handling efficiency.

5.3.1 Advanced Forecasting and Demand Planning

Data-driven forecasting, backed by machine learning and sophisticated analytics, dramatically help to improve the supply chain dynamics control by reduced stockouts and overstock circumstances, optimizes the management of inventory, and increases the customer satisfaction. In similar way, the Collaborative Planning, Forecasting, and Replenishment (CPFR) concept with foster collaboration

between suppliers and retailers improved the demand forecasting and inventory replenishment. Additionally, the CPFR enhances supply chain visibility and coordination with better demand-based supply chain dynamics control.

5.3.2 Lean and Agile Supply Chain Strategies

By implementing lean manufacturing and HVDP integrated with AM supply chain control possibly eliminate waste during the manufacturing process, improve process efficiency, reduces production costs and lowers overall supply chain costs. The integration of agile supply chains enables the development of flexibility and control during supply chain dynamics, enabling the rapid adaptation to change in market conditions or demand. It is shown proven enhancements with the ability to respond to market changes and customer needs, improving overall competitiveness.

5.3.3 Integration with Industry 4.0 Technology

With advancement of the supply chain digitalization with integrated operation of AM, supply chain dynamics are monitored and controlled with the use of IoT based Industry 4.0 technologies where it utilizes IoT sensors and devices to monitor and manage supply chain dynamics management operations in real-time. It also offers some of the additional benefits such as real-time visibility into inventory, equipment status, and environmental conditions, enhancing decision-making and operational efficiency. During the process of the cloud interfaced activities, the security of the data communication is crucial and improved secure data transfer with the integration of blockchain technology. This strategy implements blockchain for transparent and secure tracking of goods throughout the supply chain which boosts traceability and reduces fraud.

The total production cost possibly decreases by using a variety of robotic systems for large-scale automated additive building such as articulated, cable-suspended, gantry/crane, and climbing robots. and highlights in which manner these robotic solutions are enabling multiple tasks or processes in additive construction [159]. This deployment of automation and robotics for repetitive tasks in warehousing, manufacturing, and distribution which greatly benefits with enhanced production efficiency, reduces labour costs, and minimizes human error.

5.3.4 Sustainability and Circular Economy

Challenges remain in integrating AM with Circular Economy (CE) strategies, including technology maturity, workforce skills, and economic viability. This adoption of AM in CE contexts requires consideration of supply chain actors, drivers, key AM decisions, and operational practices [160]. Multi-criteria decision-making techniques are aid in addressing challenges in AM sustainability and supply chain dynamics management. To fully realize AM potential for sustainability, stakeholders must overcome critical barriers and align AM activities with CE principles to possibly meet the

control over supply chain dynamics optimization which greatly impacts the performance of the AM supply chain management [161].

Conventionally, sustainable design incorporates sustainability into product design by using eco-friendly materials and processes which reduces environmental impact, meets regulatory requirements that are appeals to environmentally conscious consumers. Furthermore, CE design focuses on products for reuse, recycling, or remanufacturing to close the loop on resource usage. This considerably eliminates waste, decreases resource consumption, and opens new economic prospects through recycling and refurbishment.

5.3.5 Risk Management and Resilience

AM help to create closed-loop supply chains, with manufacturers playing a crucial role in improving resilience. However, AM adoption barriers lead to supply chain vulnerabilities, such as reliance on specialty sources and raw material availability, potentially compromising resilience. Despite these challenges, AM potential to enhance supply chain resilience is significant, particularly in mitigating disruptions caused by global crises like the COVID-19 pandemic [162].

AM also mitigate supply chain risks during disruptions like the SARS-COV2 pandemic and offers benefits like enhanced supply chain resilience and reduces the impact of disruptions [163]. Successful AM adoption often involves interorganizational collaboration, enabling companies to leverage external expertise without significant capital investment [164]. The complexity and dependency-reduction potential of AM in supply chains is influenced by various factors, including economic, industry, geographical, and technological considerations [165]. This diversifies suppliers and sources to reduce dependency on single suppliers or regions and minimizes risks associated with supplier failure or geopolitical issues and ensures continuity of supply in the AM supply chain dynamic conditions.

By integrating these HVDP concepts into the supply chain, organizations possibly achieve greater efficiency, responsiveness, and sustainability, ultimately leading to improved overall performance and competitiveness. The impact of the proposed strategy is evaluated using case study-based analysis in the subsequent section.

5.4 EMPIRICAL RESEARCH EVALUATION

The proposed research of transformative impacts of integrated HVDP in the management of the supply chain dynamics are evaluated with empirical data from industrial case study. Hence, this analysis is leveraged to assess practical implications on supply chain dynamics, cost structures, and consumer behaviour, using a mixed-method approach that combines qualitative insights from

industry experts with quantitative analysis of pre- and post-adoption metrics. Analysing with real-life instances of businesses incorporating HVDP concepts into the supply chain dynamics control of the particular company and evaluate the effects on resilience and efficiency. Additionally, the Key Performance Indicators (KPI) such as lead times, inventory levels, customization capabilities, and environmental impact, demonstrates the performance improvements after integrating HVDP in the 3D/4D printing supply chain dynamics control are discussed in this analysis section.

5.4.1 Case Study Selection

Company X is chosen as a case study to explore sustainable development and issues in open design. Company X is a start-up corporation located in India, creating phones with modular structures that are customized, repaired, and upgraded to be fairer to customers. The expanded availability of AM adopted accessories allows Company X to gain a larger market share by attractive to mainstream customers, resulting in a stronger influence on the supply chain. Company X has been able to overcome the barrier of restricted accessory availability, which is normally created in big volume production lines, by using 3D/4D printing.

5.4.2 Survey Design and Instrumentation

To address the latent character of the constructs under examination, the research employs a quantitative technique with an online survey to collect data for the hypotheses addressed in section 5.2.1. The current study is part of a wider survey-based body of work by the authors to understand the influence of HVDP in AM integrated supply chain dynamics management.

Company X supply chain system dynamics model was constructed using empirical data from survey, news and company sources, Company X website, and one author user experience. Our model mimics the total number of Company X users over time using various input parameters. The model construction analyses the data which is 60 months after Company X began production, when the milestone of 136,000 consumers was met. It mimics Company X sales throughout the first five years of its existence and forecasts future sales. The proposed model is to demonstrate how 3D/4D printing helped Company X expand from a small batch production aimed at a niche market to an established phone brand supplied by numerous mobile network carriers throughout Europe.

The model-based analysis also demonstrates the manner in which Company X might grow into a product of mainstream carried by several large network operators, therefore acquiring a notable place in the business of mobile phone and influencing change with competitive manufacturers through HVDP, AM and sustainability of social principles. Our simulation model examines how incorporating HVDP affects supply chain dynamics, including flexibility in production and accessory

supply for Company X 3D/4D AM product. Using 3D/4D has enabled Company X to provide a wide range of components that would've been impossible to supply due to limited initial manufacturing numbers.

5.4.3 Simulated Model for Supply Chain System Dynamics

The proposed system dynamics model simulates the amount of Company X consumers over time. The presented model properly predicts Company X future owing to two factors. The model parameters and variables are selected based on empirical data. The model which is illustrated in Figure 5.9 allows for evaluating potential possibilities for Company X future customer growth.

Fairness consumers are the first to purchase the Company X known as innovators and early adopters because of the unique socially responsible manufacturing process and influence in future purchasing decisions. There are 5,000 initial customers who are pre-ordered before the launch of sale of Company X product in the proposed model. Company X goal drives a steady rise of 1,920 consumers every month (based on past sales data). As the number of regular consumers rises, these consumers either become regular customers otherwise quit the brand due to it no longer being a good product. Table 5.2 provides the explanations for the variables mentioned in model as illustrated in Figure 5.9.

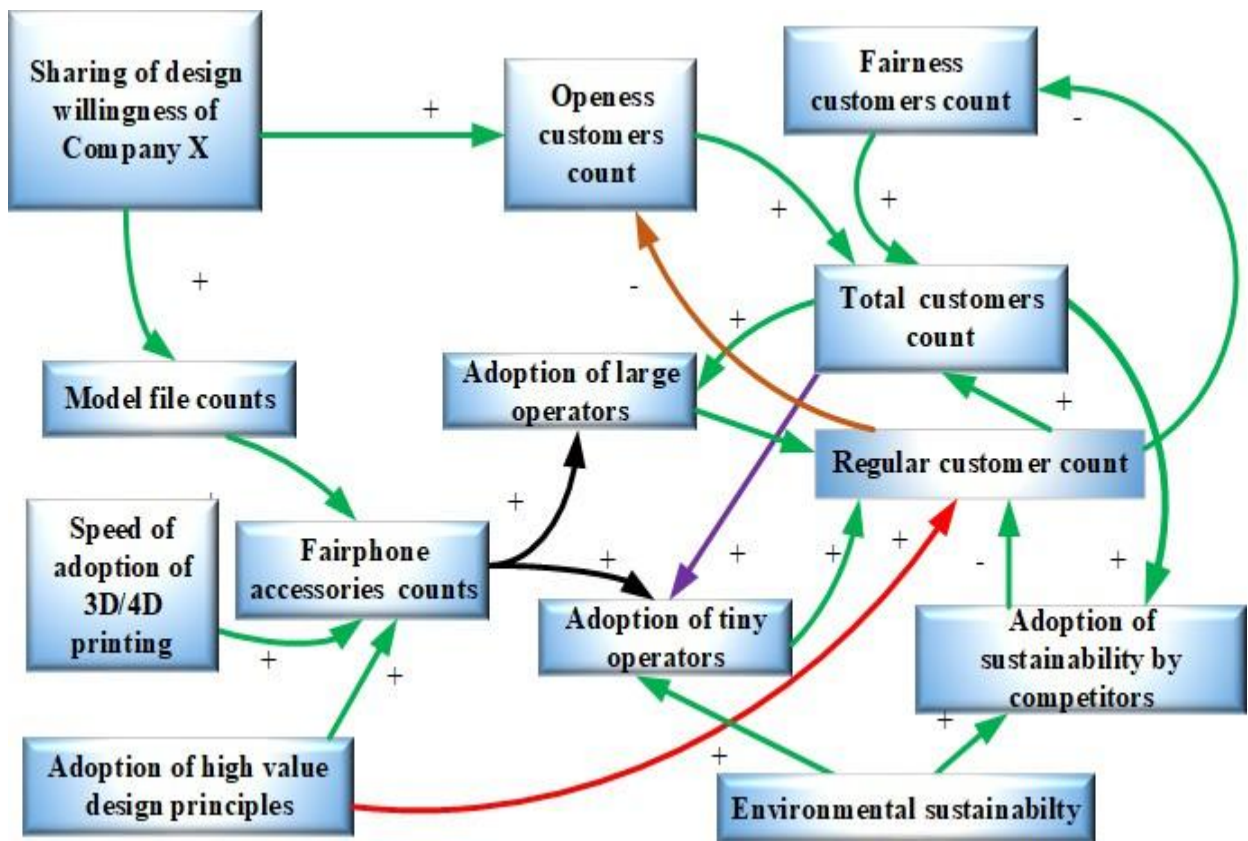


Figure 5.9 Simplified simulation model of the supply chain dynamics with 3D/4D adoption

Table 5.2 Explanations for the variables mentioned in Figure 5.9

Variable	Description
Fairness Customers count	The total number of consumers earned by Company X in the supply chain.
Openness Customers count	Company X openness policy has garnered a significant count of consumers.
Regular Customers count	Total count of people who purchase the Company X.
Total customers count	The sum of all sorts of consumers
Speed of Adoption of 3D/4D Printing	Parameter describing in which way quickly society adopt with 3D/4D printing.
Environmental Sustainability	The parameter that determines the extent to which consumers of mainstream purchasing decision impacted by social sustainability ideas.
Sharing of design willingness of Company X	Decision of Company X to release phone designs, allowing anyone to create and 3D/4D printed components.
Model Files counts	Customers may print the accessories from a variety of various files.
Company X Accessories count	Number of various components available for Company X (a consequence of 3D/4D printing adoption).
Adoption of tiny operators	Company X adoption by small network operators is determined by cumulative sales and the availability of accessories.
Adoption of large operators	Company X adoption by big network carriers is determined by cumulative sales and the availability of accessories.
Adoption of sustainability by competitors	Competitive level of implementation of sustainable supply chain methods

Openness customers purchase phone because these customers admire Company X open concept, notably the design files availability that allow them to create its own components. In this regard, customers akin to buyers drawn to open-source solutions in the software business. In the innovation diffusion model, consumers are innovators and early adopters, and began the process of purchasing Company X, 13 months after the device debut when it made the files available. Company X eagerness to design sharing, paired with increased customer openness, leads to the community designing accessory files.

The ensuing development in community-designed accessories enables for the sale of a wide range of supplementary items. These are accessible as digital models that may be printed using the customer own printer or through 3D/4D hubs, a global network of 3D/4D service providers. As the quantity of 3D/4D printers in use expanded, so did the availability of accessories. Company X declared that no longer model files shared for 3D/4D printing 55 Months after manufacturing began, because of the operational concerns with the 3D/4D Hub network.

Customers of regular are known as purchased the Company X from mobile network providers. When renewing its membership, customers chose the device over a variety of other phone brands for reasons unrelated to sustainability. Customers typically buy phones in conjunction with a subscription renewal. So that the network providers play a crucial role in the mobile phone industry. Due to the fact that operators of network have access to a vast client base, regular customers play a critical role in Company X success as a popular mobile phone brand.

5.4.4 Key Performance Indicators Assessment

The assessment with the integrated high-value principle of design in the 3D/4D AM adopted supply chain dynamics is evaluated with the key performance indicators like cost reduction, lead time, inventory levels, environmental impact in the subsequent sections.

The objective is to understand the effects of HVDP with 3D/4D adoption on supply chain dynamics to satisfy the supply chain customers. The analysis is conducted to understand the factors that influence Company X supply chain by adjusting two scenario-dependent variables. Two key elements are included in the proposed impact study for the adoption of 3D/4D printing in supply chain dynamics like the speed at which adoption occurs and the HVDP concept that promotes sustainable environmental beneficial with transformative effect and Company X success.

5.5 RESEARCH SURVEY FINDINGS

In order to analyze the transformational effects of the suggested integrated strategy of 3D/4D printing and high value principles in the supply chain dynamics, the results of the simulated model and the experimentally observed data have been provided in this subsection.

5.5.1 Comparison of Supply Chain Dynamics Model

System dynamics models consist of variables and expressions. The empirical base ensures that the parameters remain mainly constant. These constants were found via information from firms, websites, and industry news. To replicate Company X original 60-month sales, our investigation identified openness and fairness customers. Figure 5.10 compares our simulation model conclusions to observable data from an empirical investigation of Company X total sales over a sixty-month period.

The demonstrated values roughly correspond to the observed data points. The simulated Company X sales shown by the blue line closely reflect the observed sales represented by the orange squares, demonstrating a continuous climb with intermittent plateaus until cumulative Company X sales reach 135000 units of empirical data and 140,000 units of simulated data. The matching of the simulated data with the observed points indicates that the model is useful for forecasting Company X sales patterns.

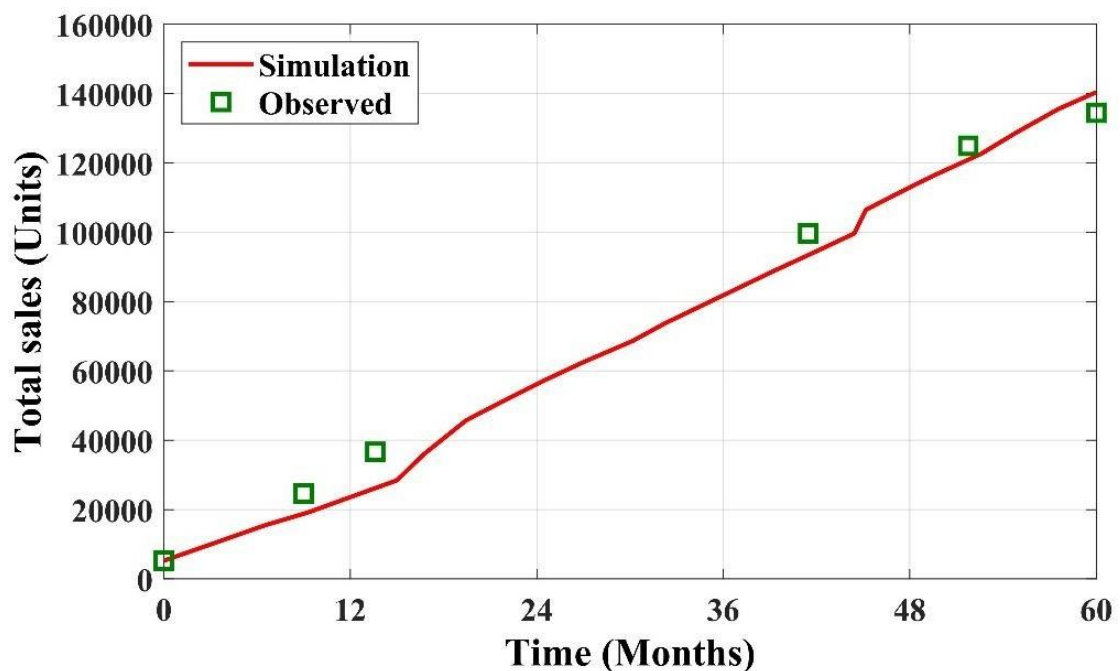


Figure 5.10 Comparison with simulated and empirical research data

However, there may be some slight variances due to elements that the simulation did not capture, such as Company X promotion and good or bad user experiences published on social networks, forums and media.

5.5.2 Scenario with Impact Assessment Of 3D/4D Adoption in Supply Chain Dynamics

The 3D/4D Printing speed of adoption is a metric that measures in what way widely 3D/4D printing is embraced in society and how it affects supply chain dynamics. Rapid adoption of 3D/4D printing

may lead to faster accessory existence, which is essential for small network operators to implement Company X. In addition to the basic case study that has been supported by survey evidence, there are two hypothetical scenarios: one with a faster adoption rate (3D/4D faster) and one with a slower adoption rate. These varied rates of 3D/4D printing adoption have a direct influence on Company X accessory availability, as shown in Figure 5.11.

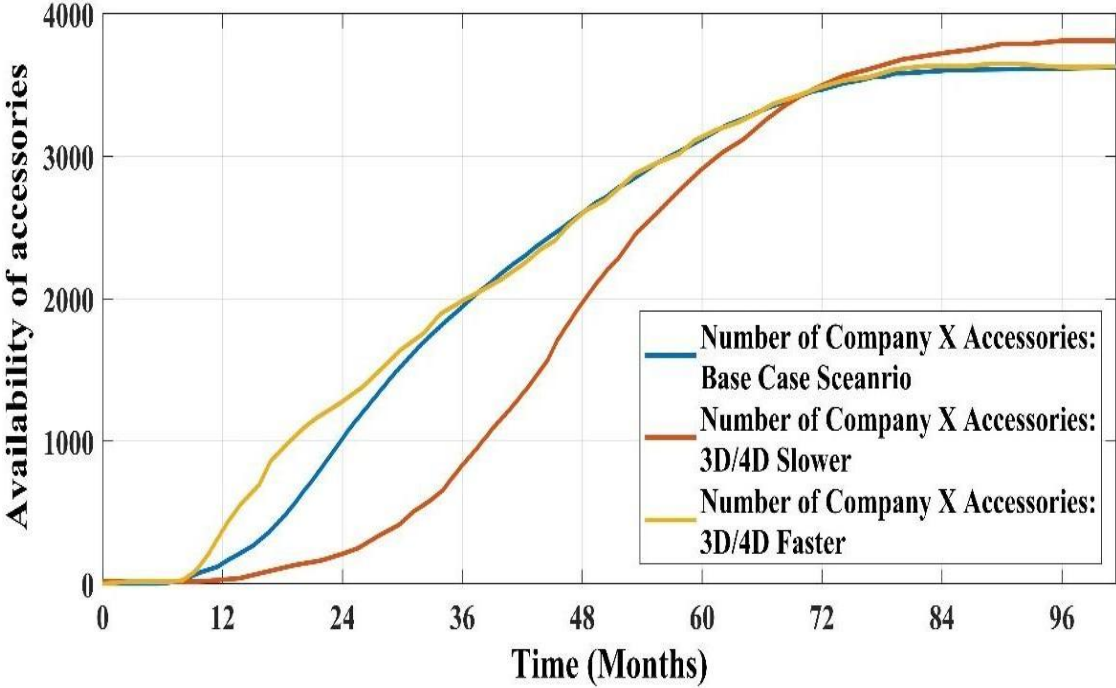


Figure 5.11 Influence of 3D/4D printing adoption on Company X accessory availability

When compared to the base case scenario, faster 3D/4D printing raised the availability of Company X accessories by 1200 counts in the first 24 months, whereas slower 3D/4D printing achieved the same range after 46 months, indicating slower impacts with operators of tiny networks, as illustrated in Figure 5.11.

5.5.3 Scenario with Impact of Integrated High-Value Design Principle Adoption Analysis

Cost reduction is one of the most important performance measures, and its inclusion in the impact analysis is beneficial. The key improvements in AM adopted supply chain dynamics with traditional AM adoption and HVDP integration are depicted in Figure 5.12, which shows a linear increase in cost as the number of product customizations increases. When the proposed high value concept is implemented, cost values remain consistent for an expanded number of items with a customizable base.

The examination of impacts by the adoption of the high value principle on inventory levels in Figure 5.13, where the high value principle adoption is compared with standard AM implemented supply

chain for 12 months. The integrated HVDP concepts appear to significantly reduce necessary inventory levels from 58 to 25 over a 12-month period while maintaining the same periodic swings as traditional adoption. This decrease may result in cost savings, less waste, and more responsive supply chain operations.

