A STUDY ON ENABLERS AND BARRIERS OF ADDITIVE MANUFACTURING ADOPTION IN INDUSTRY 4.0: AN AHP APPROACH

A DISSERTATION
SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF THE DEGREE
OF
MASTER OF TECHNOLOGY
IN
PRODUCTION ENGINEERING

Submitted by:
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I, Rehan Kumar Bavoria student of M. Tech. fourth Semester, Department of Mechanical Engineering, hereby declare that the project dissertation titled “A STUDY ON ENABLERS AND BARRIERS OF ADDITIVE MANUFACTURING ADOPTION IN INDUSTRY 4.0: AN AHP APPROACH” which is submitted by us to the Department of Mechanical Engineering, Delhi Technological University, Delhi, in partial fulfillment of the requirement for the award of the degree of Master of Technology, is original and not copied from any source without citation. This work has not previously formed the basis for the award of any degree, diploma, associateship, fellowship or other similar title or recognition.

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I hereby certify that the Project titled "A STUDY ON ENABLERS AND BARRIERS OF ADDITIVE MANUFACTURING ADOPTION IN INDUSTRY 4.0: AN AHP APPROACH" which is submitted by Rehan Kumar Bavoria (2K21/PRD/16), Department of Mechanical Engineering, Delhi Technological University, Delhi in partial fulfillment of the requirement for the award of the degree of Master of Technology, is a record of the project work carried out by the students under my supervision.

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ABSTRACT

Industry 4.0 is the next generation of manufacturing that utilizes technologies like the artificial intelligence (AI), Internet of Things (IoT), and Additive Manufacturing (AM). Additive manufacturing has the potential that can revolutionize the manufacturing industry by enabling mass customization, reducing waste, and increasing design freedom. However, there are several barriers that hinder the widespread adoption of AM in Industry 4.0, including the lack of standardization, high costs, limited material selection, intellectual property and legal issues, quality and safety concerns, lack of skilled labor, and environmental concerns. On the other hand, there are several enablers that could facilitate the adoption of AM in Industry 4.0, including the Triple Helix, accessibility, capitalization, resource material, suffusing labor, interoperability & compatibility, optimization, AI, entrepreneurship, and personalization. This study aims at exploring the impact of additive manufacturing on Industry 4.0 by analyzing the barriers and enablers and determining their relative importance using the Analytic Hierarchy Process (AHP) technique. The results show that intellectual property and legal issues are the most significant barrier, followed by limited material selection. Among the enablers, suffusing labor and accessibility are the most important factors. The results of this study may offer insightful information about the possibilities of additive manufacturing in Industry 4.0 and may serve as a roadmap for further research and development in this area.

Keywords: Additive manufacturing, Standardization, Industry 4.0, Cost reduction, Material availability.

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LIST OF SYMBOLS & ABBREVIATIONS

AM – Additive Manufacturing

I 4.0 – Industry 4.0

HAL – Hindustan Aeronautics Limited

BEL – Bharat Electronics Limited

GE – General Electric

BMW – Bayerische Motoren Werke Aktiengesellschaft

AI – Artificial Intelligence

CI – Consistency Index

Ri – Random Index

CR – Consistency Ratio

λ_{max} – Principal Eigen Values of Matrix

N – Order of Matrix

CHAPTER 1

INTRODUCTION

The fourth industrial revolution, known as "Industry 4.0," is characterised by the digitalization of manufacturing processes and the integration of cutting-edge technologies (Bauernhansl et al., 2014). It involves the fusion of digital and physical systems, including robotics, the Internet of Things, artificial intelligence, and big data analytics (Wuest et al., 2016). The Industry 4.0’s main aim is to create smart factories that are highly digitized, connected, and automated, leading to improved efficiency, productivity, and flexibility. One of the technologies that has gained significant attention within the context of Industry 4.0 is additive manufacturing, also known as 3D printing (Gibson et al., 2010). Additive manufacturing enables the production of components by building them layer by layer using various materials, such as polymers, ceramics, metals, and composites. This technology has a number of benefits that are consistent with Industry 4.0's guiding principles. For instance, the fabrication of complicated geometries, customisation, quick prototyping, and on-demand manufacturing are all made possible by additive manufacturing. (Berman, 2012).