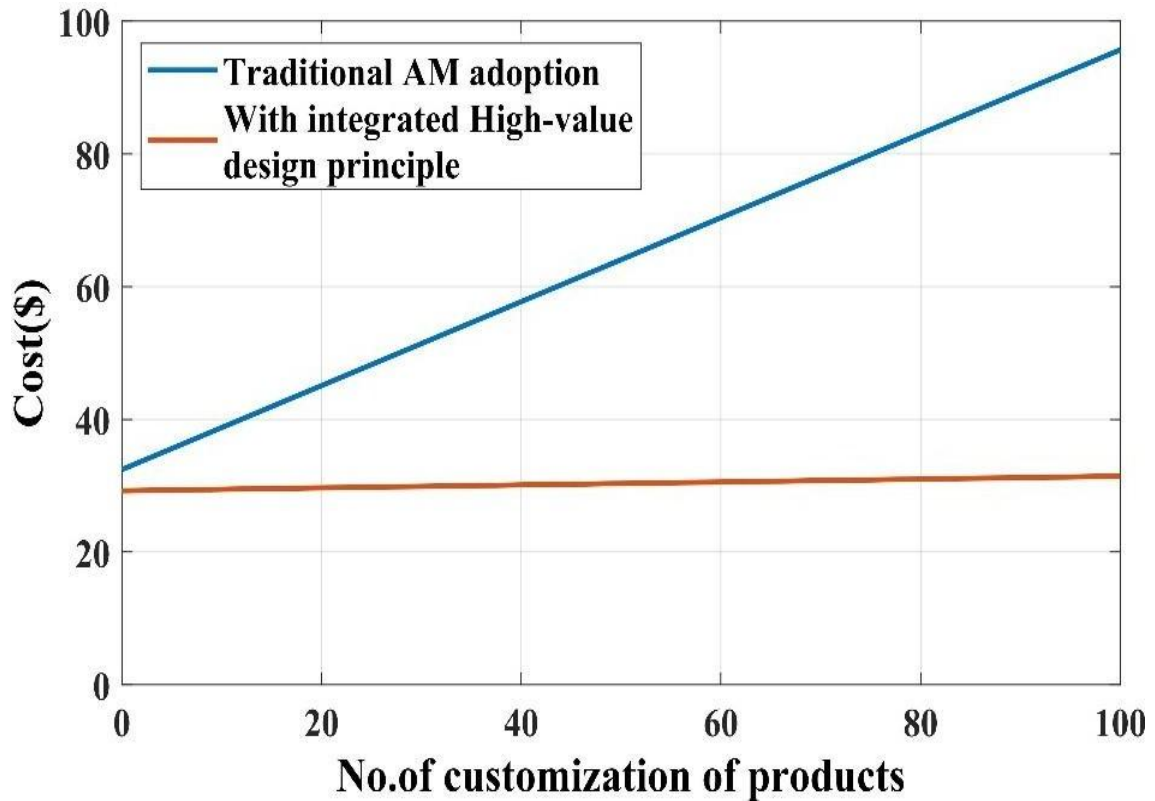


Figure 5.12 Analysis of cost reduction by proposed integration in supply chain dynamics

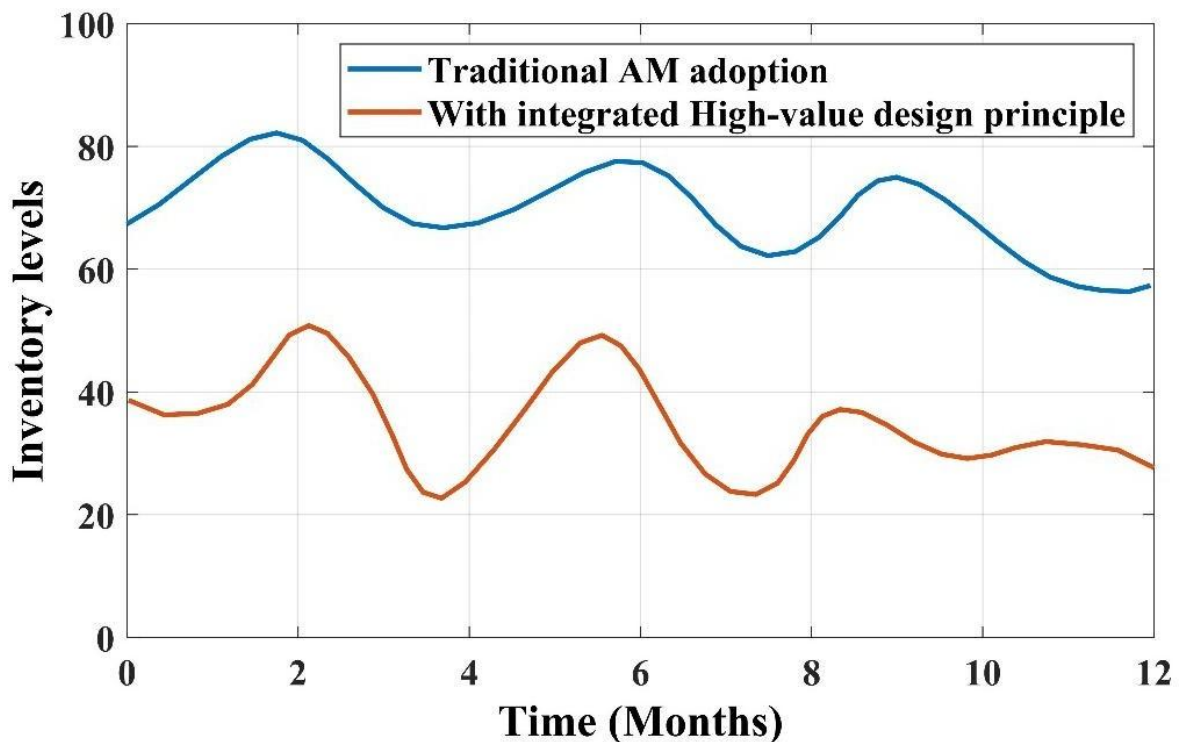


Figure 5.13 Analysis of inventory levels by proposed integration in supply chain dynamics

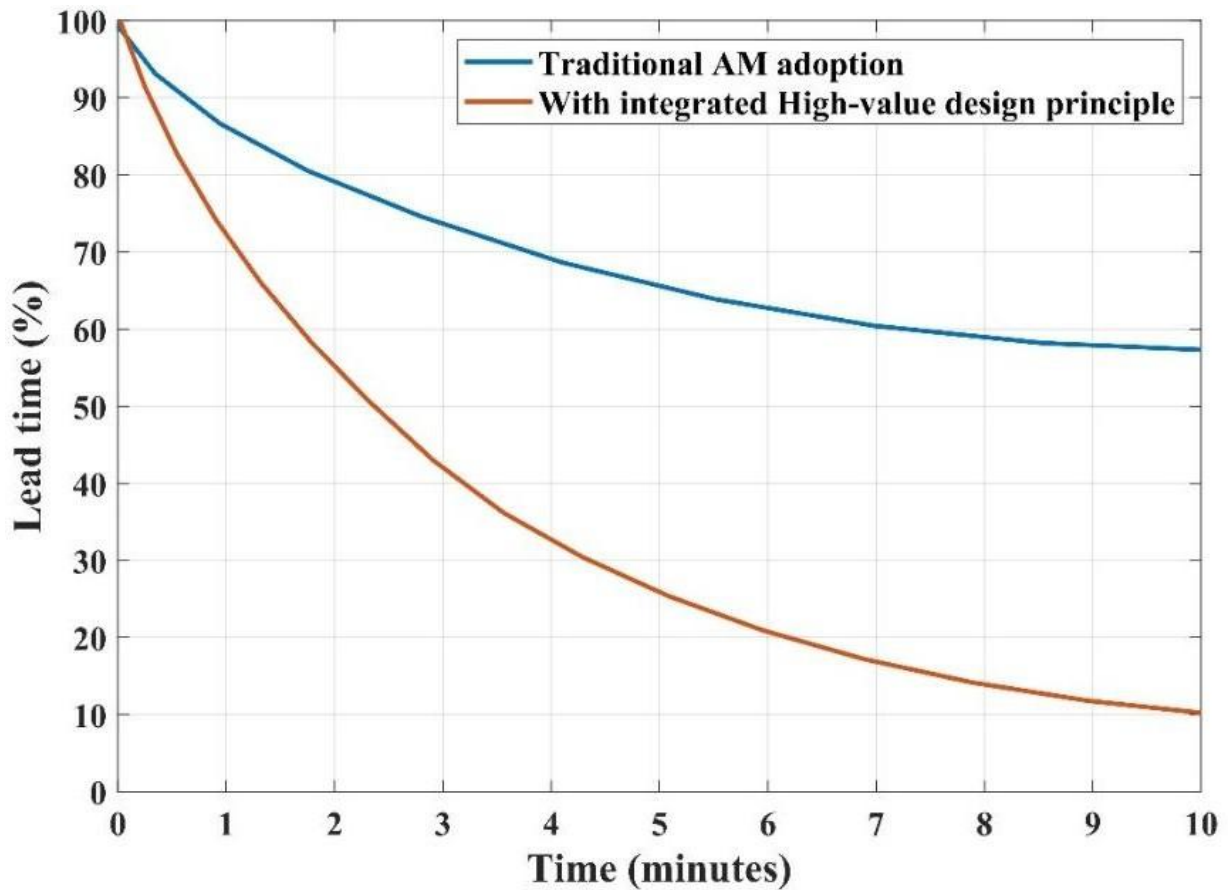


Figure 5.14 Analysis of lead time by proposed integration in supply chain dynamics

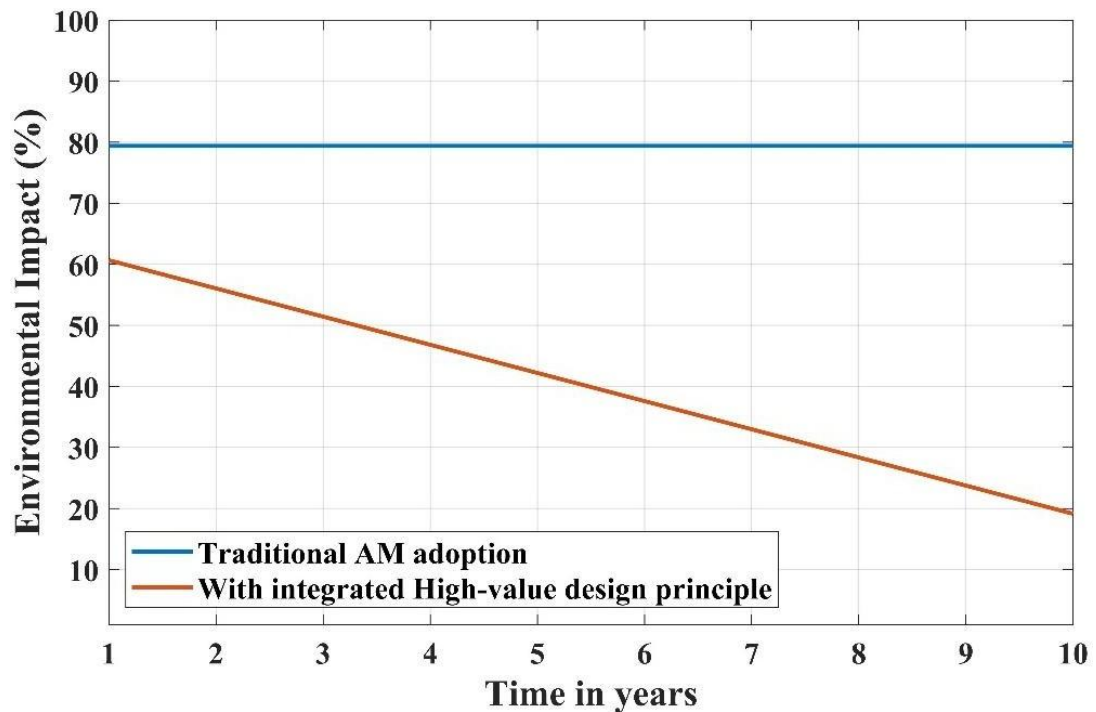


Figure 5.15 Analysis of environmental impact by proposed integration

Figure 5.14 shows an examination of the effects of the high value principle adoption on lead time reduction during a 10-minute period, comparing it to standard AM implemented supply chain dynamics. Traditional AM decreased lead time by 65%, whereas the implementation of integrated

high-value principles reduced lead time by 10%. This demonstrates faster processing and more efficient operation, reducing lead time quickly and dramatically as compared to standard AM adoption. Figure 5.15 shows an examination of the environmental effect of adopting the high value principle, which is contrasted to standard AM-adopted supply chain dynamics. For the past ten years, conventional AM has maintained a high environmental impact while remaining essentially unchanged. For the same ten-year period, adopting the integrated high value approach lowered the environmental effect year after year. This demonstrates the significant impact of the proposed integrated high value principle adoption on supply chain dynamics as compared to typical AM adoption.

5.6 STRATEGIC FRAMEWORK DEVELOPMENT

Adopting 3D/4D printing technology with HVDP concepts may give optimism for revolutionary supply chain dynamics based on empirical study findings. Provides additional benefits such as increased efficiency, customisation, and sustainability.

With the potential benefits of technological breakthroughs and integrated operations, identifying long-term goals for implementing 3D/4D printing technologies and connecting them with the overall company plan is critical. Evaluating the maturity of relevant 3D/4D printing technologies in terms of material compatibility, production adoption speed, and scalability to determine its usefulness for business also contributes major role. Also, by including design for manufacturability, sustainability, and customisation into the product development process greatly impacts in performance enhancement. Use of 3D/4D printing to make sophisticated, high-value goods that were previously impossible or expensive to produce and this possibly lessen by the utilization of emerging advanced digital tools to improve the co-creation process and real-time input-based creature of the customised products.

The identification of the risks and compliance requirements connected with the deployment of new technologies, such as intellectual property difficulties, quality control, and supply chain interruptions. Develop effective techniques for mitigating these hazards. Integrating circular economy concepts by designing goods for end-of-life reuse and recycling, as well as investing in skills development and workforce transformation, to ensure a customer-centric supply chain. By using data analytics to find areas for improvement and constantly optimize operations.

5.7 DISCUSSIONS WITH PROPOSED STRATEGIC FRAMEWORK

Incorporating 3D/4D printing technology with a HVDP approach may transform supply chain dynamics, allowing organizations to achieve considerable efficiency, cost savings, and increased

customer satisfaction. The analysis findings validated the integrated adoption of the AM and addressed research hypothesis H₁. Similarly, research hypothesis H₂ was addressed and supply chain dynamics improvement was transformed by high value principles with positive correlation.

Additionally, it appears that the high value principle integration with supply chain resilience and efficiency, respectively, is represented by hypotheses H₃ and H₄, which indicate appealing gains. The defined strategy framework offers a complete approach to implementing these technologies, ranging from harmonizing organizational vision to promoting innovation and forming collaborations. Following this approach allows organizations to efficiently use 3D/4D printing to alter its operations and assure long-term success in an increasingly competitive market.

This chapter proposed impact analysis on the supply chain dynamics during the adoption of the 3D/4D printing AM process and HVDP are conducted with simulated model along with empirical research in this research work. The comparison of the both simulation and observed data from the survey with the case company of Company X supply chain are compared found some close relation among them. The performance effectiveness of the adoption integration is presented by using metrics like cost reduction, lead times, inventory levels and environmental impact. Practical applications across sectors such as automotive, healthcare, and aerospace possibly show successful implementations of proposed integration technologies, showcasing its ability to accelerate time-to-market for high-value products and foster a more adaptive and efficient supply chain model. Ultimately, the research provided a strategic framework for businesses looking to adopt 3D/4D printing technologies, positioning them to drive manufacturing innovation and reshape global supply chain landscapes towards sustainable, HVDP -driven models.

CHAPTER- 6

CHAPTER 6: SUSTAINABILITY AND COST OPTIMIZATION IN 3D/4D PRINTING: USING FISH BONE DIAGRAMS FOR PRINTABILITY IMPROVEMENT

6.1 INTRODUCTION

3D printing or additive manufacturing has revolutionized modern production processes; now it supports rapid prototyping, mass customization, and cost-effective manufacturing across an array of industries [166]. Additive manufacturing creates objects layer wise, using only the essential amount of material [167]. Hence, this kind of manufacturing often wastes little material and therefore has a lesser environmental impact compared to the traditional subtractive method [168]. Complex geometries, which are difficult or impossible to manufacture using conventional methods, can be created using the advantage of 3D printing.

The respective industries like healthcare, aerospace, automotive, and construction now enjoy this benefit. For example, patient-specific prosthetics, dental implants, and surgical models are constructed with an unmatched degree of precision [169]. In aerospace, lightweight components solid enough to save fuel are a boon, while in construction, 3D printing technology is being tested to craft structures and materials. 3D printing also facilitates localized manufacturing on demand by decentralized production, diminishing reliance on global supply chains and lessening transportation costs. This, in turn, reduces the time to market, thus enabling manufacturers to react swiftly to market dynamics, customization, and logistical issues.

In addition, advancements in multi-material and bio-printing have unveiled new avenues in tissue engineering, regenerative medicine, and green product development [170]. The capacity to rapidly iterate designs, maximize structural integrity, and minimize production lead times has transformed 3D printing into a fundamental tool in research, innovation, and industry, opening the door to a more sustainable, efficient, and responsive manufacturing future [171].

The integration of sustainability and cost minimization in 3D and 4D printing has come into focus with industries trying to lessen the material wastage, energy, and overall manufacturing cost while increasing efficiency and environmental stewardship [172]. Sustainable 3D/4D printing emphasizes the use of biodegradable, recyclable, and renewable materials like PLA, PBAT, and bio-based composites that help in reducing ecological footprint. Also, improvement in energy-efficient additive

manufacturing technologies, closed-loop recycling technologies, and intelligent material usage helps minimize the carbon footprint [173,174].

Cost reduction measures such as process automation, topology optimization, and multi-material printing enable industries to attain high accuracy with low resource utilization. The emergence of 4D printing, which includes shape-memory components that change shape over time as a response to environmental stimuli, further promotes sustainability by allowing for self-assembling structures and lowering the cost of assembly and maintenance [175]. Through the use of sustainable materials and creative cost-saving methods, 3D and 4D printing are opening doors to environmentally friendly, economically feasible, and technologically sophisticated manufacturing solutions in various sectors.

6.1.1 Sustainable 3D/4D Printing Development

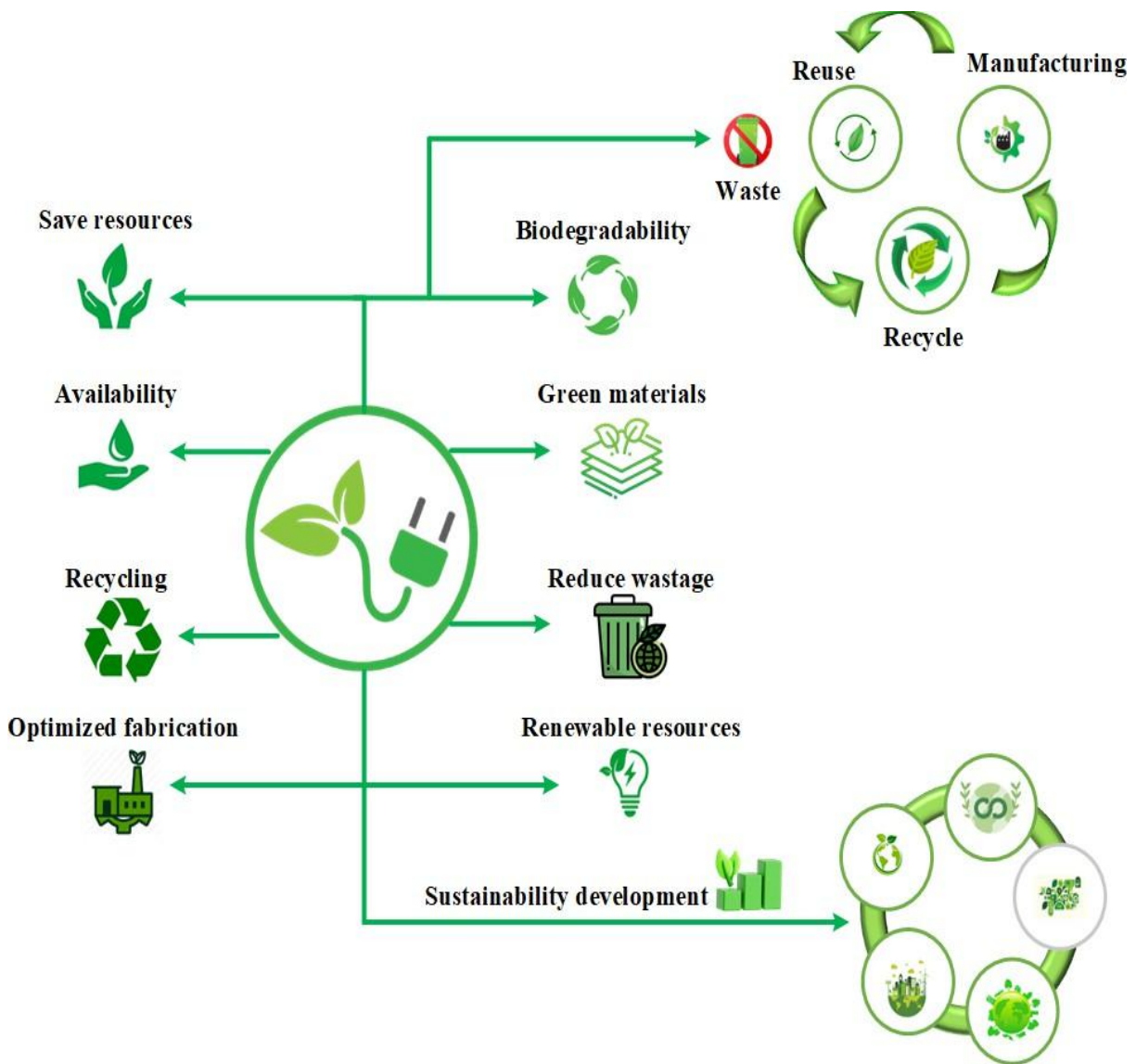


Figure 6.1 Framework for sustainable development of 3D/4D printing

The framework for sustainable development of 3D/4D printing, organized around green practices and circular economy, is presented in Figure 6.1. At the core of this framework is the integration of green energy and bio-based materials to drive the fabrication process. The framework includes green materials, biodegradable composites, and renewable sources, all of which will help minimize the environmental footprint. The process, by ensuring the fabrication is optimised to minimize waste and improve availability, ensures efficient use of resources, while minimizing waste. These ideas will contribute to the improvement of material efficiency, ensure resources are conserved, and promote the employment of manufacturing components that are recyclable and reusable [176].

Furthermore, the concept reinforces recycling, reuse, and remanufacturing as key aspects in progressing towards circular production. In circular products, the goal is to minimize waste by promoting biodegradability and recycling to reduce the carbon footprint and minimize adverse effects on the environment. This closed-loop cycle is working toward a sustainable development that suggests each stage of production and/ or use is designed to promote the environment. When sustainable principles are incorporated in 3D/4D printing, there exist opportunities for industries to create innovative, environmentally sound manufacturing processes that adopt a global movement to address climate change and resource depletion.

6.1.2 Cost Optimization in 3D/4D Printing Implementation

Cost optimization in 3D/4D printing development involves optimizing the materials, energy, and processes involved in production. The major benefit of 3D/4D printing, as opposed to traditional manufacturing, is the process of AM. Products are built one layer at a time instead of removing material to create a shape. Additive manufacturing produces less waste than a subtractive process, thereby saving money associated with the use of raw materials and reducing waste management costs. On-demand manufacturing eliminates inventory and reduces storage space, resulting in lower costs related to warehousing and logistics. Additionally, manufacturers can produce optimized designs and prototypes that decrease the number of physical iterations, leading to saved time and costs in the development process [177].

Furthermore, cost savings increase with local manufacturing, which reduces shipping and tax costs. There are also savings associated with materials made from renewable and green sources, especially when paired with energy-efficient manufacturing processes. For example, 4D printing utilizes smart materials that can self-assemble or change shape when stimulated. This eliminates informal assembly and significantly reduces labor and tooling costs. 3D/4D printing is becoming more cost-effective due to advances in material science and digital fabrication. The benefits of 3D/4D printing are increasingly attractive when coupled with sustainable options, and improving product longevity reduces lifecycle costs.

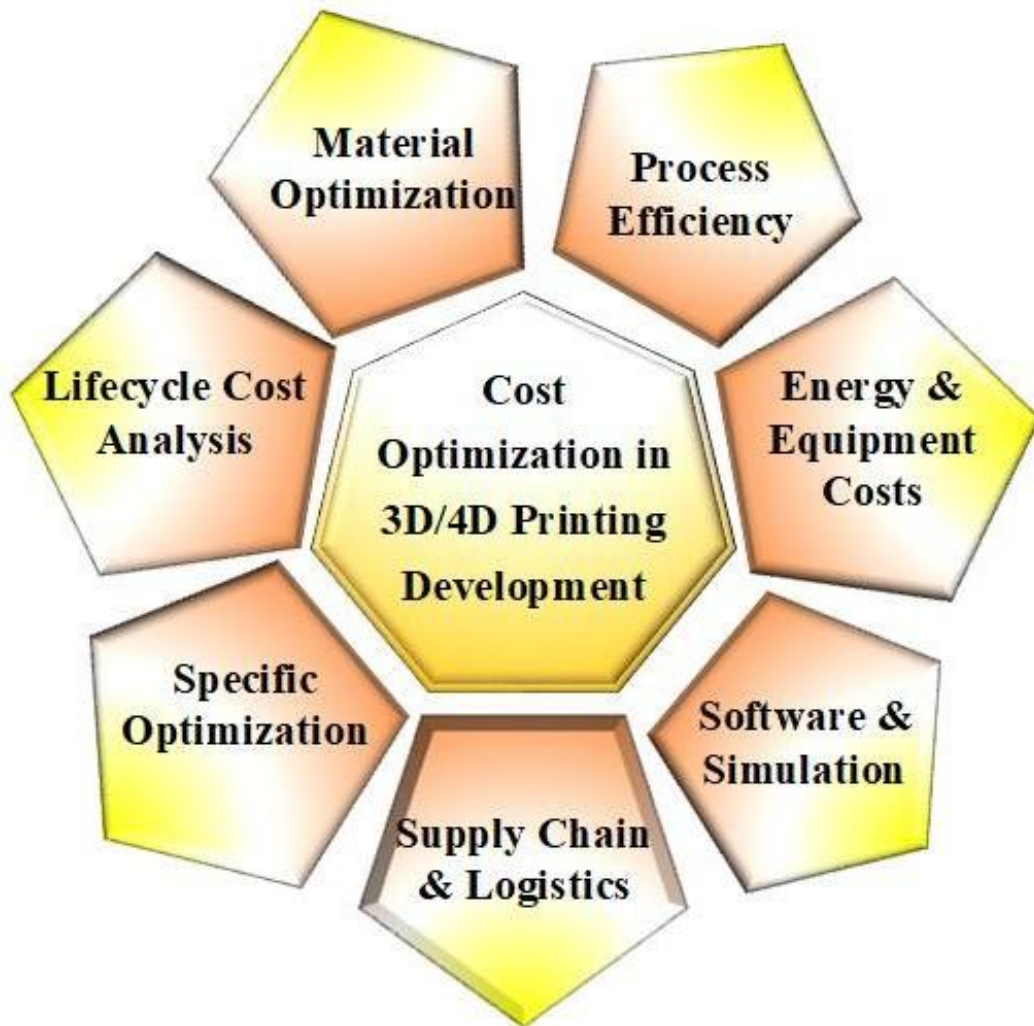


Figure 6.2 Overview of Cost Optimization in 3D/4D Printing Development

Figure 6.2 depicts an overview system for cost reduction in 3D/4D printing development with various interdependent variables correlated with costs. The goal of cost reduction without sacrificing performance and quality is associated with Material Optimization, which imposes cost effective, sustainable, and high-performance materials that help to reduce both the amount used and expense. Process Efficiency involves moving towards efficiency in workflows that help to reduce time while minimizing wasted resources. Energy and Equipment Costs convey the way to reduce operational costs by managing energy usage and equipment assets. Reducing the amount of trial and error and contributing to the costs of sufficiency by accurately modeling and predicting is done through Software and Simulation. Supply Chain & Logistics optimization is the reduction of delays, and overhead while managing sourcing, inventory, and distribution efficiently. Specific Optimization is customized parameters and strategies for unique applications or parts that produce the lowest cost-to-performance ratios. At last, it includes Lifecycle Cost Analysis, which includes the total cost from design to disposal, eliminating long-term economic mismanagement as a concern. Together, these areas develop a strategic path to developing cost-effective, scalable, and sustainable additive manufacturing solutions.

6.1.3 Fish Bone Diagrams

The Fishbone Diagram is a visual tool for systematically identifying the root causes of quality problems. Fishbone Diagrams allow individuals to systematically break apart and study an observed effect from all plausible causes. A Fishbone Diagram resembles the skeleton of a fish, with the main “spine” being the problem, with the diagonal “bones” extending to represent major categories of causes, each of which can be subdivided into causes.

The Fishbone Diagram assists teams in mapping out problem-solving processes in an orderly fashion. The Fishbone Diagram has the following advantages: it identifies root causes and sub-causes through a structured approach; it fosters collaborative discussion through group input; and it signifies areas to collect data and conduct analysis. It can be presented as simply labelled branches for each cause or sub-cause, and it may include any other qualitative and quantitative information. The diagram includes properties such as risk, codes, sequence of events, or any evaluation upon assessing both risks individually or collectively, to the extent you deem pertinent. The Fishbone Diagram analyses quality issues and is also a valuable tool for identifying and managing risk across complex processes. The structure of the fish bone diagram is displayed in Figure 6.3.

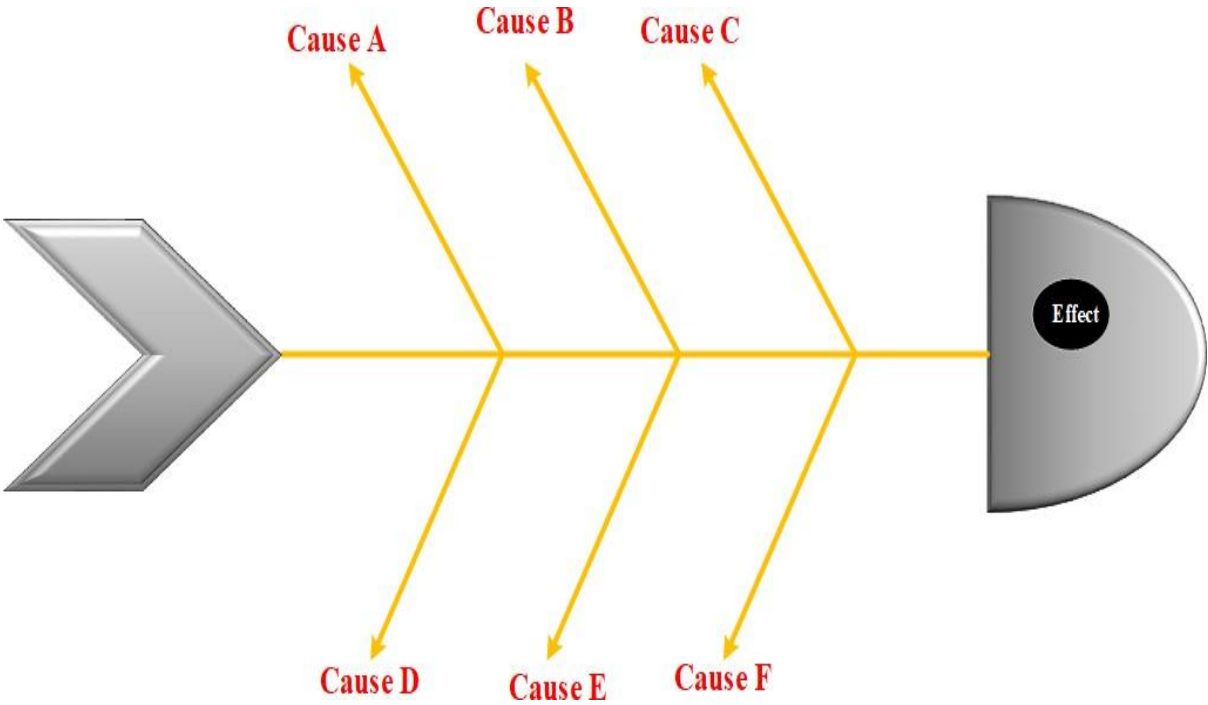


Figure 6.3 Structure of Fishbone Diagram

6.2 SUSTAINABILITY AND COST OPTIMIZATION IN 3D/4D PRINTING

Figure 6.4 depicts the development and refining of optimal 3D printing parameters through laser-based additive manufacturing, Design for Manufacturing (DfM), Design for Additive Manufacturing

(DfAM) considerations, and systematic performance analysis. Proposed part focused on three key process controls LP, WFR, and Layer Overlap (LO) each influencing major aspects such as melting efficiency, deposition rate, material utilization, porosity, and inter-layer bonding. Moving to the top right, Design for Manufacturing principles guide the selection of the **“Optimal Printing Parameters of All Four Objective Optimizations,”** ensuring that manufacturing constraints and performance requirements are fully addressed. Beneath these design parameters, the figure illustrates performance responses through a fishbone diagram, which helps identify and categorize potential issues (e.g., structural flaws, thermal distortion) by examining root causes. In parallel, the diagram shows International Standard Organization (ISO) standard fabricated samples, underscoring the importance of adhering to industry benchmarks and verifying that printed components meet standardized criteria.

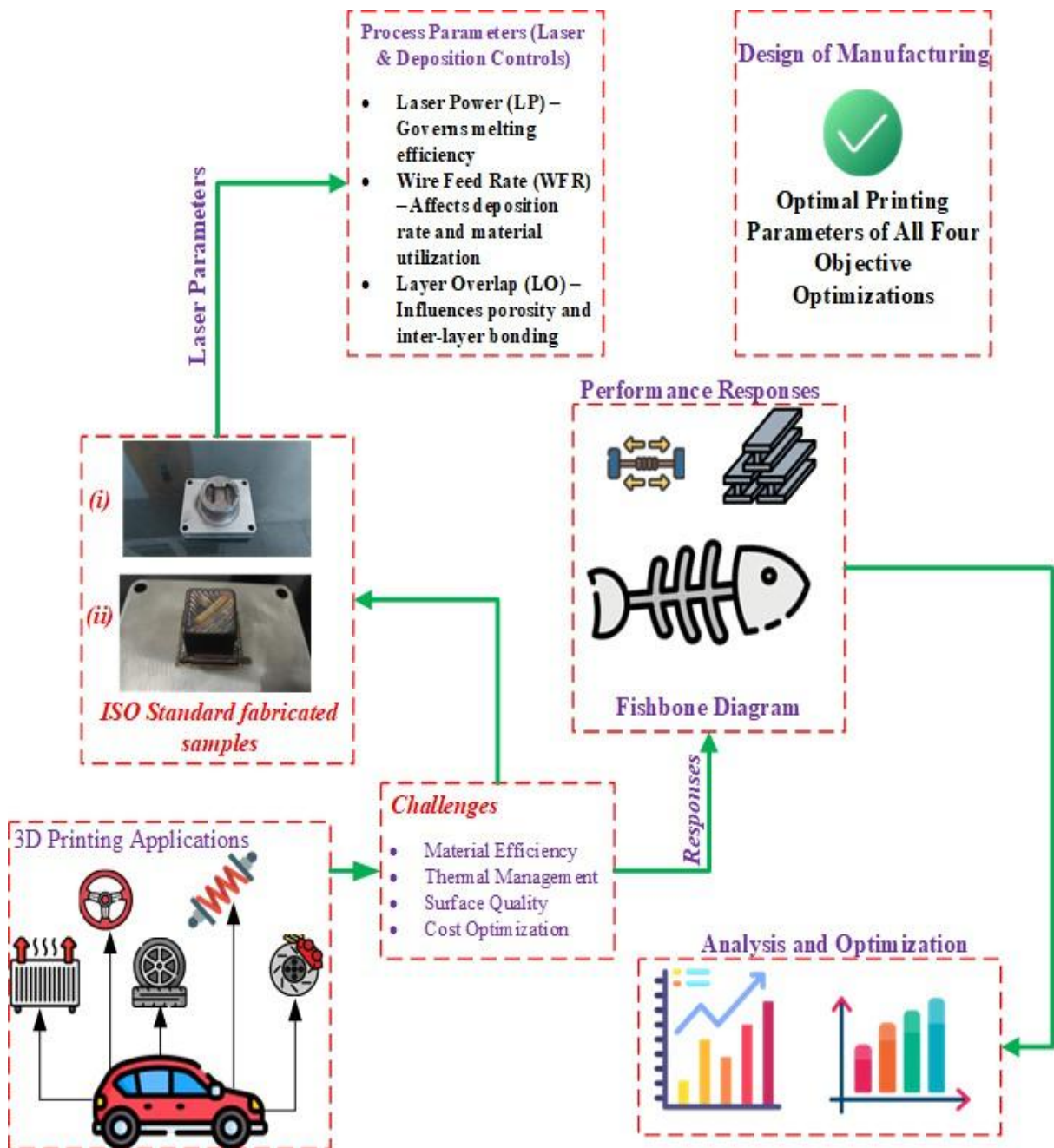


Figure 6.4 Sustainability and cost optimization in 3D/4D printing

At the lower left, 3D printing applications are symbolized, indicating the generalizability of such methods to all sorts of components like wheels, springs, and radiators. Besides it, major challenges such as material efficiency, thermal management, surface quality, and cost optimization are clearly enumerated, setting the functional challenges that have to be addressed in the process of additive manufacturing. Lastly, at the bottom right, analysis and optimization represent the data-driven optimization of both process parameters and material properties, illustrated through graphs and microscopic examinations that expose surface integrity, defect existence, or other indicators of quality. With each of these steps combined.

6.2.1 Analysis of Sustainability and Cost Optimization in 3D/4D Printing Through Fishbone Diagram

Figure 6.5 shows a fishbone diagram (Ishikawa Diagram) with major factors affecting sustainability and cost minimization in 3D/4D printing [178,179]. The diagram classifies causes into six major categories: man, machine, method, material, measurement, and environment. The category of man points out the human errors like inaccurate design geometry and wrong 3D model inputs, which result in wastage of material. The machine category deals with technical specifications such as accuracy, resolution, orientation of parts, and build time, stressing the need for proper calibration.

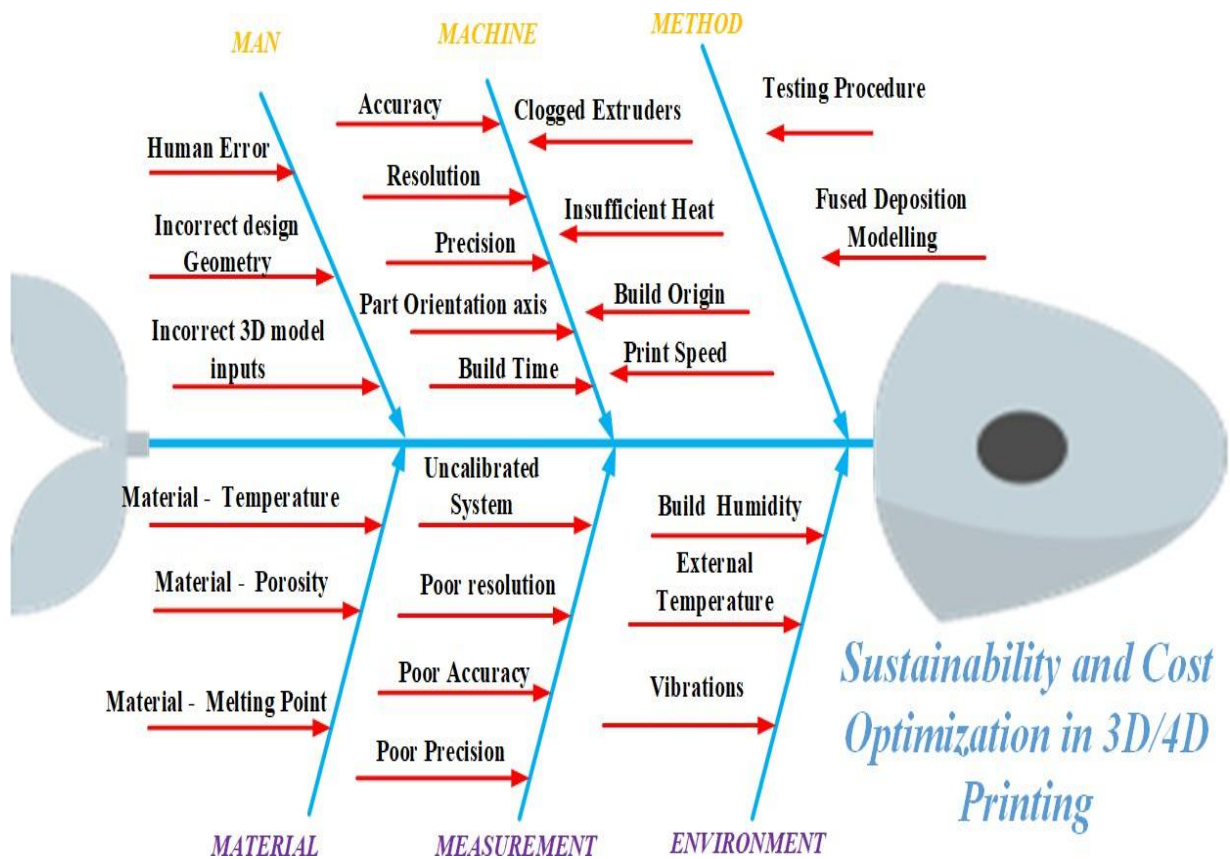


Figure 6.5 Analysis of sustainability through fishbone diagram

The method category resolves problems concerning materials technology, including congested extruders, lack of heat, rate of print, and testing protocol, all of which affect efficiency and quality. The material category takes into account temperature, porosity, and melting point, emphasizing the importance of using appropriate materials to maximize durability, while the measurement category deals with system calibration problems, resolution, and precision, which affects the accuracy of the final product. The environmental category comprises elements such as humidity, ambient temperature, and vibrations, which may cause variations in print quality. This systematic analysis assists in the detection of root causes of inefficiencies, allowing for focused improvements in process optimization, material choice, and cost savings to foster sustainable and efficient additive manufacturing.

6.2.2 Materials

The research utilized austenitic stainless steels for both substrate and wire materials. AISI 301 wires, 0.5 mm in diameter and employed alongside AISI 316 substrates which is 10 mm thick. Table 6.1 presents the nominal chemical composition of these alloys.

Table 6.1 Chemical composition of the materials

AISI 316	Wt. %
C	0.09
Si	0.75
Mn	2
P	0.046
S	0.04
Cr	17-19
Mo	3-4
Ni	11-15
Fe	Bal

6.2.3 Laser Metal Wire Deposition System

An LMWD is an advanced additive manufacturing system for cutting-edge metal 3D printing. It is a Meltio 3D printer with an integrated, built-in wire feeder. The system allows the controlled, continuous deposition of a metal wire feedstock, melted layer-by-layer to create complex metal parts. The LMWD or welding station is effective for fabricating, repairing, or improving metal parts with high geometric and material accuracy. The welding station includes a Nd: YAG laser source with high energy density and precision. The Nd: YAG laser delivers energy pulses for a very short time

microseconds to milliseconds, and so can be controlled with great precision regarding heat input and melt pool size. Figure 6.6 displays the Working principle of LMWD technique.

The laser's Pulse Repetition, usually given in units hertz (Hz) determines how fast laser pulses are provided to the process and ultimately provides thermal control that is vital to achieving quality during metal deposition. In many applications, pulsed lasers will also lower thermal distortion, reduce residual stresses, and provide fine surface finishes. These qualities are coupled with properly managing the aspects of metal deposition, making LMWD or welding ideal for producing high-performance metal components required for aerospace, healthcare, and industrial applications. [180].

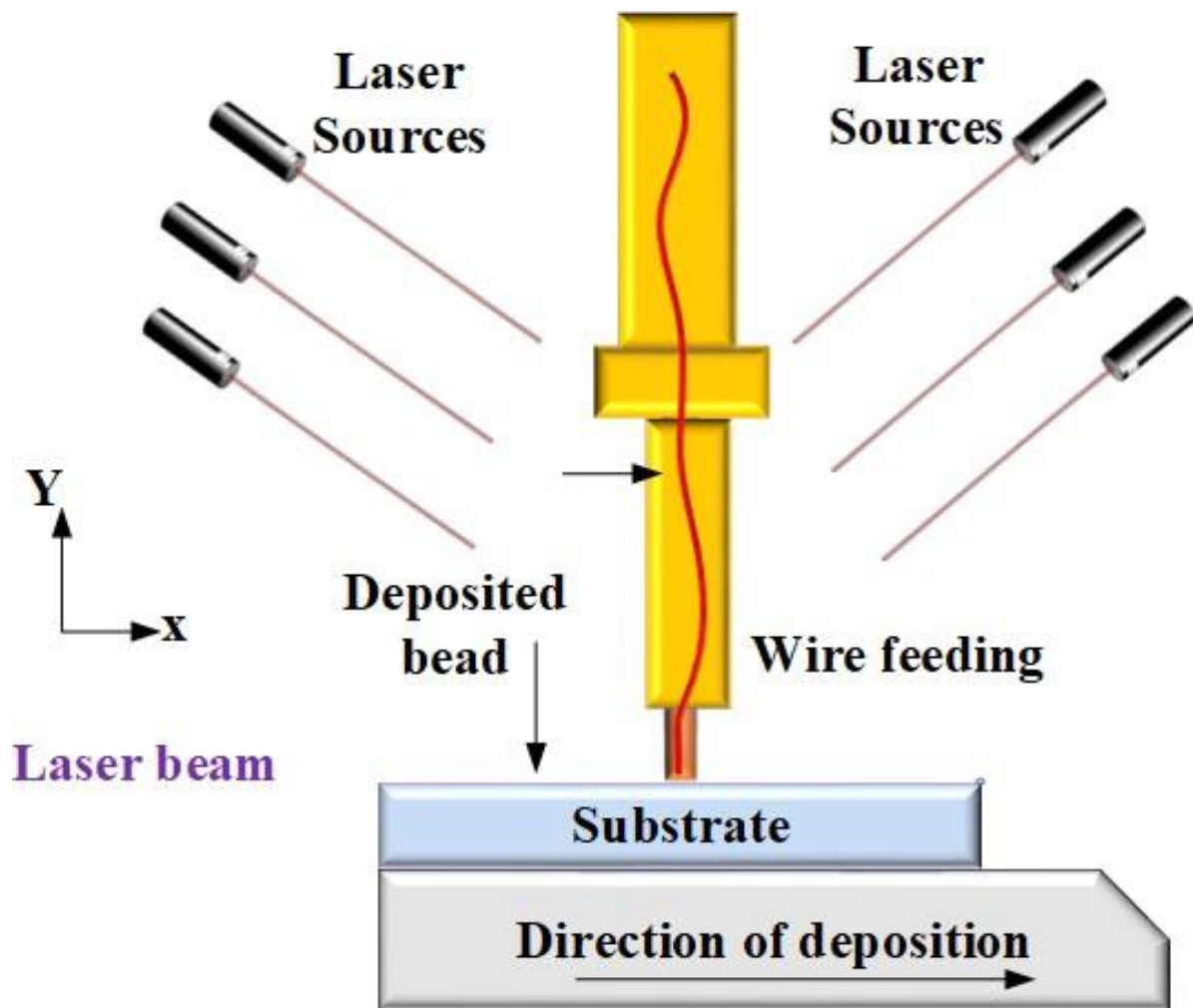


Figure 6.6 Working principle of LMWD technique

The Maximum Peak Power (P_{peak}) of the pulses reaches 10 kW, resulting in maximum average power of 140 W and Pulse Energy (E) of 60 J. Fiber delivery is utilized for transporting the laser beams from the sources to the upper heads, employing a 0.6 mm fibre, 400 mm collimating lens, and 250 mm focal lens. This setup achieves a very fine spot of 0.35 mm diameter, with the capability to adjust the maximum spot diameter between 0.4 mm and 0.6 mm automatically. Main parameters of the prototype of LMWD system are shown in Table 6.2.