Furthermore, **additive manufacturing** contributes to resource efficiency by minimizing the material waste as well as energy consumption (Kellens et al., 2017). In the context of Industry 4.0, additive manufacturing helps sustainability goals by completely removing the need for expensive tooling and minimising material waste associated with traditional production techniques. When considered within the larger context of Industry 4.0, the integration of additive manufacturing facilitates the development of extremely adaptable and quick-to-change production processes. The digital ecosystem of Industry 4.0 may be smoothly connected with additive manufacturing by combining technologies like AI, IoT, and data analytics (Wuest et al., 2016). Predictive maintenance, parameter optimisation, and real-time control and monitoring of additive manufacturing processes are all made possible by this integration. In the framework of Industry 4.0, previous studies have examined the uses and prospects of additive manufacturing. Its uses in a variety of sectors, including the automotive, aerospace, healthcare, and consumer products, have been studied by researchers. They have looked into the advantages and difficulties of using additive manufacturing, such as material choice, design complexity, and post-processing needs. The effects of additive manufacturing on supply chains, business models, and logistics have also been the subject of research, which have shed important light on the possibilities of additive manufacturing in the context of Industry 4.0 (Bauernhansl et al., 2014; Wuest et al., 2016; Berman, 2012).

In conclusion, additive manufacturing plays a significant role in the realization of Industry 4.0 objectives. Its integration into the digital ecosystem of Industry 4.0 enables the creation of highly sustainable and flexible production systems. By leveraging advanced technologies and data-driven approaches, additive manufacturing enhances customization, productivity, and resource efficiency. Research on additive manufacturing within the framework of Industry 4.0 is ongoing, with the goal of maximising its potential and addressing the opportunities and constraints related to its deployment.

1.1 INDUSTRY 4.0 AND ITS IMPACT

The fourth industrial revolution, commonly referred to as "Industry 4.0," has arisen as a disruptive force in the manufacturing industry. It includes incorporating cutting-edge digital technologies into conventional manufacturing procedures to usher in a new era of automation, networking, and data-driven decision-making (Schwab, 2017). This paradigm shift is reshaping industries across the globe and driving significant changes in production systems and business models. The notion of Industry 4.0 has its origins in the early 2010s, when the German government initially announced it as a component of its high-tech manufacturing plan. The term "Industrie 4.0" was coined to signify the next phase of industrial development, characterized by the fusion of physical and digital systems (Kagermann et al., 2013). Since then, Industry 4.0 has gained global recognition and has become a focal point for, policy-making, research, and industry initiatives. Industry 4.0 is having a significant impact on many aspects of the manufacturing ecosystem. It provides previously unheard-of potential to boost production, efficiency, and competitiveness. Industry 4.0 supports the development of intelligent manufacturing and supply chains by utilising cutting-edge technology like artificial intelligence (AI), the Internet of Things (IoT), cloud computing, big data analytics, and robotics (Shrouf et al., 2014). These linked, smart factories have sensors and actuators that continuously gather and communicate massive volumes of data. Following analysis, this data is used to forecast maintenance requirements, enhance production procedures, and facilitate proactive decision-making (Wuest et al., 2016). The ability to harness data and derive actionable insights is a key driver of operational excellence and agility in Industry 4.0 (Porter & Heppelmann, 2014). Moreover, Industry 4.0 facilitates the integration of the physical with the digital worlds, blurring the boundaries between virtual and physical systems. By fusing physical elements with computational power and connection, cyber-physical systems (CPS) play a crucial role in this integration (Lee et al., 2015). CPS enable the seamless coordination of systems, machines, and humans, leading to increased flexibility, automation, and customization in manufacturing processes. The transformative impact of Industry 4.0 extends beyond the factory floor and encompasses the entire value chain. It enables new business models, such as servitization and mass customization, where products are tailored to individual customer needs (Gebauer et al., 2017). Furthermore, Industry 4.0 fosters closer collaboration and integration across various stakeholders, including suppliers, partners, and customers, leading to enhanced supply chain responsiveness and visibility (Chae et al., 2014).

In summary, Industry 4.0 represents a disruptive force that is revolutionizing the manufacturing landscape. It leverages advanced digital technologies to create interconnected, smart, and data-driven production systems. The impact of Industry 4.0 is vast, ranging from improved operational efficiency and productivity to the enablement of new business models and enhanced collaboration across the value chain. As we delve deeper into this thesis, we will explore how additive manufacturing specifically fits into Industry 4.0 and what it means for manufacturing in the future.

1.2 ADDITIVE MANUFACTURING IN INDUSTRY 4.0

Due to its potential to completely transform current production procedures, additive manufacturing, often known as 3D printing, has recently attracted a lot of interest and awareness. In the context of Industry 4.0, the fourth industrial revolution marked by the incorporation of digital technologies into manufacturing processes, it has emerged as a crucial technology (Gao et al., 2015). When compared to traditional manufacturing techniques, additive manufacturing has some special advantages and capabilities, such as the capacity to reduce material waste, produce complicated geometries, and facilitate rapid prototyping (Frazier, 2014). The use of additive manufacturing in the Industry 4.0 paradigm has the potential to alter a number of industries, from the aerospace and automotive to the custom manufacturing. Researchers have investigated the use of additive manufacturing to create customised items, working prototypes, and even end-use components (Kumar et al., 2019). The technology has been employed to manufacture intricate components with complex geometries, such as lightweight aircraft parts and medical implants (Zhang et al., 2018).