Table 6.2 Major parameters of the prototype of LMWD system

Feature	Value
Dimension W×D×H	570x700x1200 mm
Envelope ratio of print	146x170x380 mm
Total Weight	260 kg
Power Source	1300 W
Type of laser	06 Nos 200 W direct diode lasers
Wavelength of laser	978 nm
Type of Wire Feed	Up to 3 x K400 spools
Wire Feedstocks	0.9-1.3 mm wire diameter
Cooling Chamber	Water-cooled chiller
Control Chamber	Closed-loop chamber
Input Power	209/240 V single phase
Power Consumption ratio	3-6 kW peak depending on selected option

The welding stations consist of 4 linear and 2 rotation axes, enabling precise control of Speed (v) via numerical control [181]. The wire feeder systems, named Lach, is controlling through a LabVIEW interfaces, which regulates the WFR and synchronizes laser emissions at the beginning of each new layers. Various nozzle dimensions are employed to accommodate different wire sizes.

6.2.4 Analysis of Sustainability and Optimization of 3D Printing

Sustainability in 3D/4D printing largely depends on energy efficiency [182]. The total energy consumption per unit time expressed as:

$$E_{total} = P_{machine}t + P_{pre/post}t_{prep} \quad (6.1)$$

where, E_{total} signifies Total energy consumed (J), $P_{machine}$ denotes power of the 3D/4D printer (W), t denotes printing time (s), $P_{pre/post}$ signifies power used in pre/post-processing (W), t_{prep} denotes pre/post-processing time (s).

The sustainability of printing depends on the efficient use of material, minimizing waste [183,184]:

$$\eta_{mat} = \frac{M_{Final}}{M_{Input}} \quad (6.2)$$

where η_{mat} denotes material efficiency (%), M_{Final} signifies mass of the final product (kg), M_{Input} denotes initial mass of material used (kg).

For high sustainability, η_{mat} should be maximized by optimizing support structures and reducing waste.

Total cost per printed unit considers material cost, energy cost, and machine time cost is given as follow:

$$C_{total} = C_{mat} + C_{energy} + C_{machine} \quad (6.3)$$

where C_{total} signifies the total cost per unit, C_{mat} denotes the material cost, C_{energy} signifies the energy cost, $C_{machine}$ denotes the machine usage cost per unit time.

In 4D printing, smart materials enable self-healing, reducing waste and increasing longevity. The sustainability factor (S_f) linked to the material's lifecycle through degradation rate (λ) and self recovery potential (Γ)

$$S_f = \frac{1}{1 + \lambda - \Gamma} \quad (6.4)$$

A higher S_f indicates better sustainability and cost-effectiveness.

Layer thickness (t_{layer}) impacts both material usage and energy efficiency. The optimal layer thickness minimizes cost while maintaining strength:

$$t_{opt} = \arg \min_{t_{layer}} \left[C_{total} + \frac{K_{fail}}{t_{layer}^n} \right] \quad (6.5)$$

where K_{fail} defines the failure risk cost factor, n denotes the empirical coefficient related to material properties and thinner layers improve quality but increase printing time and cost.

A Pareto optimization approach balances cost (C_{total}) and sustainability (S_f) using a weighted function:

$$\min \left[w_1 C_{total} + w_2 \frac{1}{S_f} \right] \quad (6.6)$$

where w_1, w_2 are weights assigned to cost and sustainability, and x signifies the design parameters such as material, layer thickness, and energy settings.

6.3 RESULTS AND DISCUSSIONS

The Results and Discussion section emphasizes the comprehensive analysis of mechanical performance, sustainability, and cost-effectiveness factors of the additive manufacturing domain, particularly emphasizing the 3D and 4D printing types. Through detailed experimental analysis is performed to study the structural integrity and durability of these materials under different loading and environmental conditions. Moreover, the dimensional accuracy and surface finish concerning the adhesion between layers are also analysed and evaluated.

The study will also constitute an economic measure, which will consider measures such as material cost, time to manufacture or create a prototype, labour, and post-processing. These measures will indicate the cost-benefit ratio and the viability of point added manufacturing at identified production rates. In the discussion, the findings to provide an overall impression of the net impact of 3D and 4D printing in contemporary manufacturing in terms of performance, sustainability, and economic return, to better inform future approaches to new industrialisation and improved production practices are provided.

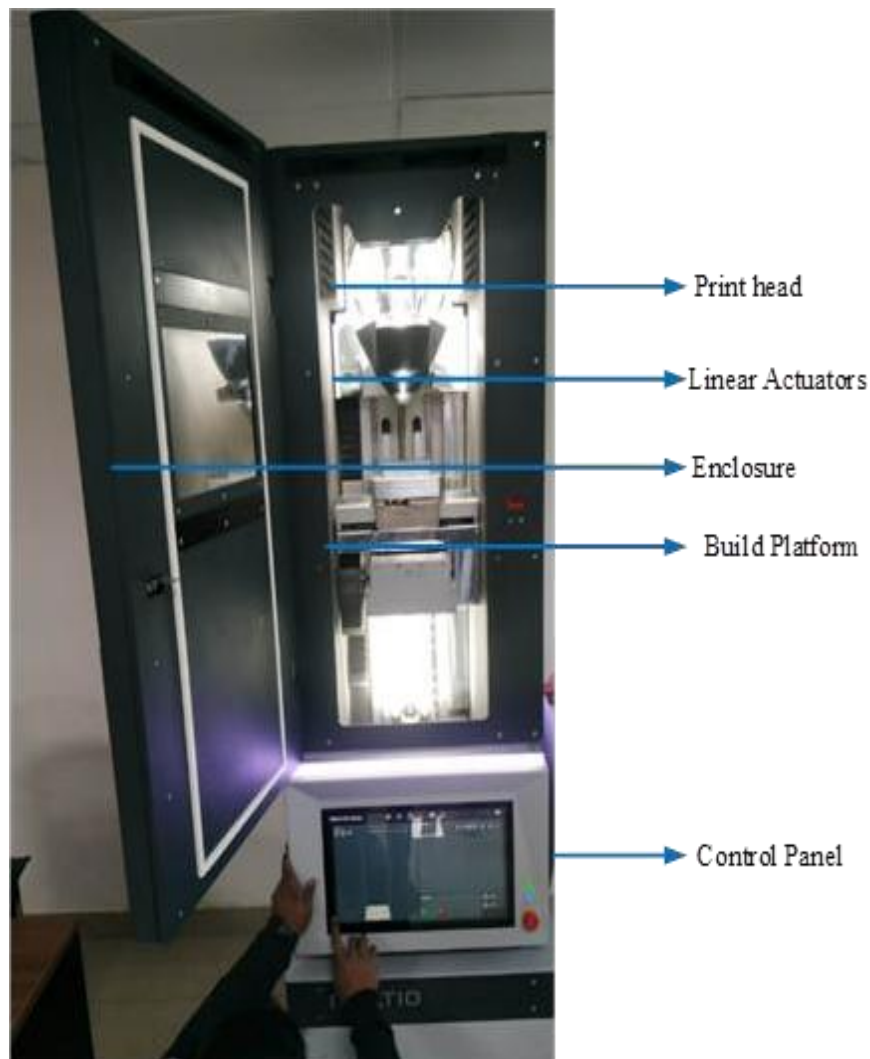


Figure 6.7 Specimen setup in the Meltio 3D Printer

6.3.1 Instrumentation Framework

Figure 6.7 illustrates the analytical specimen setup for LMWD of Meltio M2000-DLX 3D printer is a high-performance AM system featuring a 200W diode laser surrounded by six additional laser units, ensuring uniform energy distribution for precise material deposition. It boasts a dual-extrusion system capable of handling high-strength carbon fibre composites and versatile thermoplastics, with a generous build volume of 600 mm * 600 mm * 600 mm. An AI-driven slicer optimizes material usage and print times, while a closed-loop cooling system maintains optimal temperatures to prevent overheating. Main parameters of the prototype of LMWD system are shown in Table 6.3.

The welding stations consist of 4 linear and 2 rotation axes, enabling precise control of speed (v) via numerical control. The wire feeder systems, named Lach, is controlling through a LabVIEW interfaces, which regulates the Wire Feed Rates (WFR) and synchronizes laser emissions at the beginning of each new layers. Various nozzle dimensions are employed to accommodate different wire sizes.

Table 6.3 Main parameters of the prototype of LMWD system

Feature	Value
Dimension ($W * D * H$)	570×700×1200 mm
Envelope ratio of print	146×170×380 mm
Total Weight	260 kg
Power Source	1300 W
Type of laser	06 Nos 200 W direct diode lasers
Wavelength of laser	978 nm
Type of Wire Feed	Up to 3 × K400 spools
Wire Feedstocks	0.9-1.3 mm wire diameter
Cooling Chamber	Water-cooled chiller
Control Chamber	Closed-loop chamber
Input Power	209/240 V single phase
Power Consumption ratio	3-6 kW peak depending on selected option

The printer robust aluminium frame and heated build platform ensure durability and excellent first-layer adhesion. High-precision stepper motors and linear guides provide smooth, accurate movements for high-resolution prints. Additional features include a touchscreen interface for

intuitive control, an enclosed build chamber for safety, and a filtration system to manage fumes and particulates, making the Meltio M2000-DLX ideal for industrial applications requiring precision and reliability.

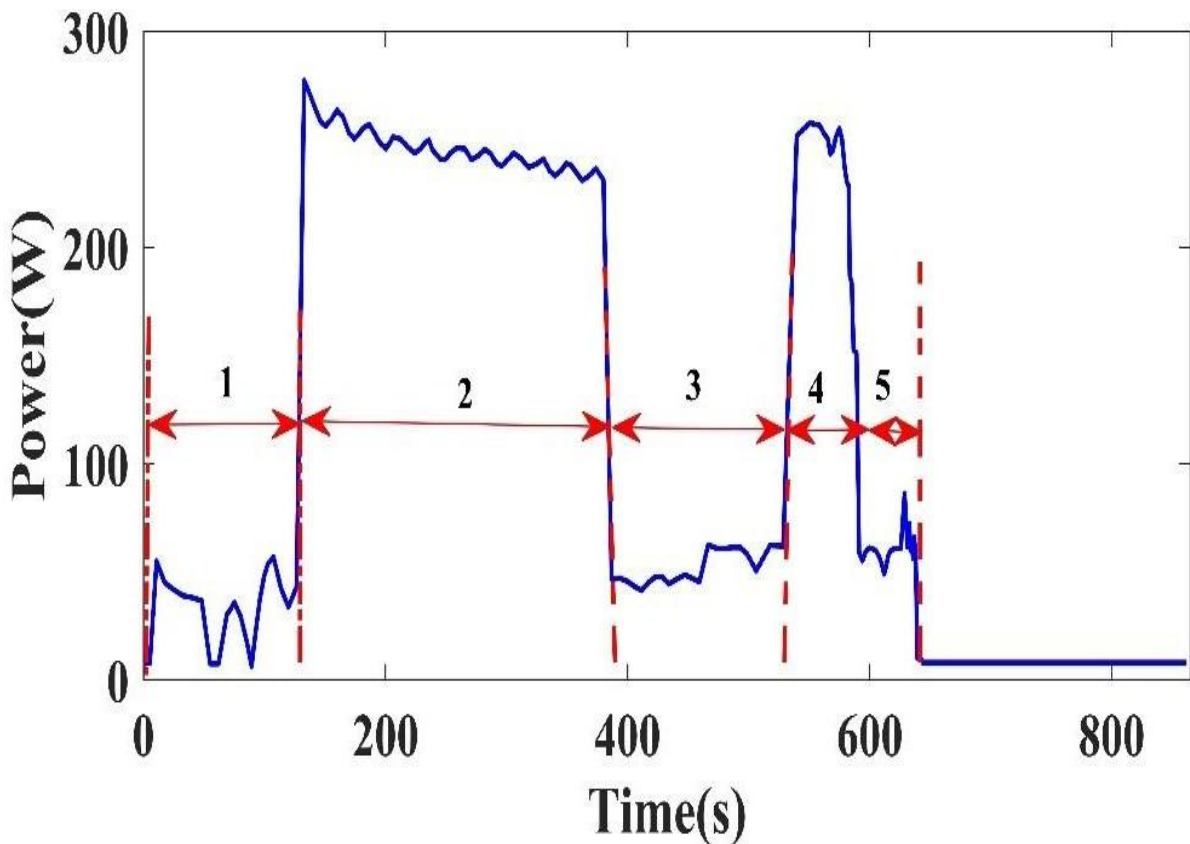


Figure 6.8 Energy consumption of printing cycle

Figure 6.8 represents the power utilization of the printing cycle as it moves over time and reveals inconsistencies of power intake throughout stages. At the outset, power increases immediately to eventually reach a baseline at about 100W. Subsequent is the central body printing process with which power waves about and passes peaks above 200W. Then a fall, followed by the occurrence of an analogous repeat first stage of another peak is realized.

6.3.2 Optimal Printing Factors of All Single-Objective Optimizations

The printed parts are inspected after making, and experimental dimensional accuracy mean values and signal-to-noise ratios are obtained for carbon emissions and three different printing costs. From the estimations using the provided formula, the mean effect plot for all the factors is calculated, thus resulting in computing optimal parameters for all the individual objectives. Moreover, the contribution factor for every objective is obtained through Analysis of Variance (ANOVA) calculations, and the results are summarized in the supplementary section.

Based on dimensional accuracy enhancement, when precision in width is needed, the best parameters are as follows: 95% cooling fan setting, 18 mm/s of printing speed, 195°C of the nozzle thermal

condition, 35°C of the build plate thermal condition, and 0.28 mm of layer thickness. For minimal tolerance in thickness, the suggested settings are altered to a fan speed of 45%, a printing rate of 22 mm/s, a nozzle thermal condition of 215°C, a bed thermal condition of 65°C, and a layer thickness of 0.12 mm. If the objective is to minimize carbon footprint and electricity usage, the most effective parameters are a fan rotation rate of 98%, a printing rate of 28 mm/s, a nozzle thermal condition of 185°C, a bed thermal condition of 18°C, and a layer thickness of 0.32 mm. To minimize material costs, the optimal settings are a fan rotation rate of 48%, a printing speed of 27 mm/s, a nozzle thermal condition of 205°C, a bed thermal condition of 28°C or 18°C, and a layer thickness of 0.31 mm. When reducing labor expenses, the optimal conditions include a fan rotation rate of 55%, a printing rate of 32 mm/s, a nozzle thermal condition of 198°C, a bed thermal condition of 32°C, and a layer thickness of 0.29 mm.

Among the most influential factors, layer thickness had the greatest effect on width accuracy, material costs, and labour expenses, accounting for 50.12%, 55.34%, and 85.76%, respectively. While delta-type printers are preferable in high-speed production, stepper motor motion-caused errors in mechanical dimensions, pulley positions, and stretching belts result in print inaccuracies. Further, the end-positioning precision of the three-axis parallel motion system is compromised due to kinematic errors, with the resulting larger deviation from part precision based on distance away from the center. These inaccuracies significantly contributed to overall width, length, and thickness accuracy with contributions of 27.45%, 28.62%, and 43.87%, respectively. Carbon emissions and electricity usage are also largely controlled by the bed temperature, which contributed 61.23% of influence.

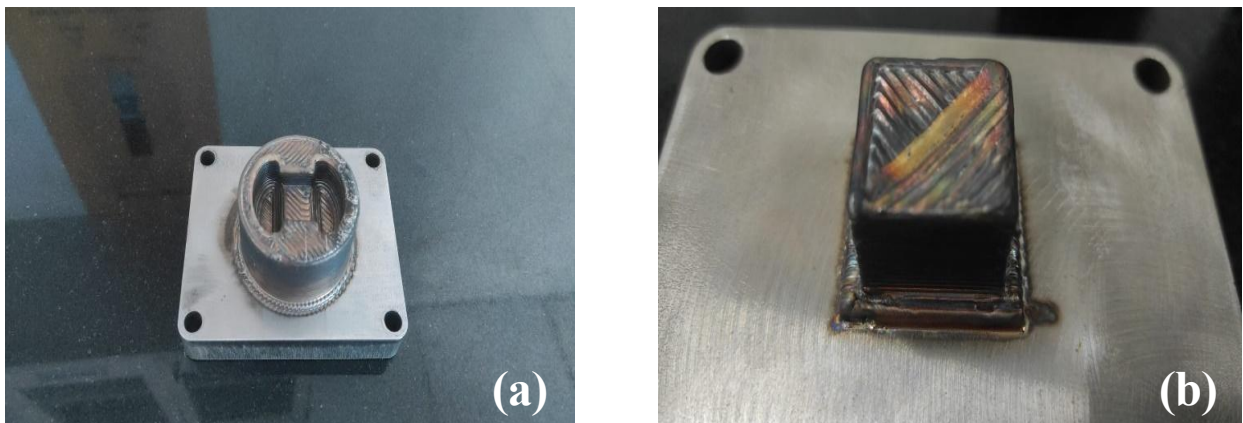


Figure 6.9 (a) Circular Insert with Internal Features (b) Rectangular Block with Angled Channels

Figure 6.9 (a) and (b) depict components printed using a Meltio 3D Printer. Figure 6(a) shows a circular insert with internal features, characterized by a cylindrical shape with internal threaded or grooved elements. This part potentially serves as an insert for a larger assembly or as a custom connector piece. Figure 6.9 (b) showcases a rectangular block with distinct angled channels or

grooves, which could function as a guide or alignment block in a mechanical assembly. Both components demonstrate the precision and versatility of metal 3D printing in creating intricate and functional parts. Table 6.4 depicts the mean values and S/N ratios of the analysis.

Table 6.4 Mean values and S/N ratios of the analytical outcomes

Num.	W (Mean)	W (SNR)	OW (Mean)	OW (SNR)	OL (Mean)	OL (SNR)	Carbon Dioxide Emissions (Mean)	Material Cost (Mean)	Material Cost (SNR)	Labor Cost (Mean)	Labor Cost (SNR)	Electricity Cost (Mean)	Electricity Cost (SNR)
1	0.28	10.52	0.48	6.84	0.75	2.78	28.80	39.45	270.23	-49.72	2.31	-7.61	0.05
2	0.55	5.91	0.61	3.89	0.66	2.01	44.75	45.89	273.91	-48.73	4.36	-12.40	0.07
3	0.42	7.42	0.58	5.10	0.80	2.11	41.92	47.31	269.87	-50.01	9.32	-20.31	0.08
4	0.71	6.39	0.71	1.35	0.73	1.62	42.80	46.90	272.76	-48.93	3.72	-10.65	0.09
5	0.63	3.78	0.62	4.52	0.85	2.21	40.25	41.33	273.19	-48.73	3.98	-18.90	0.06
6	0.38	9.41	0.72	5.03	0.88	1.94	30.21	30.87	272.83	-49.10	7.23	-11.52	0.12
7	0.62	4.85	0.65	4.15	0.79	2.68	33.97	44.89	271.78	-48.50	5.83	-12.75	0.14
8	0.74	6.65	0.69	3.85	0.98	0.90	43.22	43.76	273.45	-48.20	5.92	-10.33	0.09
9	0.67	7.23	0.62	3.75	0.82	1.98	35.60	48.10	273.31	-48.73	3.41	-9.71	0.13
10	0.52	6.48	0.59	4.52	0.77	3.21	42.99	49.70	271.99	-49.12	2.67	-8.92	0.10
11	0.48	8.92	0.64	4.03	0.72	1.43	37.80	35.32	266.10	-48.53	1.97	-7.61	0.14
12	0.39	9.82	0.72	5.42	0.84	2.40	46.39	37.99	265.88	-48.73	1.89	-6.73	0.11
13	0.56	5.62	0.74	3.89	0.92	2.79	30.94	36.74	273.18	-48.73	4.91	-12.63	0.08
14	0.62	4.37	0.67	3.98	0.81	3.15	39.22	37.20	273.65	-48.73	6.73	-10.05	0.07
15	0.47	6.91	0.63	3.86	0.79	1.78	39.97	45.32	268.88	-48.73	3.17	-8.26	0.09
16	0.51	7.37	0.72	2.78	0.82	2.23	42.69	38.88	272.33	-48.73	7.12	-13.76	0.06
17	0.43	6.89	0.75	3.02	0.88	2.79	35.22	40.94	273.28	-48.73	5.29	-14.48	0.12

Figure 6.10 illustrates the mean effects plots for various parameters related to sustainability and cost optimization. Figure 6.10 (a) depicts the mean effects plot for W, where Signal-to-Noise Ratio (SNR) values range from approximately 4 dB to 9 dB, with factor E achieving the highest SNR at Level 1, while others fluctuate. Figure 6.10 (b) shows the mean effects plot for OW, with SNR values spanning 2 dB to 5 dB, where factor E follows a decreasing trend, while factors A, B, and D exhibit fluctuations. In Figure 6.10 (c), the mean effects plot for OL shows SNR values between 1 dB and 5 dB, with factor B increasing, whereas factor E declines from Level 1 to Level 2 before stabilizing.

Figure 6.10 (d) presents the mean effects plot for carbon dioxide emissions, where SNR values range from 25 dB to 31 dB, with factor B achieving the highest SNR at Level 2 while factor E declines. Figure 6.10 (e) represents material cost, with SNR values varying from 36 dB to 44 dB, where factor E steadily declines while factor D exhibits an increasing trend. Lastly, Figure 6.10 (f) illustrates electricity cost, with SNR values ranging between -48.8 dB and -48.6 dB, showing a significant drop for factor E, while other factors remain relatively stable. Overall, the variations in SNR values across different parameters indicate the differing influence of factors A, B, C, D, and E, highlighting distinct trends in cost and environmental parameters. Table 6.5 depicts all the multi objective optimal constraints.

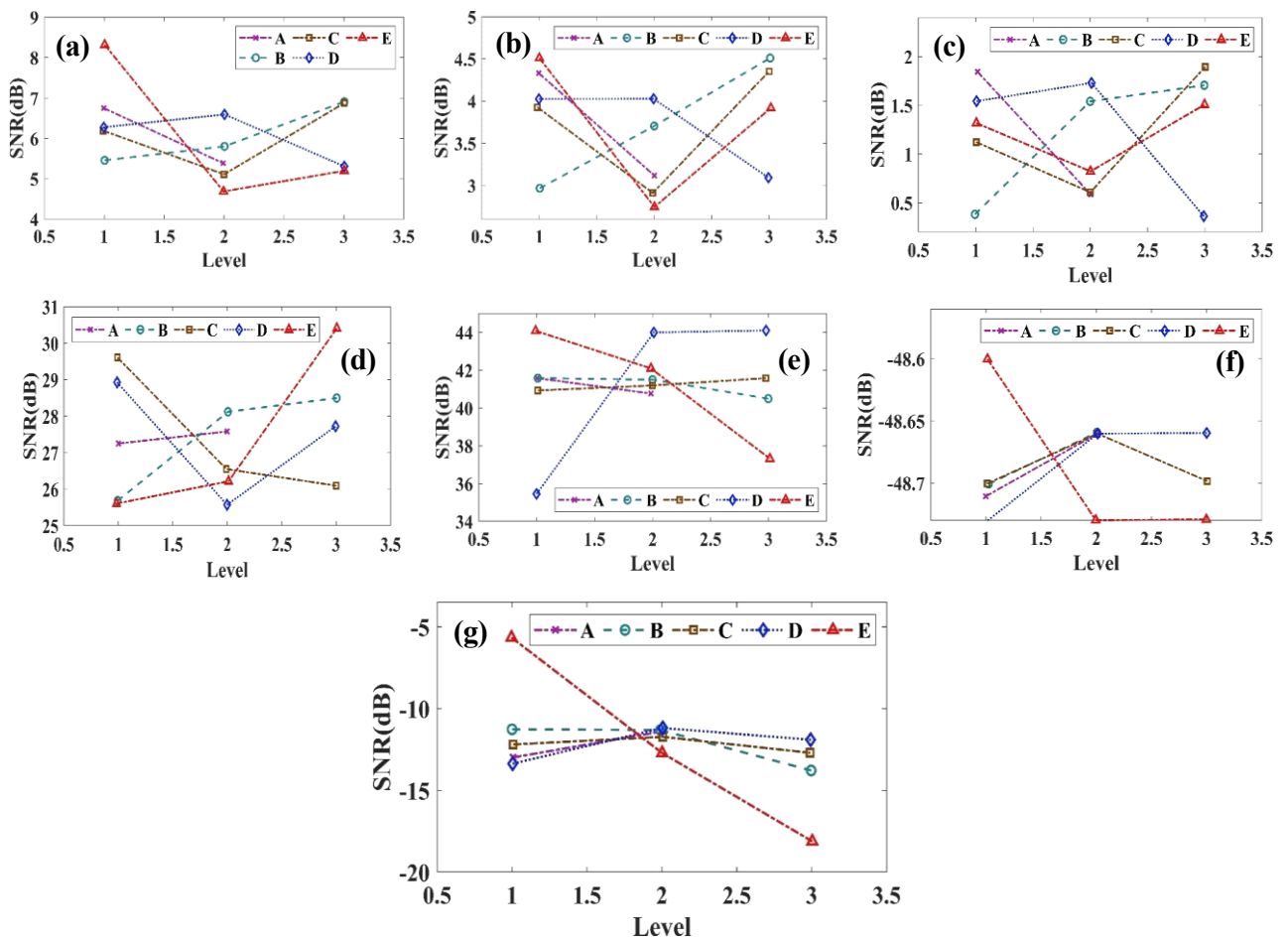


Figure 6.10 Mean effects plot: (a) W (Weight), (b) OW (Operational Waste), (c) OL (Overlapping Layers) (e) carbon dioxide emissions, (f) material cost, (g) labour cost, (h) electricity cost

Figure 6.11 represents the impact of different factors (A, B, C, D, and E) to the SNR for various sustainability and cost parameters, such as W, OW, OL, CO₂ emissions, material cost, labor cost, and electricity cost. Each bar is stacked with different colors indicating the proportion of each factor's influence, with the purple section representing the error component. The contributions vary across parameters, with factor E (cyan) and the error component having a significant influence in most cases, while other factors show varying degrees of impact.

Table 6.5 All multi objective optimal constraints

Multi-objective	Goal	Weighting Strategy	Best Parameters
1	Precision in Dimensions	Evenly Distributed	A, B, C, D, E
2	Precision in Dimensions and Emissions Reduction	Ranges from 2:8 to 8:2	
3	Printing Expenditure	Equally Distributed	
4	Precision in Dimensions and Printing Expenditure	Ranges from 3:7 to 7:3	
5	Precision, Emission Reduction, and Cost Minimization	7:2:1	

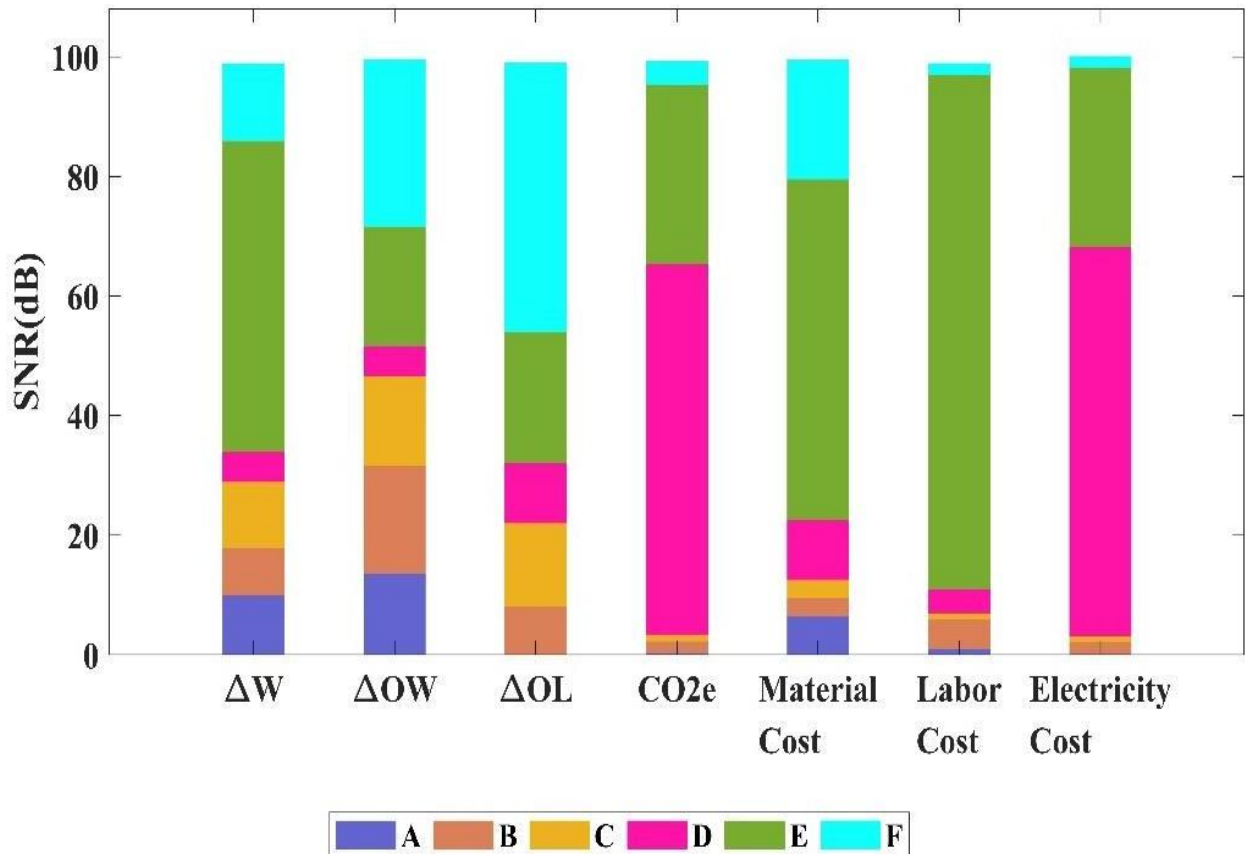


Figure 6.11 Impact of variables of all single objectives

6.3.3 Mechanical Analysis

The mechanical optimization and sustainability analysis in 3D printing is centered on Young's modulus, wear rate, and hardness to assess material performance and longevity. Optimization of

these properties provides structural integrity, minimizes material wastage, and maximizes sustainability through the enhancement of component lifespan and efficiency.

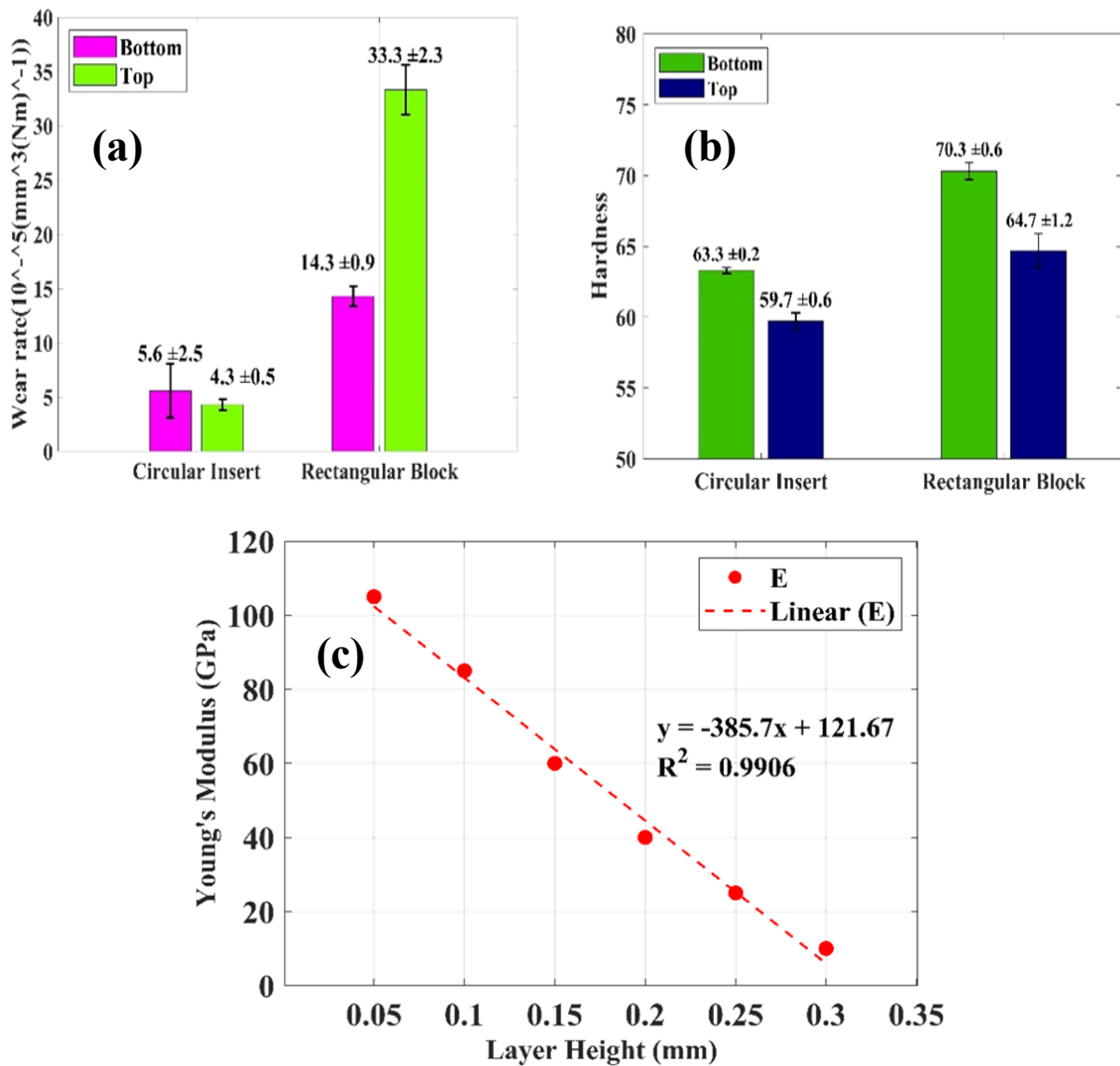


Figure 6.12 Mechanical analysis of (a) Wear rate (b) Hardness (c) Young's Modulus

Figure 6.12 presents the mechanical analysis of wear rate, hardness, and Young's modulus. In Figure 6.12 (a), wear rate is higher for the rectangular block (33.3 ± 2.3) compared to the circular insert (5.6 ± 2.5 for the bottom and 4.3 ± 0.5 for the top). Figure 6.12 (b) shows hardness values, where the rectangular block exhibits higher hardness (70.3 ± 0.6 for the bottom and 64.7 ± 1.2 for the top) compared to the circular insert (63.3 ± 0.2 for the bottom and 59.7 ± 0.6 for the top). Figure 6.12 (c) illustrates the variation of young's modulus with layer height, following a linear trend ($y = -385.7x + 121.67$) with an R^2 value of 0.9906, indicating a strong negative correlation. Table 6.6 depicts the means for energy consumed.

Figure 6.13 denotes the printed material coefficient of friction analysis on a measured length. The coefficient of friction in the material which is tested first is higher and more variable with values between 0.09 and 0.1. The second material has a more stable and minimum coefficient of friction

with values from 0.07 to 0.08. Both materials exhibit the starting fluctuations before approaching a relatively stable state, with the initial material maintaining consistently maximum levels of friction throughout the distance.

Table 6.6 Means for energy consumed

Parameter	DF	Sum Sq.	Adjusted Sum Sq.	Mean Sq.	F-Value	P-Value	% Impact
Layer Depth	2	0.1923	0.1923	0.0956	7.85	0.041	6.25
Infill Design	2	0.2396	0.2396	0.1198	9.15	0.029	7.85
Angle of Orientation	2	1.0521	1.0521	0.5261	41.8	0.003	33.70
Print Direction	2	1.1452	1.1452	0.5726	45.6	0.001	36.72
Base Position	2	0.3715	0.3715	0.1857	14.3	0.017	12.15
Layer Depth * Infill Design	2	0.0093	0.0093	0.00465	1.02	0.897	0.32
Layer Depth * Angle of Orientation	2	0.0372	0.0372	0.0186	0.73	0.582	1.27
Layer Depth * Print Direction	2	0.0681	0.0681	0.01703	1.35	0.412	2.22
Error	4	0.0516	0.0516	0.0129	-	-	-
Total	26	3.1654	-	-	-	-	-

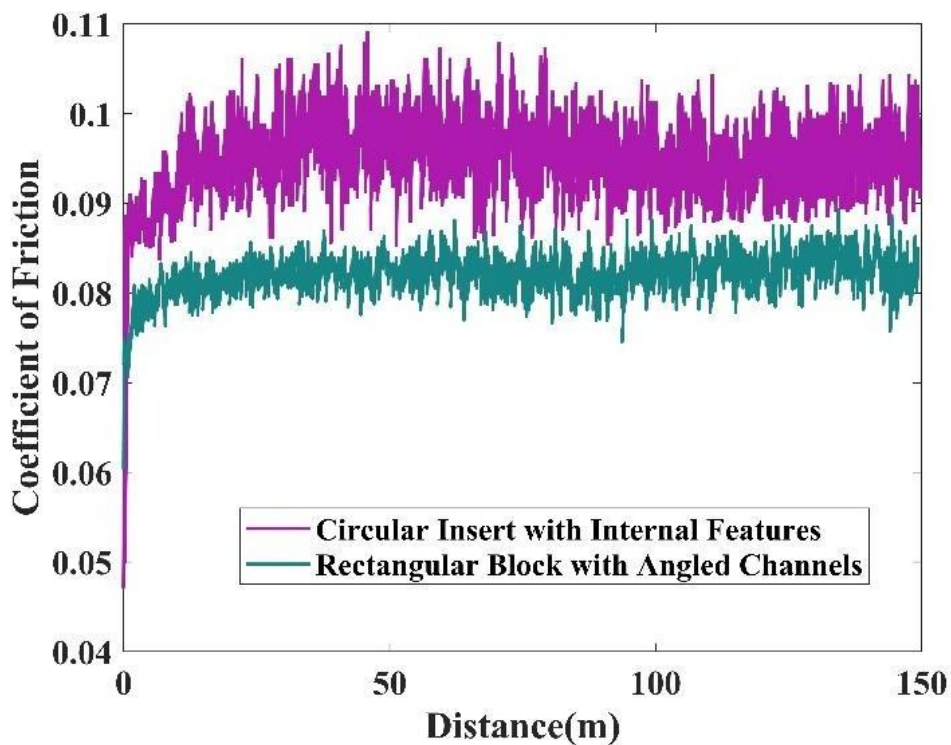


Figure 6.13 Analysis of coefficient of friction of printed materials

This chapter points to the application of 3D/4D printing in product development, focusing on role in DfM and DfAM. It is analysed through mechanical analysis that the selection of the material has a noteworthy effect on durability and performance. The wear rate test proved that rectangular blocks had a greater wear rate of 33.3, while circular inserts had lower readings of 5.6 and 4.3 for bottom and top sections, respectively. Hardness testing proved that rectangular blocks recorded better hardness readings of 70.3 and 64.7 against circular inserts with 63.3 and 59.7. The Young's modulus variation with layer thickness had a good impact on linear relationship with an R^2 of 0.9906, providing a significant influence of layer thickness on mechanical strength property. In comparison to conventional manufacturing, 3D and 4D printing exhibited greater efficiency through minimizing material wastage and enhancing assembly accuracy. The outcomes highlight the imperative of design strategies being optimized with DfA, DfM, and DfAM to ensure superior performance and variability in applications. Finally, the research highlights additive manufacturing's capacity for achieving cost-effective, sustainable high-performance design.

CHAPTER- 7

CHAPTER 7: RESULTS AND ANALYSIS

Advanced printing is subjected to factors such as build capacity, build smoothness, and printing resolution, and more, ideally depending on the kind of printer used for prototype. This literature explains that, out of all printers, FDM uniquely provides the user with affordability, simplicity in setup and operation, and printing at the necessary resolution. Even though, it has difficulties with interfacial bonding (such as stress spots, delamination, porosity, and voids) during the integration of different materials. Furthermore, because of thermal concerns, the material extruder head needs to be changed often during the Fused Deposition Modeling process. These limitations are linked to the efficiency of fabrication and have a direct effect on expense of AM, which includes labor expenses for post- processing requirements, equipment maintenance costs, and material costs. Recently integrated AM processing with SLA/ DLP, and multi-material printers, and Continuous Liquid Interface Production (CLIP) interface techniques offer significant resolution and precision which mitigate the previously described drawback related with cost. Moreover, Cu-based SMA is less expensive and simpler to work during post-printing procedures. Based on research of 3D/4D printing market, reached investments around USD 63 million in 2019 and significantly anticipated increase to 537 million USD in 2025 because of current advancements in the cost effectiveness with integrated fabrication process. Wire & Arc AM's (WAAM) scalability and cost-effectiveness make it ideal for quick prototyping and on-demand manufacturing, with shorter lead times and less material waste.

With the help of the newest integrated fabrication techniques, such as LWMAM, DLP, SLS, and EBM in line with AI, ML, IoT, and augmented reality techniques, optimized designing and accurate manufacturing with the participation of intelligence materials is necessary to enhance the precision and caliber of items that are 3D/4D printed. Researchers usually use graded metamaterial design concepts to improve quality from a structural point of view. It illustrates various ML based optimizing strategies for 3D/4D printing. Inkjet based printers give the customer the option to print with several materials and colors. Additionally, ink jet provides non-porosity build-up, a high gloss and surface smoothness, rapid printing, and the arrangement of components in a gradient rather than chunks with discernible distinction. The most popular gradient elements include material, wall thickness, variety of cell design, etc. As a result, the material's ability to absorb energy is increased, also impact and blast loads are reduced. Furthermore, gradient items in steady-state structures enable multi-stability effects that possesses mechanically as well as additional physiological features such as resolution, surface finish of the stable state of metamaterial arrays in recent years.

3D/4D printing also facing some challenges due to the inability to forecast the changes that 4D printed items undergo over time and in various environments, designers and engineers require advanced modelling and simulation tools. Understanding material behaviour is essential for designers and engineers want to model and simulate 3D/4D printed things. This calls for an understanding of the molecular and microstructural characteristics of 3D/4D materials as well as the capacity to precisely simulate how it behaves in various scenarios. The development of simulators for 3D/4D printed items is challenging. The intricate relationships between the materials, printing process, and object stimuli must be taken into consideration by latest technologies. Fabrication complexities such as scalability, resolution and accuracy also exist in the current stage. In-situ alloy production at the interface of bi-materials is challenging to define due to its non-equilibrium nature. Defects at grain boundaries, such as microcracks, are common during the process of printing metal materials. Besides, problems including inadequate interfacial bonding, poor surface quality and scalability, high levels of cross-contamination, and restricted manufacturing throughput. Technical advancements, including the creation of CAD programs, protocols, and processes, are necessary in addition to fundamental comprehension.

The problems associated with the industrial-based 3D/4D printer's scaling-up operation is examined, along with its implications for product quality and total cost. These include design and simulation-related concerns. Moreover, interpretation is essential to efficiently and successfully accomplishing design goals in large-scale 3D/4D production. To make sure that the manufactured goods fulfil the required criteria, designers must properly comprehend the design specifications. When dealing with large volumes of data such as CAD models, modeling outcomes, sensor data etc. Interpretation is critical for making educated decisions over the process of manufacturing, from choice of materials to process optimization in supply chain management. Designing goods that provide value and satisfaction requires a thorough understanding of end consumer's need and preferences. When it comes to material characteristics, purpose of design, sustainability consideration, and future trends, interpretation aids in translating the findings of feedback from consumers, market patterns, and accessibility research into practical design improvements that support the overall design goals in the application fields of 3D/4D printing. Moreover, because of the emerging importance of bulk production in industries like soft robotics. The present rareness of postponement applications of in real-world situations is projected to change as industries increasingly employ large-scale 3D/4D printing technologies to increase supply chain efficiency, flexibility, and response to altering market needs.

The research effectively addresses the challenges in laser metal wire deposition by optimizing deposition conditions and parameters to enhance material efficiency and control over deposition characteristics. Key findings include that material use efficiency remains high under stable

deposition conditions but declines with increased fluence levels. For instance, efficiency drops due to higher fume and dross production at fluence levels above 59 J/mm^2 . Multi-layer deposition shows improved efficiency within a narrower fluence range, particularly between 30.25 and 32.46 J/mm^2 . The coefficient of friction increases with higher scanning speeds, such as rising from 0.7 to 0.74 at lower sliding velocities of 0.5 m/sec . Higher power levels significantly boost deposition rates, with the rate increasing from $500 \text{ mm}^3/\text{min}$ at 1000 W to $900 \text{ mm}^3/\text{min}$ at 1400 W . Hardness measurements indicate variability at different scanning speeds but achieve overall stability. XRD analysis confirms high crystallinity and phase integrity, maintaining material quality effectively.

Adopting 3D/4D printing technology with HVDP concepts gives optimism for revolutionary SC dynamics based on empirical study findings. Also, it provides additional benefits such as increased efficiency, customization, and sustainability. With the potential benefits of technological breakthroughs and integrated operations, identifying long-term goals for implementing 3D/4D printing technologies and connecting them with the overall company plan is critical. Evaluating the maturity of relevant 3D/4D printing technologies in terms of material compatibility, production adoption speed, and scalability to determine the usefulness for business also plays a major role. Furthermore, including design for manufacturability, sustainability, and customization in the product development process considerably improves performance. Incorporating 3D/4D printing technology with an HVDP approach may transform SC dynamics, allowing organizations to achieve considerable efficiency, cost savings, and increased customer satisfaction. The analysis findings validated the integrated adoption of the AM and addressed the research hypothesis H1. Similarly, research hypothesis H2 is addressed, and SC dynamics improvement is transformed by high-value principles with a positive correlation. Additionally, it appears that the high value principle integration with SC resilience and efficiency, as indicated by hypotheses H3 and H4, indicates significant increases in performance. The defined strategy framework offers a complete approach to implementing these technologies, ranging from harmonizing organizational vision to promoting innovation and forming collaborations. Following this approach allows organizations to efficiently use 3D/4D printing to alter their operations and ensure long term success in an increasingly competitive market.

The research points to the use of 3D and 4D printing in product development, focusing on role in DfM and DfAM. It is analysed through mechanical analysis that the selection of the material has a noteworthy effect on durability and performance. The wear rate test proved that rectangular blocks had a greater wear rate of 33.3 , while circular inserts had lower readings of 5.6 and 4.3 for bottom and top sections, respectively. Hardness testing proved that rectangular blocks recorded better hardness readings of 70.3 and 64.7 against circular inserts with 63.3 and 59.7 . The Young's modulus variation with layer thickness had a good impact on linear relationship with an R^2 of 0.9906 ,

providing a significant influence of layer thickness on mechanical strength property. In comparison to conventional manufacturing, 3D and 4D printing exhibited greater efficiency through minimizing material wastage and enhancing assembly accuracy. The outcomes highlight the imperative of design strategies being optimized with DfA, DfM, and DfAM to ensure superior performance and variability in applications. Finally, the research highlights additive manufacturing's capacity for achieving cost-effective, sustainable high-performance design.

CHAPTER- 8

CHAPTER 8: CONCLUSION, FUTURE SCOPE AND SOCIAL IMPACT

8.1 INTRODUCTION

The 3D/4D printing is an emerging structure creation process that allows for form morphing in response to external triggering chemicals. Currently, many research focuses on small to medium size 3D/4D printing of structures. As a result, to build industry-based large-scale structures, printing capabilities must be increased without sacrificing quality, cost, and speed. Advances in computer-aided design modeling have led to the development of 3D/4D products, which are essential for the large-scale manufacture of structures for various engineering purposes. Supply chain management might undergo a radical change as a result of 3D/4D printing, as it allows for localized manufacturing, shorter times of lead, and lower costs of inventory. To efficiently satisfy production demands in light of the present demand for customized products, a more responsive, adaptive, efficient, flexible, and cost-effective supply chain is needed. Additionally, 3D/4D printing introduces the creation of objects that change shape or function over a time basis, adding a layer of functionality that enhances the product performance and lifecycle management. Furthermore, conventional manufacturing methods have always been riddled with shortcomings such as wastage of material, design limitations, and added cost of manufacturing. Conventional methods fail to work efficiently with complex geometries, leading to wasteful use of material and longer production time. In contrast to this, the advent of 3D and 4D printing eliminated such shortcomings by improving design freedom, minimizing waste, and enhancing the manufacturing process.

8.2 MAJOR FINDINGS

This research highlights the significant potential of LMWD as an advanced AM technique for creating complex solid structures with high precision and material efficiency. By focusing on the single deposition technique within LMWD, the material usage and calculated DEC, considering critical factors such as wire feed rate, laser power, and deposition speed, are evaluated. Detailed analysis revealed that the coefficient of friction increases with higher scanning speeds, with a more pronounced impact at lower sliding velocities. Additionally, notable fluctuations in deposition rate and hardness are observed, particularly at the lowest scanning speed. Moreover, an effect analysis of supply chain dynamics during the adoption of the 3D/4D printing AM method and HVDP concepts is done by using a simulated model. The performance effectiveness of the adoption integration is

presented by using metrics like cost reduction, lead times, inventory levels, and environmental impact. Practical applications across sectors such as automotive, healthcare, and aerospace possibly shown successful implementations of proposed integration technologies, showcasing their ability to accelerate time-to-market for high-value products and foster a more adaptive and efficient supply chain model. The research points to the use of 3D and 4D printing in product development, focusing on the role in DfM and DfAM. It is analysed through mechanical analysis that the selection of the material has a noteworthy effect on durability and performance.

8.3 FINDINGS REGARDING EFFICIENT PRODUCTION AND MATERIAL WASTAGE

The research work found that the coefficient of friction increased slightly with scanning speed, rising from 0.7 at 0.4 m/min to 0.74 at 0.6 m/min, and showed a smaller increase from 0.68 to 0.685 at 1 m/sec. Higher power levels significantly boosted deposition rates, particularly at 0.4 m/min, where it rose from 500 mm³/min at 1000 W to 900 mm³/min at 1400 W. Hardness measurements varied with scanning speed, showing higher and more variable values at lower speeds. XRD analysis confirmed distinct peaks for Fe, Ni, Cr, and Mo phases in SS316, indicating high crystallinity and maintained material integrity post-3D printing. These findings emphasize the necessity of optimizing deposition parameters to enhance DEC, leading to more efficient production processes with minimal material wastage.

8.4 FINDINGS REGARDING COST-EFFECTIVE SUPPLY CHAIN

The research provided a strategic framework for businesses looking to adopt 3D/4D printing technologies, positioning them to drive manufacturing innovation and reshape global supply chain landscapes towards sustainable, HVDP-driven models. The case study based empirical research has proven possible transformative improvements when adopting high-value design and optimizing supply chain dynamics by enhancing performance metrics like lead time, inventory levels, efficiency, flexibility, environmental sustainability, and customization capabilities. This localized production capability reduces lead times by 65% and transportation costs by 67%, resulting in more responsive and agile supply chains.

8.5 FINDINGS REGARDING SUSTAINABILITY AND COST OPTIMIZATION

The research points to the use of 3D and 4D printing in product development, focusing on role in DfM and DfAM. It is analysed through mechanical analysis that the selection of the material has a

noteworthy effect on durability and performance. The wear rate test proved that rectangular blocks had a greater wear rate of 33.3, while circular inserts had lower readings of 5.6 and 4.3 for bottom and top sections, respectively. Hardness testing proved that rectangular blocks recorded better hardness readings of 70.3 and 64.7 against circular inserts with 63.3 and 59.7. The Young's modulus variation with layer thickness had a good impact on the linear relationship with an R^2 of 0.9906, providing significant influences of layer thickness on mechanical strength property.

8.6 CONCLUDING REMARKS

These findings emphasize that process parameters must be optimized to decrease material waste and increase deposition efficiency, which is presently 90%. In comparison to conventional manufacturing, 3D and 4D printing exhibited greater efficiency through minimizing material wastage and enhancing assembly accuracy. The outcomes highlight the imperative of design strategies being optimized with DfA, DfM, and DfAM to ensure superior performance and variability in applications. Finally, the research highlights additive manufacturing's capacity for achieving cost-effective, sustainable, high-performance design.

8.7 SIGNIFICANCE OF THE STUDY

The importance of this study is rooted in its thorough exploration of LMWD, which is a game-changing method for additive manufacturing of intricate solid structures. By homing in on optimizing process parameters to boost material properties and structural integrity, this research plays a key role in pushing forward metal additive manufacturing technologies for high-performance uses. The paper emphasizes the interesting possibilities of decentralized, on-demand manufacturing motivated by creative design ideas and investigates further the role of 3D and 4D printing could radically change supply chain dynamics.

The study also discusses important topics related to cost optimization and sustainability in 3D/4D printing. The study offers a systematic framework to pinpoint the underlying causes of manufacturing inefficiencies and defects, directing focused interventions for quality improvement through the use of fishbone diagrams for printability improvement. When taken as a whole, the results provide insightful information for the manufacturing scaling of additive manufacturing innovations, encouraging design, sustainability, and manufacturing effectiveness innovation.

8.8 FUTURE SCOPE

Future works must be oriented towards optimizing some critical process parameters, such as scanning speed, laser power, and feed rate, to strike a balance among the deposition rate, mechanical

properties, and COF in LMWD. Studies on hardness uniformity, real-time monitoring of the process, variations in alloy composition, and post-processing treatments can significantly contribute toward better quality and reliability of parts. Moreover, research into multi-material deposition methodologies and long-term durability testing could broaden LMWD applications toward frontier manufacturing. Furthermore, the integration of advanced control systems with a real-time monitoring approach is necessary for enhancing the accuracy and reproducibility of LMWD processes. It is also advised that large-scale mechanical analysis and validation tests be carried out to serve as a validation step for testing the predictive ability of current optimization models.

Within this broad framework of additive manufacturing differential emergence, especially of 3D and 4D printing, future studies can ascertain their transformative effects on supply chain dynamics. This decentralization associated with additive manufacturing can automatically lead to localized production distributed across a few centers: Lowering lead times, reducing inventory costs while bolstering demand responsiveness. Research in this regard can focus on creating high-value design concepts that take full advantage of 3D/4D printing capabilities of customization and on-demand production to reinvent the traditional supply chain.

Sustainability and cost would increasingly remain concerning themes. Future research may thus employ a fishbone diagram approach to systematically identify and analyze factors affecting printability, materialized utilization, and process efficiencies, with these fishbone diagrams providing visualization aids to pinpointing root causes of print defects or inefficiencies, thereby enabling interventions targeted towards improving overall manufacturing performance.

Moreover, it is necessary to create comprehensive environmental sustainability frameworks and design guidelines specific to additive manufacturing. This includes the assessment of long-term environmental impacts posed by AM technologies, along with determining the amount of energy consumed, material waste generated, and product recyclability at the end of its life cycle. From the perspective of potential growth, further investigation into up-scaling LMWD and 3D/4D printing for large-size, complex structures, in airports, automotive, biomedical, and construction, needs to be carried out.

There would be the potential for concern for intelligent AM systems in the future, where machine learning will be used for process optimization, the potential for self-healing materials in 4D printing, and digital twins for simulation and prediction of build outcomes. With this, it is thought that the capability and commercialization of AM can be boosted as a mainstream manufacturing technology in various industrial sectors.

8.9 SOCIAL IMPACT

The presented work in this thesis has resulted in significant outcomes with both scientific and societal implications. This achievement directly aligns with the United Nations Sustainable Development Goal (SDG).

These 3D/4D printing technology increases industry-based large-scale structures without sacrificing quality, cost, and speed which are essential for the manufacture of large-scale structures for various engineering purposes. Hence thereby contributing to SDG 13: Climate Action and environmental anomalies and support for sustainable management of natural resources.

The compact, cost-effective, and scalable design of these structures ensures wide accessibility and feasibility for large-scale implementation across diverse sectors.

The technological innovations developed through this research also resonate with SDG 9: Industry, Innovation, and Infrastructure, by promoting indigenous technological advancement in the field of 3D/4D printing technology. The emphasis on utilizing locally available materials and scalable fabrication processes aligns with the vision of the “Make in India” initiative, fostering domestic innovation, reducing reliance on imported technologies, and strengthening national capacity in healthcare, environmentally sustainable, and industrial applications.

Furthermore, the work contributes indirectly to SDG 4: Quality Education, by advancing scientific knowledge in the interdisciplinary domains of science and technology. The research outcomes enrich academic curricula, inspire new student-led investigations, and build technical competencies that prepare future researchers, designers and engineers to address global scientific and societal challenges.

The methodologies, frameworks, and design principles developed in this thesis can serve as educational tools for training designers in academia and industry. Collectively, these outcomes highlight the broader and long-lasting societal relevance of the work.

The thesis not only contributes to the advancement of science and technology but also strengthens the link between research innovation and sustainable societal development. In particular, it demonstrates that high-value designs can serve as transformative tools for improving and protecting the environment, promoting local manufacturing, and fostering design excellence, thereby contributing meaningfully to several United Nations Sustainable Development Goals, most notably SDG 3, SDG 4, SDG 9, and SDG 13.

REFERENCES

- [1] Shinde, S., Mane, R., Vardikar, A., Dhumal, A. and Rajput, A., 2023. 4D printing: From emergence to innovation over 3D printing. *European Polymer Journal*, 197, p.112356.
- [2] Farid, M.I., Wu, W., Liu, X. and Wang, P., 2021. Additive manufacturing landscape and materials perspective in 4D printing. *The International Journal of Advanced Manufacturing Technology*, 115, pp.2973-2988.
- [3] Javaid, M., Haleem, A., Singh, R.P., Rab, S., Suman, R. and Kumar, L., 2022. Significance of 4D printing for dentistry: Materials, process, and potentials. *Journal of Oral Biology and Craniofacial Research*, 12(3), pp.388-395.
- [4] Goo, B., Hong, C.H. and Park, K., 2020. 4D printing using anisotropic thermal deformation of 3D-printed thermoplastic parts. *Materials & Design*, 188, p.108485.
- [5] Subash, A. and Kandasubramanian, B., 2020. 4D printing of shape memory polymers. *European Polymer Journal*, 134, p.109771.
- [6] Wang, J., Lin, X., Wang, R., Lu, Y. and Zhang, L., 2023. Self-healing, photothermal-responsive, and shape memory polyurethanes for enhanced mechanical properties of 3D/4D printed objects. *Advanced Functional Materials*, 33(15), p.2211579.
- [7] Tan, H.W., Choong, Y.Y.C., Kuo, C.N., Low, H.Y. and Chua, C.K., 2022. 3D printed electronics: Processes, materials and future trends. *Progress in Materials Science*, 127, p.100945.
- [8] Kumar, N., Ramakrishnan, S.A., Lopez, K.G., Chin, B.Z., Kumar, L., Baskar, S., Vellayappan, B.A., Fuh, J.Y.H. and Anantharajan, S.K., 2022. Current trends and future scope in 3D printing for surgical management of spine pathologies. *Bioprinting*, 26, p.e00197.
- [9] Acanfora, V., Sellitto, A., Russo, A., Zarrelli, M. and Riccio, A., 2023. Experimental investigation on 3D printed lightweight sandwich structures for energy absorption aerospace applications. *Aerospace Science and Technology*, 137, p.108276.
- [10] Alami, A.H., Olabi, A.G., Alashkar, A., Alasad, S., Aljaghoub, H., Rezk, H. and Abdelkareem, M.A., 2023. Additive manufacturing in the aerospace and automotive industries: Recent trends and role in achieving sustainable development goals. *Ain Shams Engineering Journal*, 14(11), p.102516.
- [11] Haleem, A. and Javaid, M., 2020. 3D printed medical parts with different materials using additive manufacturing. *Clinical Epidemiology and Global Health*, 8(1), pp.215-223.
- [12] Ong, J.J., Castro, B.M., Gaisford, S., Cabalar, P., Basit, A.W., Pérez, G. and Goyanes, A., 2022. Accelerating 3D printing of pharmaceutical products using machine learning. *International Journal of Pharmaceutics: X*, 4, p.100120.
- [13] Wei, P., Yang, X., Cao, Z., Guo, X.L., Jiang, H., Chen, Y., Morikado, M., Qiu, X. and Yu, D., 2019. Flexible and stretchable electronic skin with high durability and shock resistance via embedded

- 3D printing technology for human activity monitoring and personal healthcare. *Advanced Materials Technologies*, 4(9), p.1900315.
- [14] Furet, B., Poullain, P. and Garnier, S., 2019. 3D printing for construction based on a complex wall of polymer-foam and concrete. *Additive Manufacturing*, 28, pp.58-64.
- [15] Ning, X., Liu, T., Wu, C. and Wang, C., 2021. 3D printing in construction: current status, implementation hindrances, and development agenda. *Advances in Civil Engineering*, 2021(1), p.6665333.
- [16] Rouf, S., Malik, A., Singh, N., Raina, A., Naveed, N., Siddiqui, M.I.H. and Haq, M.I.U., 2022. Additive manufacturing technologies: Industrial and medical applications. *Sustainable Operations and Computers*, 3, pp.258-274.
- [17] Haleem, A. and Javaid, M., 2019. Polyether ether ketone (PEEK) and its manufacturing of customised 3D printed dentistry parts using additive manufacturing. *Clinical Epidemiology and Global Health*, 7(4), pp.654-660.
- [18] Altıparmak, S.C., Yardley, V.A., Shi, Z. and Lin, J., 2021. Challenges in additive manufacturing of high-strength aluminium alloys and current developments in hybrid additive manufacturing. *International Journal of Lightweight Materials and Manufacture*, 4(2), pp.246-261.
- [19] Prabhu, R., Simpson, T.W., Miller, S.R. and Meisel, N.A., 2022. Mastering manufacturing: exploring the influence of engineering designers' prior experience when using design for additive manufacturing. *Journal of Engineering Design*, 33(5), pp.366-387.
- [20] Liverani, A., Caligiana, G., Frizziero, L., Francia, D., Donnici, G. and Dhaimini, K., 2019. Design for Six Sigma (DFSS) for additive manufacturing applied to an innovative multifunctional fan. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 13, pp.309-330.
- [21] Darabi, R., Reis, A. and Cesar de Sa, J., Exploring the Dynamic Transition from Aging to Additive Manufacturing: Investigating Microstructural Evolution of Metastable γ "Precipitates in Inconel 625 through Coupled Phase-Field Simulation. *Advanced Engineering Materials*, p.2402374.
- [22] Abar, B.M., Kelly, C., Allen, N.B. and Gall, K., 2024. Historical perspectives on 3D printing. In *Clinical Applications of 3D Printing in Foot and Ankle Surgery* (pp. 1-16). Elsevier.
- [23] Prashar, G., Vasudev, H. and Bhuddhi, D., 2023. Additive manufacturing: expanding 3D printing horizon in industry 4.0. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 17(5), pp.2221-2235.
- [24] Panchenko, O., Kladoy, I., Kurushkin, D., Zhabrev, L., Ryl'kov, E. and Zamozdra, M., 2022. Effect of thermal history on microstructure evolution and mechanical properties in wire arc additive manufacturing of HSLA steel functionally graded components. *Materials Science and Engineering: A*, 851, p.143569.

- [25] Wang, Z., Lin, X., Kang, N., Chen, J., Tang, Y., Tan, H., Yu, X., Yang, H. and Huang, W., 2021. Directed energy deposition additive manufacturing of a Sc/Zr-modified Al–Mg alloy: effect of thermal history on microstructural evolution and mechanical properties. *Materials Science and Engineering: A*, 802, p.140606.
- [26] Ness, K.L., Paul, A., Sun, L. and Zhang, Z., 2022. Towards a generic physics-based machine learning model for geometry invariant thermal history prediction in additive manufacturing. *Journal of Materials Processing Technology*, 302, p.117472.
- [27] Ljunggren, S.A., Karlsson, H., Ståhlbom, B., Krapic, B., Fornander, L., Karlsson, L.E., Bergström, B., Nordenberg, E., Ervik, T.K. and Graff, P., 2019. Biomonitoring of metal exposure during additive manufacturing (3D printing). *Safety and health at work*, 10(4), pp.518-526.
- [28] Carneau, P., Mesnil, R., Roussel, N. and Baverel, O., 2020. Additive manufacturing of cantilever-From masonry to concrete 3D printing. *Automation in Construction*, 116, p.103184.
- [29] Jiménez, M., Romero, L., Domínguez, I.A., Espinosa, M.D.M. and Domínguez, M., 2019. Additive manufacturing technologies: an overview about 3D printing methods and future prospects. *Complexity*, 2019(1), p.9656938.
- [30] Roy, M. and Wodo, O., 2020. Data-driven modeling of thermal history in additive manufacturing. *Additive Manufacturing*, 32, p.101017.
- [31] Jung, Y.S., Park, J., Lee, S. and Shin, E.J., 2025. Characterization of thermo-responsive shape memory bio-based thermoplastic polyurethane (SMTPU) for 3D/4D printing applications. *Fashion and Textiles*, 12(1), p.3.
- [32] Zeng, S.Y., Wang, Y.T., Zheng, H., Gao, Y.C., Wang, L.P. and Tan, J.R., 2025. Design and realization of multiunit functional primitives based on 4D printing. *Advances in Manufacturing*, pp.1-16.
- [33] Yousefi, M.A., Rahmatabadi, D., Baniassadi, M., Bodaghi, M. and Baghani, M., 2025. 4D printing of multifunctional and biodegradable PLA-PBAT-Fe₃O₄ nanocomposites with supreme mechanical and shape memory properties. *Macromolecular Rapid Communications*, 46(2), p.2400661.
- [34] Bodaghi, M., Rahmani, K., Dezaki, M.L., Branfoot, C. and Baxendale, J., 2025. 3D/4D printed bio-composites reinforced by bamboo charcoal and continuous flax fibres for superior mechanical strength, flame retardancy and recoverability. *Polymer Testing*, p.108709.
- [35] Rahmatabadi, D., Yousefi, M.A., Shamsolhodaei, S., Baniassadi, M., Abrinia, K., Bodaghi, M. and Baghani, M., 2025. 4D Printing of Polyethylene Glycol-Grafted Carbon Nanotube-Reinforced Polyvinyl Chloride–Polycaprolactone Composites for Enhanced Shape Recovery and Thermomechanical Performance. *Advanced Intelligent Systems*, p.2500113.

- [36] He, L., 2025. 3D and 4D Printing of Polyethylene Terephthalate Glycol–Polypropylene Blends. *Journal of Applied Polymer Science*, p.e56972.
- [37] Bouguermouh, K., Habibi, M., Laperrière, L., Li, Z. and Abdin, Y., 2025. Designing advanced 4D printing thermo-sensitive shape memory polymer blends for enhanced mechanical and shape memory performances. *Progress in Additive Manufacturing*, pp.1-20.
- [38] Tawk, C., Spinks, G.M., in het Panhuis, M. and Alici, G., 2019. 3D printable linear soft vacuum actuators: their modeling, performance quantification and application in soft robotic systems. *IEEE/ASME Transactions on Mechatronics*, 24(5), pp.2118-2129.
- [39] Javaid, M. and Haleem, A., 2020. Significant advancements of 4D printing in the field of orthopaedics. *Journal of Clinical Orthopaedics and Trauma*, 11, pp.S485-S490.
- [40] Pandey, A., Singh, G., Singh, S., Jha, K. and Prakash, C., 2020. 3D printed biodegradable functional temperature-stimuli shape memory polymer for customized scaffoldings. *Journal of the Mechanical Behavior of Biomedical Materials*, 108, p.103781.
- [41] Tu, H., Wei, Z., Bahrami, A., Kahla, N.B., Ahmad, A. and Özkılıç, Y.O., 2023. Recent advancements and future trends in 3D concrete printing using waste materials. *Developments in the Built Environment*, 16, p.100187.
- [42] Zhu, Y., Tang, T., Zhao, S., Joralmon, D., Poit, Z., Ahire, B., Keshav, S., Raje, A.R., Blair, J., Zhang, Z. and Li, X., 2022. Recent advancements and applications in 3D printing of functional optics. *Additive Manufacturing*, 52, p.102682.
- [43] Mostafaei, A., Elliott, A.M., Barnes, J.E., Li, F., Tan, W., Cramer, C.L., Nandwana, P. and Chmielus, M., 2021. Binder jet 3D printing—Process parameters, materials, properties, modeling, and challenges. *Progress in Materials Science*, 119, p.100707.
- [44] Chen, G., Liang, X., Zhang, P., Lin, S., Cai, C., Yu, Z. and Liu, J., 2022. Bioinspired 3D printing of functional materials by harnessing enzyme-induced biomineralization. *Advanced Functional Materials*, 32(34), p.2113262.
- [45] Guddati, S., Kiran, A.S.K., Leavy, M. and Ramakrishna, S., 2019. Recent advancements in additive manufacturing technologies for porous material applications. *The International Journal of Advanced Manufacturing Technology*, 105, pp.193-215.
- [46] Zeng, S.Y., Wang, Y.T., Zheng, H., Gao, Y.C., Wang, L.P. and Tan, J.R., 2025. Design and realization of multiunit functional primitives based on 4D printing. *Advances in Manufacturing*, pp.1-16.
- [47] Peng, X., Liu, G., Wang, J., Li, J., Wu, H., Jiang, S. and Yi, B., 2023. Controllable deformation design for 4D-printed active composite structure: optimization, simulation, and experimental verification. *Composites Science and Technology*, 243, p.110265.

- [48] Jian, B., Demoly, F., Zhang, Y., Qi, H.J., André, J.C. and Gomes, S., 2022. Origami-based design for 4D printing of 3D support-free hollow structures. *Engineering*, 12, pp.70-82.
- [49] Sun, X., Yue, L., Yu, L., Shao, H., Peng, X., Zhou, K., Demoly, F., Zhao, R. and Qi, H.J., 2022. Machine learning-evolutionary algorithm enabled design for 4D-printed active composite structures. *Advanced Functional Materials*, 32(10), p.2109805.
- [50] Benyahia, K., Seriket, H., Prod'hon, R., Gomes, S., André, J.C., Qi, H.J. and Demoly, F., 2022. A computational design approach for multi-material 4D printing based on interlocking blocks assembly. *Additive Manufacturing*, 58, p.102993.
- [51] Saptaji, K., Wijaya, R.A. and Juniasih, O.A., 2025. Optimizing 4D-printed grippers: the role of finger design and thermal stimulus. *Progress in Additive Manufacturing*, pp.1-14.
- [52] Kong, D., Zhang, M., Mujumdar, A.S. and Luo, Z., 2025. Novel heterogeneous 3D printing process of protein-polysaccharide gel containing orange juice sacs: Optimization of material properties and printing parameters. *International Journal of Biological Macromolecules*, 305, p.141277.
- [53] Ejeromedoghene, O., Kumi, M., Akor, E. and Zhang, Z., 2024. The application of machine learning in 3D/4D printed stimuli-responsive hydrogels. *Advances in Colloid and Interface Science*, p.103360.
- [54] Chen, J., Kong, Y. and Huang, Q., 2024. Analysis of surimi extrusion behavior during 3D printing by modified Computational Fluid Dynamics (CFD) and quick prediction of printability using machine learning based on texture data. *Innovative Food Science & Emerging Technologies*, 94, p.103698.
- [55] de Kergariou, C., Kim, B.C., Perriman, A., Le Duigou, A., Guessasma, S. and Scarpa, F., 2022. Design of 3D and 4D printed continuous fibre composites via an evolutionary algorithm and voxel-based finite elements: application to natural fibre hygromorphs. *Additive Manufacturing*, 59, p.103144.
- [56] Raza, M.H., Besklubova, S. and Zhong, R.Y., 2024. Economic analysis of offsite and onsite 3D construction printing techniques for low-rise buildings: A comparative value stream assessment. *Additive Manufacturing*, 89, p.104292.
- [57] Sartini, M., Favi, C. and Mandolini, M., 2024. Rapid investment casting: a techno-economic analysis for evaluating VAT photopolymerisation processes. *The International Journal of Advanced Manufacturing Technology*, 134(11), pp.5717-5739.
- [58] Alzoubi, L., Aljabali, A.A. and Tambuwala, M.M., 2023. Empowering precision medicine: the impact of 3D printing on personalized therapeutic. *Aaps Pharmscitech*, 24(8), p.228.
- [59] Bahoria, B.V., Bhagat, R.M., Pande, P.B., Raut, J.M., Dhengare, S.W., Mankar, S.H., Vairagade, V.S. and Shelare, S.D., 2025. Design optimization of 3D printed concrete elements considering life

- cycle assessment and life cycle costing. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 19(3), pp.2183-2202.
- [60] Casucci, A., Cagidiaco, E.F., Verniani, G., Ferrari, M. and Borracchini, A., 2025. Digital vs. conventional removable complete dentures: A retrospective study on clinical effectiveness and cost-efficiency in edentulous patients: Clinical effectiveness and cost-efficiency analysis of digital dentures. *Journal of Dentistry*, 153, p.105505.
- [61] Lin, C.W. and Chen, T., 2019. 3D printing technologies for enhancing the sustainability of an aircraft manufacturing or MRO company—a multi-expert partial consensus-FAHP analysis. *The International Journal of Advanced Manufacturing Technology*, 105, pp.4171-4180.
- [62] Han, M., Yang, Y. and Li, L., 2022. Techno-economic modeling of 4D printing with thermo-responsive materials towards desired shape memory performance. *IISE Transactions*, 54(11), pp.1047-1059.
- [63] Weng, Y., Ruan, S., Li, M., Mo, L., Unluer, C., Tan, M.J. and Qian, S., 2019. Feasibility study on sustainable magnesium potassium phosphate cement paste for 3D printing. *Construction and Building Materials*, 221, pp.595-603.
- [64] Shahar, F.S., Sultan, M.T.H., Safri, S.N.A., Jawaid, M., Talib, A.R.A., Basri, A.A. and Shah, A.U.M., 2022. Fatigue and impact properties of 3D printed PLA reinforced with kenaf particles. *Journal of materials research and technology*, 16, pp.461-470.
- [65] Yu, Q., Zhu, B., Li, X., Meng, L., Cai, J., Zhang, Y. and Pan, J., 2023. Investigation of the rheological and mechanical properties of 3D printed eco-friendly concrete with steel slag. *Journal of Building Engineering*, 72, p.106621.
- [66] Wang, Y.C., Chen, T. and Yeh, Y.L., 2019. Advanced 3D printing technologies for the aircraft industry: a fuzzy systematic approach for assessing the critical factors. *The International Journal of Advanced Manufacturing Technology*, 105, pp.4059-4069.
- [67] Olawumi, M.A., Oladapo, B.I. and Olugbade, T.O., 2024. Evaluating the impact of recycling on polymer of 3D printing for energy and material sustainability. *Resources, Conservation and Recycling*, 209, p.107769.
- [68] Nilimaa, J., 2023. Smart materials and technologies for sustainable concrete construction. *Developments in the Built Environment*, 15, p.100177.
- [69] Cisneros-López, E.O., Pal, A.K., Rodriguez, A.U., Wu, F., Misra, M., Mielewski, D.F., Kiziltas, A. and Mohanty, A.K., 2020. Recycled poly (lactic acid)-based 3D printed sustainable biocomposites: a comparative study with injection molding. *Materials Today Sustainability*, 7, p.100027.

- [70] Long, W.J., Tao, J.L., Lin, C., Gu, Y.C., Mei, L., Duan, H.B. and Xing, F., 2019. Rheology and buildability of sustainable cement-based composites containing micro-crystalline cellulose for 3D-printing. *Journal of Cleaner Production*, 239, p.118054.
- [71] Javaid, M., Haleem, A., Singh, R.P., Suman, R. and Rab, S., 2021. Role of additive manufacturing applications towards environmental sustainability. *Advanced Industrial and Engineering Polymer Research*, 4(4), pp.312-322.
- [72] Haleem, A., Javaid, M., Singh, R.P. and Suman, R., 2021. Significant roles of 4D printing using smart materials in the field of manufacturing. *Advanced Industrial and Engineering Polymer Research*, 4(4), pp.301-311.
- [73] Niazy, D., Ashraf, M., Bodaghi, M. and Zolfagharian, A., 2024. Resilient city perspective: 4D printing in art, architecture and construction. *Materials Today Sustainability*, p.100708.
- [74] Fu, P., Li, H., Gong, J., Fan, Z., Smith, A.T., Shen, K., Khalfalla, T.O., Huang, H., Qian, X., McCutcheon, J.R. and Sun, L., 2022. 4D printing of polymers: Techniques, materials, and prospects. *Progress in Polymer Science*, 126, p.101506.
- [75] Hatami, H., Almahmeed, W., Kesharwani, P. and Sahebkar, A., 2024. Exploring the potential of 3D and 4D printing in advancing stent manufacturing for cardiovascular diseases. *European Polymer Journal*, p.113035. [81]
- [76] Lalegani Dezaki, M., Branfoot, C., Baxendale, J. and Bodaghi, M., 2024. Bio-Based Gradient Composites for 3D/4D Printing With Enhanced Mechanical, Shape Memory, and Flame-Retardant Properties. *Macromolecular Materials and Engineering*, p.2400276. [83]
- [77] Rahmatabadi, D., Khajepour, M., Bayati, A., Mirasadi, K., Yousefi, M.A., Shegeft, A., Ghasemi, I., Baniassadi, M., Abrinia, K., Bodaghi, M. and Baghani, M., 2024. Advancing sustainable shape memory polymers through 4D printing of polylactic acid-polybutylene adipate terephthalate blends. *European Polymer Journal*, 216, p.113289.
- [78] Shah, J., Snider, B., Clarke, T., Kozutsky, S., Lacki, M. and Hosseini, A., 2019. Large-scale 3D printers for additive manufacturing: design considerations and challenges. *The International Journal of Advanced Manufacturing Technology*, 104(9), pp.3679-3693.
- [79] Ali, M.H., Kurokawa, S., Shehab, E. and Mukhtarkhanov, M., 2023. Development of a large-scale multi-extrusion FDM printer, and its challenges. *International Journal of Lightweight Materials and Manufacture*, 6(2), pp.198-213.
- [80] Zhang, Y., Zhu, Y., Zheng, S., Zhang, L., Shi, X., He, J., Chou, X. and Wu, Z.S., 2021. Ink formulation, scalable applications and challenging perspectives of screen printing for emerging printed microelectronics. *Journal of energy chemistry*, 63, pp.498-513.
- [81] Shen, H., Pan, L. and Qian, J., 2019. Research on large-scale additive manufacturing based on multi-robot collaboration technology. *Additive Manufacturing*, 30, p.100906.

- [82] Jafari, R., Cloutier, C., Allahdini, A. and Momen, G., 2019. Recent progress and challenges with 3D printing of patterned hydrophobic and superhydrophobic surfaces. *The International Journal of Advanced Manufacturing Technology*, 103, pp.1225-1238.
- [83] Quan, H., Zhang, T., Xu, H., Luo, S., Nie, J. and Zhu, X., 2020. Photo-curing 3D printing technique and its challenges. *Bioactive materials*, 5(1), pp.110-115.
- [84] Zhang, Y., Zhang, Y., Yang, L., Liu, G., Chen, Y., Yu, S. and Du, H., 2021. Hardened properties and durability of large-scale 3D printed cement-based materials. *Materials and Structures*, 54, pp.1-14.
- [85] Chen, L., Guttieres, D., Koenigsberg, A., Barone, P.W., Sinskey, A.J. and Springs, S.L., 2022. Large-scale cultured meat production: Trends, challenges and promising biomanufacturing technologies. *Biomaterials*, 280, p.121274.
- [86] Anandakrishnan, N., Ye, H., Guo, Z., Chen, Z., Mentkowski, K.I., Lang, J.K., Rajabian, N., Andreadis, S.T., Ma, Z., Spornyak, J.A. and Lovell, J.F., 2021. Fast stereolithography printing of large-scale biocompatible hydrogel models. *Advanced healthcare materials*, 10(10), p.2002103.
- [87] Dörfler, K., Dielemans, G., Lachmayer, L., Recker, T., Raatz, A., Lowke, D. and Gerke, M., 2022. Additive Manufacturing using mobile robots: Opportunities and challenges for building construction. *Cement and concrete research*, 158, p.106772.
- [88] Beer, N., Hegger, I., Kaae, S., De Bruin, M.L., Genina, N., Alves, T.L., Hoebert, J. and Sporrang, S.K., 2021. Scenarios for 3D printing of personalized medicines-A case study. *Exploratory research in clinical and social pharmacy*, 4, p.100073.
- [89] Seoane-Viano, I., Xu, X., Ong, J.J., Teyeb, A., Gaisford, S., Campos-Álvarez, A., Stulz, A., Marcuta, C., Kraschew, L., Mohr, W. and Basit, A.W., 2023. A case study on decentralized manufacturing of 3D printed medicines. *International Journal of Pharmaceutics: X*, 5, p.100184.
- [90] Alkhalidi, A. and Hatuqay, D., 2020. Energy efficient 3D printed buildings: Material and techniques selection worldwide study. *Journal of Building Engineering*, 30, p.101286.
- [91] Brion, D.A. and Pattinson, S.W., 2022. Quantitative and real-time control of 3d printing material flow through deep learning. *Advanced Intelligent Systems*, 4(11), p.2200153.
- [92] Yi, Q., Pei, X., Das, P., Qin, H., Lee, S.W. and Esfandyarpour, R., 2022. A self-powered triboelectric MXene-based 3D-printed wearable physiological biosignal sensing system for on-demand, wireless, and real-time health monitoring. *Nano Energy*, 101, p.107511.
- [93] Strandhagen, J.W., Buer, S.V., Semini, M., Alfnes, E. and Strandhagen, J.O., 2022. Sustainability challenges and how Industry 4.0 technologies can address them: a case study of a shipbuilding supply chain. *Production Planning & Control*, 33(9-10), pp.995-1010.

- [94] Guerra-Zubiaga, D., Kuts, V., Mahmood, K., Bondar, A., Nasajpour-Esfahani, N. and Otto, T., 2021. An approach to develop a digital twin for industry 4.0 systems: manufacturing automation case studies. *International Journal of Computer Integrated Manufacturing*, 34(9), pp.933-949.
- [95] Ida, N., & Meyendorf, N. (2019). Handbook of Advanced Nondestructive Evaluation. doi:10.1007/978-3-319-26553-7
- [96] Jellett, C., Ghosh, K., Browne, M. P., Urbanová, V., & Pumera, M. (2021). Flexible graphite–poly(lactic acid) composite films as large-area conductive electrodes for energy applications. *ACS Applied Energy Materials*, 4(7), 6975–6981. doi:10.1021/acsaem.1c01047
- [97] Jeong, H. Y., An, S.-C., Lim, Y., Jeong, M. J., Kim, N., & Jun, Y. C. (2020). 3D and 4D printing of multistable structures. *Applied Sciences*, 10(20), 7254. doi:10.3390/app10207254
- [98] Kamran, M., & Saxena, A. (2016). A comprehensive study on 3D printing technology. *MIT International Journal of Mechanical Engineering*, 6(2), 63–9.
- [99] Kantaros, A., Ganetsos, T., & Piromalis, D. (2023). 3D and 4D printing as integrated manufacturing methods of industry 4.0. *American Journal of Engineering and Applied Sciences*, 16(1), 12–22. doi:10.3844/ajeassp.2023.12.22
- [100] Karanth, D., Puleo, D., Dawson, D., Holliday, L. S., & Sharab, L. (2023). Characterization of 3D printed biodegradable piezoelectric scaffolds for bone regeneration. *Clinical and Experimental Dental Research*, 9(2), 398–408. doi:10.1002/cre2.712
- [101] Klein, J., Stern, M., Franchin, G., Kayser, M., Inamura, C., Dave, S., ... Oxman, N. (2015). Additive manufacturing of optically transparent glass. *3D Printing and Additive Manufacturing*, 2(3), 92–105. doi:10.1089/3dp.2015.0021
- [102] Kristiawan, R. B., Imaduddin, F., Ariawan, D., Ubaidillah, & Arifin, Z. (2021). A review on the Fused Deposition Modeling (FDM) 3D printing: Filament Processing, materials, and printing parameters. *Open Engineering*, 11(1), 639–649. doi:10.1515/eng-2021-0063
- [103] Kuang, X., Roach, D. J., Wu, J., Hamel, C. M., Ding, Z., Wang, T., ... Qi, H. J. (2018). Advances in 4D printing: Materials and applications. *Advanced Functional Materials*, 29(2). doi:10.1002/adfm.201805290
- [104] Lee, B. J., Hsiao, K., Lipkowitz, G., Samuelsen, T., Tate, L., & DeSimone, J. M. (2022). Characterization of a 30 μm pixel size clip-based 3D printer and its enhancement through dynamic printing optimization. *Additive Manufacturing*, 55, 102800. doi:10.1016/j.addma.2022.102800
- [105] Leschok, M., Cheibas, I., Piccioni, V., Seshadri, B., Schlüter, A., Gramazio, F., ... Dillenburger, B. (2023). 3D printing facades: Design, fabrication, and assessment methods. *Automation in Construction*, 152, 104918. doi:10.1016/j.autcon.2023.104918

- [106] Li, X., Fan, L., Li, R., Han, Y., & Li, J. (2023). 3D/4D printing of β -cyclodextrin-based high internal phase emulsions. *Journal of Food Engineering*, 348, 111455. doi:10.1016/j.jfoodeng.2023.111455
- [107] Lipkowitz, G., Coates, I., Krishna, N., Shaqfeh, E. S. G., & DeSimone, J. M. (2024). Methods for modeling and real-time visualization of clip and ICLIP-based 3D printing. *Giant*, 17, 100239. doi:10.1016/j.giant.2024.100239
- [108] Lipkowitz, G., Samuelsen, T., Hsiao, K., Lee, B., Dulay, M. T., Coates, I., ... DeSimone, J. M. (2022). Injection continuous liquid interface production of 3D objects. *Science Advances*, 8(39). doi:10.1126/sciadv.abq3917
- [109] Liu, F., Quan, R., Vyas, C., & Aslan, E. (2022). Hybrid biomanufacturing systems applied in tissue regeneration. *International Journal of Bioprinting*, 9(1), 646. doi:10.18063/ijb.v9i1.646
- [110] Liu, Y.-Q., Xiong, Z., Zhang, Y.-L., & Liu, H. (2023). Breakthroughs in projection-enabled Additive Manufacturing: From novel strategies to cutting-edge applications. *The Innovation*, 4(3), 100395. doi:10.1016/j.xinn.2023.100395
- [111] Mahmood, A., Akram, T., Chen, H., & Chen, S. (2022). On the evolution of additive manufacturing (3D/4D printing) technologies: Materials, applications, and challenges. *Polymers*, 14(21), 4698. doi:10.3390/polym14214698
- [112] Mahmood, A., Akram, T., Shenggui, C., & Chen, H. (2023). Revolutionizing manufacturing: A review of 4D printing materials, stimuli, and cutting-edge applications. *Composites Part B: Engineering*, 266, 110952. doi:10.1016/j.compositesb.2023.110952
- [113] Maines, E. M., Porwal, M. K., Ellison, C. J., & Reineke, T. M. (2021). Sustainable advances in SLA/DLP 3D printing materials and Processes. *Green Chemistry*, 23(18), 6863–6897. doi:10.1039/d1gc01489g
- [114] Manshor, M. R., Alli, Y. A., Anuar, H., Ejeromedoghene, O., Omotola, E. O., & Suhr, J. (2023). 4D printing: Historical evolution, computational insights and emerging applications. *Materials Science and Engineering: B*, 295, 116567. doi:10.1016/j.mseb.2023.116567
- [115] Muhindo, D., Elkanayati, R., Srinivasan, P., Repka, M. A., & Ashour, E. A. (2023). Recent advances in the applications of Additive Manufacturing (3D printing) in drug delivery: A comprehensive review. *AAPS PharmSciTech*, 24(2). doi:10.1208/s12249-023-02524-9
- [116] Nastaj, A., & Wilczyński, K. (2021). Optimization and scale-up for polymer extrusion. *Polymers*, 13(10), 1547. doi:10.3390/polym13101547
- [117] Nie, Z., Jung, S., Kara, L. B., & Whitefoot, K. S. (2019). Optimization of part consolidation for minimum production costs and time using additive manufacturing. *Journal of Mechanical Design*, 142(7). doi:10.1115/1.4045106

- [118] Niu, X., Li, N., Du, Z., & Li, X. (2023). Integrated gradient tissue-engineered osteochondral scaffolds: Challenges, current efforts and future perspectives. *Bioactive Materials*, 20, 574–597. doi:10.1016/j.bioactmat.2022.06.011
- [119] Noroozi, R., Arif, Z. U., Taghvaei, H., Khalid, M. Y., Sahbafar, H., Hadi, A., ... Chen, X. (2023). 3D and 4D bioprinting technologies: A game changer for the biomedical sector? *Annals of Biomedical Engineering*, 51(8), 1683–1712. doi:10.1007/s10439-023-03243-9
- [120] Novak, J. I., & O'Neill, J. (2019). A design for additive manufacturing case study: Fingerprint stool on a BigRep one. *Rapid Prototyping Journal*, 25(6), 1069–1079. doi:10.1108/rpj-10-2018-0278
- [121] Nurhudan, A. I., Supriadi, S., Whulanza, Y., & Saragih, A. S. (2021). Additive manufacturing of metallic based on extrusion process: A Review. *Journal of Manufacturing Processes*, 66, 228–237. doi:10.1016/j.jmapro.2021.04.018
- [122] Panda, S. K., Dalijet, S. P., Lokre, S. S., & Naman, V. (2022). Distributed Ledger Technology in the construction industry using Corda. *The New Advanced Society*, 15–41. doi:10.1002/9781119884392.ch2
- [123] Parandoush, P., & Lin, D. (2017). A review on additive manufacturing of polymer-fiber composites. *Composite Structures*, 182, 36–53. doi:10.1016/j.compstruct.2017.08.088
- [124] Pricci, A., & Percoco, G. (2024). A generalized method aiming at predicting the polymer melt flow field in the metering zone of large-scale single-screw extruders. *The International Journal of Advanced Manufacturing Technology*. doi:10.1007/s00170-024-13346-9
- [125] Palumbo, J. and Chandra, S., 2023. Additive manufacturing of complex structures and flow channels using wire-arc thermal spray. *Journal of Manufacturing Processes*, 107, pp.459-471.
- [126] Su, G., Shi, Y., Li, G., Zhang, G. and Xu, Y., 2023. Improving the deposition efficiency and mechanical properties of additive manufactured Inconel 625 through hot wire laser metal deposition. *Journal of Materials Processing Technology*, 322, p.118175.
- [127] Su, G., Shi, Y., Li, G., Zhang, G. and Xu, Y., 2024. Highly-efficient additive manufacturing of Inconel 625 thin wall using hot-wire laser metal deposition: Process optimization, microstructure, and mechanical properties. *Optics & Laser Technology*, 175, p.110763.
- [128] Fu, Y., Demir, A.G. and Guo, N., 2023. Additive manufacturing of Ti-6Al-4V alloy by micro-laser metal wire deposition with pulsed wave emission: processability and microstructure formation. *The International Journal of Advanced Manufacturing Technology*, 126(5), pp.2693-2711.
- [129] Mbodj, N.G., Abuabiah, M., Kandaoui, M.E., Yaacoubi, S. and Plapper, P., 2023. Parametric modeling approach in laser wire additive manufacturing process. *Welding in the World*, 67(4), pp.885-895.

- [130] Mehrabi, O., Seyedkashi, S.H. and Moradi, M., 2023. Experimental and response surface study on additive manufacturing of functionally graded steel-inconel wall using direct laser metal deposition. *Optics & Laser Technology*, 167, p.109707.
- [131] Carvalho, G.H. and Campatelli, G., 2023. Deposition strategies using arc oscillation to improve the fabrication of solids by wire arc additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 128(3-4), pp.1559-1576.
- [132] Dehaghani, M.R., Tang, Y., Panicker, S., Wu, D., Coatanea, E. and Wang, G.G., 2023. Modeling and optimization of height-related geometrical parameters for thin wall structures manufactured by metal additive manufacturing. *The International Journal of Advanced Manufacturing Technology*, 129(9), pp.4663-4675.
- [133] Liu, X., Zhang, Y., Su, Y., Geng, C., Liu, Y., He, J. and Lu, A., 2024. 4D printing of cellular silicones with negative stiffness effect for enhanced energy absorption and impact protection. *Composites Part B: Engineering*, 282, p.111561.
- [134] Kumar, A., Kumar, P., Mittal, R.K. and Singh, H., 2023. Printing file formats for additive manufacturing technologies. *Advances in Additive Manufacturing*, pp.87-102.
- [135] Son, D., Kim, S. and Jeong, B., 2021. Sustainable part consolidation model for customized products in closed-loop supply chain with additive manufacturing hub. *Additive Manufacturing*, 37, p.101643.
- [136] Kumar, R., Kumar, M. and Chohan, J.S., 2021. The role of additive manufacturing for biomedical applications: A critical review. *Journal of Manufacturing Processes*, 64, pp.828-850.
- [137] Zhang, L., Chen, X., Zhou, W., Cheng, T., Chen, L., Guo, Z., Han, B. and Lu, L., 2020. Digital twins for additive manufacturing: a state-of-the-art review. *Applied Sciences*, 10(23), p.8350.
- [138] Kamble, S., Belhadi, A., Gupta, S., Islam, N., Verma, V.K. and Solima, L., 2023. Analyzing the barriers to building a 3-D printing enabled local medical supply chain ecosystem. *IEEE Transactions on Engineering Management*.
- [139] Zhou, X., Ren, L., Song, Z., Li, G., Zhang, J., Li, B., Wu, Q., Li, W., Ren, L. and Liu, Q., 2023. Advances in 3D/4D printing of mechanical metamaterials: From manufacturing to applications. *Composites Part B: Engineering*, 254, p.110585.
- [140] Antezana, P.E., Municoy, S., Ostapchuk, G., Catalano, P.N., Hardy, J.G., Evelson, P.A., Orive, G. and Desimone, M.F., 2023. 4D printing: The development of responsive materials using 3D-printing technology. *Pharmaceutics*, 15(12), p.2743.
- [141] Aldawood, F.K., 2023, February. A comprehensive review of 4D printing: state of the arts, opportunities, and challenges. In *Actuators* (Vol. 12, No. 3, p. 101). MDPI.
- [142] Demoly, F. and André, J.C., 2024. 4D Printing: Bridging the Gap between Fundamental Research and Real-World Applications. *Applied Sciences*, 14(13), p.5669.

- [143] Khalid, M.Y., Arif, Z.U. and Ahmed, W., 2022. 4D printing: technological and manufacturing renaissance. *Macromolecular Materials and Engineering*, 307(8), p.2200003.
- [144] Nejatpour, M., Fallah, A. and Koc, B., 2024. An overview of 4D printing of smart multifunction continuous fiber-reinforced composites: recent advances and novel applications. *Advanced Composites and Hybrid Materials*, 7(5), pp.1-40.
- [145] Muhindo, D., Elkanayati, R., Srinivasan, P., Repka, M.A. and Ashour, E.A., 2023. Recent advances in the applications of additive manufacturing (3D printing) in drug delivery: a comprehensive review. *AAPS PharmSciTech*, 24(2), p.57.
- [146] Ghazal, A.F., Zhang, M., Mujumdar, A.S. and Ghamry, M., 2023. Progress in 4D/5D/6D printing of foods: Applications and R&D opportunities. *Critical Reviews in Food Science and Nutrition*, 63(25), pp.7399-7422.
- [147] Persaud, A., Maus, A., Strait, L. and Zhu, D., 2022. 3D bioprinting with live cells. *Engineered Regeneration*, 3(3), pp.292-309.
- [148] Ma, G., Buswell, R., da Silva, W.R.L., Wang, L., Xu, J. and Jones, S.Z., 2022. Technology readiness: A global snapshot of 3D concrete printing and the frontiers for development. *Cement and Concrete Research*, 156, p.106774.
- [149] Abdulrahman, M.D. and Yuvaraj, M., 2023. Improving agility and resilience of automotive spares supply chain: The additive manufacturing enabled truck model. *Socio-Economic Planning Sciences*, 85, p.101401.
- [150] Xie, D., Xin, J., Wang, H. and Xiao, L., 2023. Identifying critical factors affecting the resilience of additive manufacturing architecture supply chain. *Buildings*, 13(4), p.997.
- [151] Rinaldi, M., Caterino, M. and Macchiaroli, R., 2022. Additive manufacturing and supply chain configuration: Modelling and performance evaluation. *Journal of Industrial Engineering and Management*, 15(1), pp.103-123.
- [152] Ahmed, R., Heese, H.S. and Kay, M., 2023. Designing a manufacturing network with additive manufacturing using stochastic optimisation. *International Journal of Production Research*, 61(7), pp.2267-2287.
- [153] Cui, W., Yang, Y. and Di, L., 2023. Modeling and optimization for static-dynamic routing of a vehicle with additive manufacturing equipment. *International Journal of Production Economics*, 257, p.108756.
- [154] Sossou, G., Demoly, F., Gomes, S. and Montavon, G., 2022. An assembly-oriented design framework for additive manufacturing. *Designs*, 6(1), p.20.
- [155] Tuvayanond, W. and Prasittisopin, L., 2023. Design for manufacture and assembly of digital fabrication and additive manufacturing in construction: a review. *Buildings*, 13(2), p.429.

- [156] Roxas, C.L.C., Bautista, C.R., Dela Cruz, O.G., Dela Cruz, R.L.C., De Pedro, J.P.Q., Dungca, J.R., Lejano, B.A. and Ongpeng, J.M.C., 2023. Design for manufacturing and assembly (DfMA) and design for deconstruction (DfD) in the construction industry: Challenges, trends and developments. *Buildings*, 13(5), p.1164.
- [157] Egan, P.F., 2023. Design for Additive Manufacturing: Recent Innovations and Future Directions. *Designs*, 7(4), p.83.
- [158] Burke, H., Zhang, A. and Wang, J.X., 2023. Integrating product design and supply chain management for a circular economy. *Production Planning & Control*, 34(11), pp.1097-1113.
- [159] Khosravani, M.R. and Haghghi, A., 2022. Large-scale automated additive construction: overview, robotic solutions, sustainability, and future prospect. *Sustainability*, 14(15), p.9782.
- [160] Hettiarachchi, B.D., Brandenburg, M. and Seuring, S., 2022. Connecting additive manufacturing to circular economy implementation strategies: Links, contingencies and causal loops. *International Journal of Production Economics*, 246, p.108414.
- [161] Tavares, T.M., Ganga, G.M.D., Godinho Filho, M. and Rodrigues, V.P., 2023. The benefits and barriers of additive manufacturing for circular economy: A framework proposal. *Sustainable Production and Consumption*, 37, pp.369-388.
- [162] Ghaderi, Z., Shakori, H., Bagheri, F., Hall, C.M., Rather, R.A. and Moaven, Z., 2024. Green supply chain management, environmental costs and supply chain performance in the hotel industry: the mediating role of supply chain agility and resilience. *Current Issues in Tourism*, 27(13), pp.2101-2117.
- [163] Meyer, M.M., Glas, A.H. and Eßig, M., 2022. A Delphi study on the supply risk-mitigating effect of additive manufacturing during SARS-COV-2. *Journal of Purchasing and Supply Management*, 28(4), p.100791.
- [164] Priyadarshini, J., Singh, R.K., Mishra, R., Chaudhuri, A. and Kamble, S., 2023. Supply chain resilience and improving sustainability through additive manufacturing implementation: a systematic literature review and framework. *Production Planning & Control*, pp.1-24.
- [165] Jimo, A., Braziotis, C., Rogers, H. and Pawar, K., 2022. Additive manufacturing: A framework for supply chain configuration. *International Journal of Production Economics*, 253, p.108592.
- [166] Zhu, W., Li, S., Long, H., Dong, S., Wang, K. and Peng, Y., 2025. Simulation analysis and optimization of 3d printed continuous carbon fiber reinforced composites. *Composite Structures*, 355, p.118840.
- [167] Yi, J., Deng, B., Peng, F., Yan, A., Li, Z., Shen, J., Yan, R. and Xie, X., 2025. Study on the parameters optimization of 3D printing continuous carbon fiber-reinforced composites based on CNN and NSGA-II. *Composites Part A: Applied Science and Manufacturing*, 190, p.108657.

- [168] Chen, E.S., Ahmadianshalchi, A., Sparks, S.S., Chen, C., Deshwal, A., Doppa, J.R. and Qiu, K., 2025. Machine Learning Enabled Design and Optimization for 3D-Printing of High-Fidelity Presurgical Organ Models. *Advanced Materials Technologies*, 10(1), p.2400037.
- [169] Hematibahar, M., Milani, A., Fediuk, R., Amran, M., Bakhtiary, A., Kharun, M. and Mousavi, M.S., 2025. Optimization of 3D-printed reinforced concrete beams with four types of reinforced patterns and different distances. *Engineering Failure Analysis*, 168, p.109096.
- [170] Semenchuk, V.M., Chumaevskii, A.V., Rubtsov, K.V., Rubtsov, V.E., Gurianov, D.A., Savchenko, N.L. and Kolubaev, E.A., 2025. Optimization of 3d-printing of bronze by wire-arc additive manufacturing. *Russian Physics Journal*, pp.1-7.
- [171] Motgi, R., Jatti, V.K., Tamboli, S. and Dhalait, J., 2025. Lattice Structure Optimization of 3D Printed TPMS under Different Loading Conditions Using Regression Machine Learning. *Mechanics of Advanced Composite Structures*.
- [172] Shokrollahi, P., Garg, P., Wulff, D., Hui, A., Phan, C.M. and Jones, L., 2025. Vat photopolymerization 3D printing optimization: Analysis of print conditions and print quality for complex geometries and ocular applications. *International Journal of Pharmaceutics*, 668, p.124999.
- [173] Johnson, J.E., Jamil, I.R., Pan, L., Lin, G. and Xu, X., 2025. Bayesian optimization with Gaussian-process-based active machine learning for improvement of geometric accuracy in projection multi-photon 3D printing. *Light: Science & Applications*, 14(1), p.56.
- [174] Vălean, C., Linul, E. and Rajak, D.K., 2025. Compressive performance of 3D-printed lightweight structures: Infill pattern optimization via Multiple-Criteria Decision Analysis method. *Results in Engineering*, 25, p.103936.
- [175] Jin, W., Caron, J.F. and Ouellet-Plamondon, C.M., 2025. Minimizing the carbon footprint of 3D printing concrete: Leveraging parametric LCA and neural networks through multiobjective optimization. *Cement and Concrete Composites*, 157, p.105853.
- [176] Khalid, M.Y., Arif, Z.U., Noroozi, R., Hossain, M., Ramakrishna, S. and Umer, R., 2023. 3D/4D printing of cellulose nanocrystals-based biomaterials: Additives for sustainable applications. *International Journal of Biological Macromolecules*, 251, p.126287.
- [177] Bodaghi, M., Wang, L., Zhang, F., Liu, Y., Leng, J., Xing, R., Dickey, M.D., Vanaei, S., Elahinia, M., Hoa, S.V. and Zhang, D., 2024. 4D printing roadmap. *Smart materials and structures*, 33(11), p.113501.
- [178] Gu, S., Du, G., Su, Y., Zhang, Y., Zhang, Y., Li, L., Pang, H. and Zhou, H., 2025. Architectural design and optimization of internal structures in 3D printed electrodes for superior supercapacitor performance. *Journal of Colloid and Interface Science*, 677, pp.21-29.
- [179] Bayati, A., Ahmadi, M., Rahmatabadi, D., Khodaei, M., Xiang, H., Baniassadi, M., Abrinia, K., Zolfagharian, A., Bodaghi, M. and Baghani, M., 2025. 3D printed elastomers with superior

stretchability and mechanical integrity by parametric optimization of extrusion process using Taguchi Method. *Materials Research Express*, 12(1), p.015301.

[180] Zhang, Y., Zheng, W., Feng, X., Wang, Y., Ji, Q., Ma, K., Wu, F., Xue, Y., Guo, W. and Lu, B., 2025. Wet Twisting Treatment, Process Parameter Optimization and Mechanical Failure Mechanisms of 3D printed Carbon Fibre Reinforced Composites. *Composites Communications*, p.102308.

[181] Alex, Y., Divakaran, N.C., Pattanayak, I., Lakshyajit, B., Ajay, P.V. and Mohanty, S., 2025. Comprehensive study of PLA material extrusion 3D printing optimization and its comparison with PLA injection molding through life cycle assessment. *Sustainable Materials and Technologies*, 43, p.e01222.

[182] Ganitano, G.S., Maruyama, B. and Peterson, G.L., 2025. Accelerated Multiobjective Calibration of Fused Deposition Modeling 3D Printers Using Multitask Bayesian Optimization and Computer Vision. *Advanced Intelligent Systems*, p.2400523.

[183] Vendittoli, V., Polini, W. and Walter, M.S., 2025. Multi-response optimization of the dimensional and mechanical properties of 3D-printed polylactic acid part by response surface methodology. *Progress in Additive Manufacturing*, pp.1-18.

[184] Linh, P.N., Tu, N.Q., Nguyen, V.C. and Pham, V.T., 2025. Optimization of PLA 3D Printing Parameters using a Combined SMART-MOORA Multi-Criteria Decision-Making Approach. *Engineering, Technology & Applied Science Research*, 15(1), pp.19460-19465.



Review on advancements in 3D/4D printing for enhancing efficiency, cost-effectiveness, and quality

Ajay Solanki¹ · M.S. Ranganath² · Ajay K. S. Singholi³

Received: 10 April 2024 / Accepted: 17 July 2024 / Published online: 3 August 2024
© The Author(s), under exclusive licence to Springer-Verlag France SAS, part of Springer Nature 2024

Abstract

Three Dimensional and Four Dimensional (3D/4D) printing has widespread popularity because of its shape-changing capabilities in various applications. 3D Printing makes only stationary structured products whereas 3D/4D printing enables an object to change its configuration in response with different external stimuli. Researchers from many fields have examined an extensive array of 3D/4D printing using proofs-of-concept. In spite of a lot of efforts, needs more advancement in the structural quality and efficiency to satisfy significant industrial applications which ensure cost effective manufacturing. Thus, the intension of review exercise is to draw attention to the recent metamaterials, manufacturing methods, computational insights of creative and integrated design, and latest uses of 3D/4D printing. An overview of integrated computation design strategies and its contribution in enhancing efficient use of smart materials in vast applications also presented and concluded with the findings like systematically incorporating sustainability variables into cost-effectiveness analyses with recent advancements in additive manufacturing tailored with human material interaction aids industries to make informed decisions that align with economic goals. Future views are critically explored and encouraging the collaboration with fabrication methods directs research efforts in a way incorporating advanced 3D/4D product design methods that satisfy industry and customer demands.

Keywords 3D/4D printing · Smart metamaterials · Integrated design · Shape memory polymer · Fused deposition modelling

1 Introduction

Modern, innovative 3D/4D printing methods have expanded the application domains for customized fabricated manufacturing of products because of its many benefits, including material reduction, fast processing times, low costs,

customization, and less waste [1, 2]. Due to the applicable regions benefits over traditional tactics in terms of design, quality and cost and its potential has been increasing [3]. Rapid prototyping is just another name for 3D printing and defined by specific restrictions with regard to material selectivity [4]. The 3D printing robot made its debut in 1984 and created by Charles W. (Chuck) Hull. In 1989, S. Scott and Lisa Crump, along with manufacturer Stratasys Ltd., made many advanced improvements over years.

Great breakthroughs have been made possible by rapid expansion of 3D/4D printing is lowered the production cost [5]. Improvement of several prototype modeling in applications ranging from aircraft to nano sized structures [6, 7]. 3D/4D printing makes use of intelligent materials to build certain intelligently designed target structures where conversion occurs with regard to specific external input circumstances such as light, electricity, magnetism, humidity [8–10]. The comparison of 3D and 3D/4D printing using smart multi material based technology is depicted in the Fig. 1.

✉ Ajay Solanki
ajay100lanki@rediffmail.com

M.S. Ranganath
ranganathdce@gmail.com

Ajay K. S. Singholi
ajay.s@ipu.ac.in

¹ Department of Design, Delhi Technological University, New Delhi 110042, India

² Department of Mechanical Engineering, Delhi Technological University, New Delhi 110042, India

³ Department of USAR, University School of Automation and Robotics, New Delhi 110092, India

Journal of Advanced Manufacturing Systems
Vol. 24, No. 3 (2025) 573–594
© World Scientific Publishing Company
DOI: 10.1142/S021968672550026X



Laser Metal Wire Deposition for Additive Manufacturing of Complex Solid Structures

Ajay Solanki*

*Department of Design
Delhi Technological University
New Delhi, Delhi 110042, India
ajay100lanki@rediffmail.com*

Ranganath Singari

*Department of Mechanical Engineering
Delhi Technological University
New Delhi, Delhi 110042, India
ranganathdce@gmail.com*

Ajay Singholi

*Department of USAR
University School of Automation and Robotics
New Delhi, Delhi 110092, India
ajay.s@ipu.ac.in*

Received 29 August 2024

Accepted 20 November 2024

Published 24 December 2024

Researchers previously encountered challenges in achieving high material efficiency and precise control in laser metal wire deposition, such as variability in friction, fluctuations in deposition rates, and inconsistent hardness across different scanning speeds and power settings. This research focuses on the single deposition technique within laser metal wire deposition, evaluating material usage and deposition efficiency by analyzing factors like wire feed rate, laser power, and deposition speed. Findings indicate that coefficient of friction increases with higher scanning speeds, particularly at a sliding velocity of 0.5 m/s. Furthermore, there were considerable changes in hardness and deposition rate, with the largest deposition rate occurring at the lowest scanning speed of 0.4 m/min. These findings emphasize that process parameters must be optimized in order to decrease material waste and increase deposition efficiency, which is presently 90%. The research implications are significant for industries requiring complex, high-quality metal components, positioning laser metal wire deposition as a key solution for modern manufacturing challenges.

Keywords: Laser metal wire deposition; material efficiency; deposition efficiency; coefficient of friction; scanning speed; hardness fluctuations.



REVIEW PAPER

Optimizing 3D/4D Printing for Large-Scale Prototyping: A Comprehensive Review on Speed, Cost, and Quality Challenges

Ajay Solanki¹ · M. S. Ranganath² · Ajay K. S. Singholi³

Received: 6 January 2025 / Accepted: 14 June 2025 / Published online: 3 July 2025
 © The Institution of Engineers (India) 2025

Abstract Three Dimensional and Four-Dimensional (3D/4D) printing is an emerging structure creation process that allows for form morphing in response to external triggering chemicals. Many studies currently concentrate on small to medium-sized 3D/4D printing of structural components. As a result, in order to build industry-based large-scale structures, printing capabilities must be increased without sacrificing quality, cost, and speed. Advances in computer-aided design modeling have led to the development of 3D/4D products, which are essential for the large-scale manufacture of structures for various engineering purposes. The primary objective of the review is to evaluate obstacles encountered when scaling up prototype modeling from small to large scale in the last decade. Also, aimed to develop novel design strategies for printing process optimization with reduced time and increased productivity without compromising efficiency. Furthermore, cost-effective design and quality assurance control techniques, along with obstacles, are highlighted. In the aim of extending the term of 3D/4D printing, this research provides current innovations, numerous optimizing approaches, applications, and concludes by discussing future prospects in large-scale prototype manufacturing.

Keywords Additive manufacturing · Large scale prototyping · Design optimization · Speedy 3D/4D printing · Continuous liquid interface production

Abbreviations

AM	Additive manufacturing
3D/4D	Three dimensional and four-dimensional
CAD	Computer-aided design
SMA	Shape memory alloy
FDM	Fused deposition modeling
BJ	Binder jetting
PPE	Personal protective equipment
ABS	Acrylonitrile butadiene styrene
PC	Polycarbonate
MWCNTI	Multiwall carbon nanotube insulator
ML	Machine learning
BAAM-CI	Big area additive manufacturing-cincinnati incorporated
BAAM	Additive manufacturing
CLIP	Continuous liquid interface production
NIST	National institute of standards and technology
ISO	International organization for standardization
NASA	National aeronautics and space administration
ONR	Office of naval research
NIH	National Institutes of Health
NDE	Nondestructive evaluation
WAAM	Wire arc additive manufacturing
SLA	Stereolithography
CNC	Computerized numerical control
CAGR	Compound annual growth rate
SMP	Shape memory polymer
SLS	Selective laser sintering
MJ	Material jetting

✉ Ajay Solanki
 ajay100lanki@rediffmail.com

¹ Department of Design, Delhi Technological University, New Delhi 110042, Delhi, India

² Department of Mechanical Engineering, Delhi Technological University, New Delhi 110042, Delhi, India

³ University School of Automation and Robotics, Guru Gobind Singh Indraprastha University, New Delhi, Delhi 110092, India

Transformative Impact of 3D/4D Printing on Supply Chain Dynamics through High-Value Design Concepts

Ajay Solanki*

*Department of Design
Delhi Technological University
New Delhi, Delhi 110042, India
ajay100lanki@rediffmail.com*

Ranganath M. S.

*Department of Mechanical Engineering
Delhi Technological University
New Delhi, Delhi 110042, India
ranganathdce@gmail.com*

Ajay K. S. Singholi

*Department of University School of Automation and Robotics
Guru Gobind Singh Indraprastha University
New Delhi, Delhi 110092, India
ajay.s@ipu.ac.in*

Received 14 July 2025

Accepted 11 October 2025

Published

Supply chain management is poised for a transformative shift through the adoption of 3D and 4D printing technologies, which enable localized manufacturing, lead time reductions of up to 65%, and inventory cost savings of approximately 67%. These technologies support the growing demand for customized products by fostering a supply chain that is more responsive, adaptive, flexible, efficient, and cost-effective. 4D printing further enhances product lifecycle management by allowing objects to change shape or function over time, improving overall performance and longevity. The proposed impact analysis demonstrates streamlined adaptation of manufacturing processes, contributing to environmental sustainability through significant waste reduction. Empirical results from the case study of Company X reveal transformative outcomes in performance metrics, with supply chain efficiency increasing from 45 to nearly 100 units, and 3D/4D printing adoption surging from 2% to 98% between 2016 and 2024. Integration of high-value design principles and additive manufacturing improved key dimensions like agility, visibility, collaboration, and flexibility by 15–20 points each, while stakeholder support remained strong, with 62.5% endorsing 3D/4D adoption, 67.8% favoring



DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)
Shahbad Daultpur, Main Bawana Road, Delhi-42

PLAGIARISM VERIFICATION

Title of the Thesis “DEVELOPMENT OF A NEW PRODUCT DESIGN PROCESS TO IMPROVISE DESIGN FOR MANUFACTURING USING 3D/4D PRINTING TECHNOLOGY”.

Total Pages 187 Name of the Scholar Ajay Solanki.

Supervisor (s)

- (1) Prof. Ranganath M. Singari, Founder Head, Department of Design, Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.
- (2) Prof. Ajay K. S. Singholi, Professor, University School of Automation and Robotics, Guru Gobind Singh Indraprastha University-EDC, Delhi.

Department of Design.

This is to report that the above thesis was scanned for similarity detection. Process and outcome is given below:

Software used: Turnitin Similarity Index: 03 %, Total Word Count: 47,194.

Date:

Candidate's Signature

Signature of Supervisor(s)

Curriculum Vitae

AJAY SOLANKI

Research Scholar, Department of Design
Delhi Technological University,
Bawana Road, Delhi-110042
Mobile: 📞 +91-9013442063
e-mail: ajaysolanki_2k22phddes01@dtu.ac.in

PERSONAL INFORMATION

- **Nationality:** Indian
- **Gender:** Male
- **Spoken Languages:** English, Hindi
- **Present Address:** Room No. TW4 TF31, Department of Mechanical Engineering, Delhi Technological University, Bawana Road, Delhi- 110042

PRESENT POSITION

- *Assistant Professor*, Department of Mechanical Engineering, Delhi Technological University, Bawana Road, Delhi-110042
- *Research Scholar*, Department of Design, Delhi Technological University, Bawana Road, Delhi-110042
- **PhD Supervisors:** *Prof. Ranganath M.S.* (Professor & Founder Head, DoD, DTU) and *Prof. Ajay K.S. Singholi* (Professor, USAR, GGSIPU-EDC)

ACADEMIC QUALIFICATIONS

- ✓ **PhD (Thesis Submitted) in Design**, Department of Design, Delhi Technological University, Bawana Road, Delhi-110042
- ✓ **M. Tech in Mechanical Engineering (Computer Aided Design)**, Department of Mechanical Engineering, DCR University of Science & Technology, Murthal (Sonapat), Haryana Division/Class: 1st
- ✓ **B. Tech in Mechanical Engineering**, CCS University Campus, Meerut, UP, Division/Class: 1st

- ✓ 12th with *Physics, Chemistry, Mathematics, Computer Science, English*, CBSE, Delhi, India Division/Class: 1st
- ✓ 10th standard with *Mathematics, English, Science, Social Science, Sanskrit*, CBSE, Delhi, India Division/Class: 1st

TEACHING EXPERIENCE

- ✓ 14+ years in Delhi Technological University, Delhi