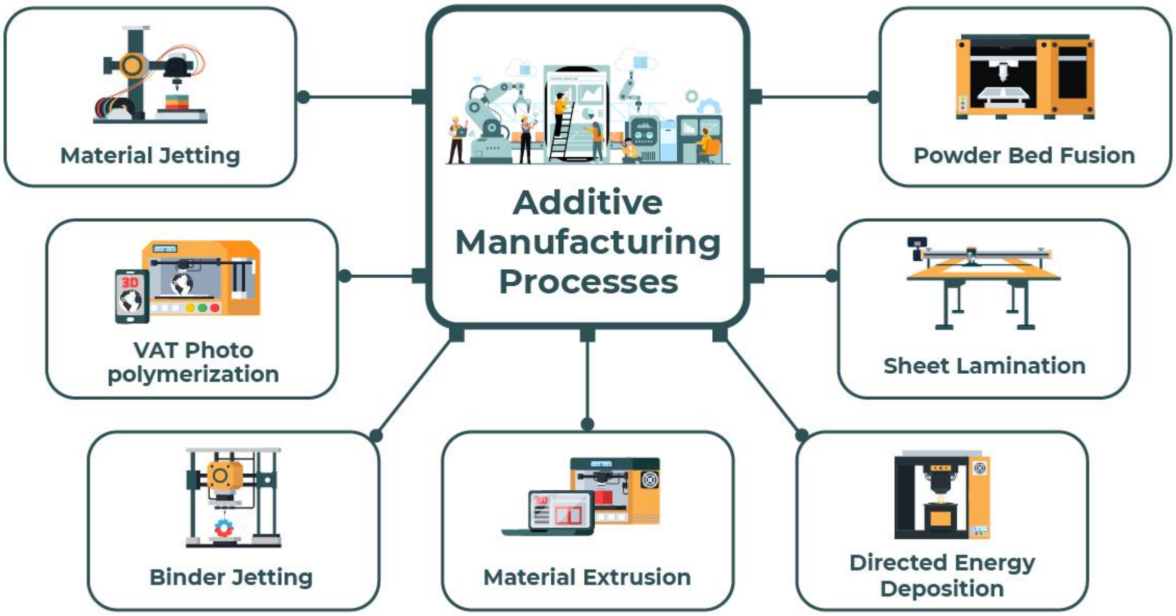


Figure 1 AM Processes

(Bhagyashri et al., 2021)

The various AM processes are briefly described under **Table 1**:

***Table 1** AM Processes*

Additive Manufacturing Process	**Description**	**Applications**	**Reference**
Fused Deposition Modeling (FDM)	To produce an object with FDM, a thermoplastic filament is melted and deposited one layer at a time. It is widely utilised and reasonably priced.	Prototyping, low-cost production, tooling	(Crump, 1992; Bellini & Güçeri, 2003)
Stereolithography (SLA)	SLA selectively cures a liquid photopolymer resin using a UV laser, hardening it layer by layer. It provides a smooth surface finish and excellent precision.	Prototyping, dental, jewelry, consumer products	(Hull, 1986; Crump, 1991)
Selective Laser Sintering (SLS)	SLS uses a laser to carefully fuse powdered materials, such metals or polymers, one layer at a time. It makes it possible to produce intricate	Prototyping, functional parts, aerospace, automotive	(Deckard, 1986; Kruth et al., 1991)

	components and useful prototypes.		
Digital Light Processing (DLP)	DLP concurrently cures a liquid photopolymer resin with a digital light projector. Compared to SLA, it offers faster printing rates.	Prototyping, dentistry, jewelry, consumer products	(Smalley, 1988; Kodama, 1981)
Binder Jetting	Binder jetting is the process of applying a liquid binder over a layer of powdered material, fusing the fragments to create an item. Sand moulds and metal parts are two popular uses for it.	Sand molds, metal parts, architectural models	(Sachs et al., 1990; Kruth et al., 1993)
Material Jetting	Inkjet printheads are used in the material jetting process to layer-by-layer deposit liquid photopolymer materials, which are then hardened to form the product. It makes it possible to print in multiple colours and materials.	Prototyping, multi-material objects, dental models	(Simpson et al., 1988; Sachs et al., 1992)

Electron Beam Melting (EBM)	EBM creates high-strength, completely dense metal parts with intricate geometries by selectively melting and fusing metal powder particles.	Aerospace components, medical implants, tooling	(Kamath et al., 1992; AlMangour et al., 2017)
Direct Metal Laser Sintering (DMLS)	A powerful laser is used in the DMLS method of metal additive manufacturing to selectively melt and fuse metal powder particles. It has excellent accuracy and can make complex metal pieces.	Complex metal parts, aerospace, automotive	(Deckard et al., 1999; Kruth et al., 2004)
Selective Laser Melting (SLM)	SLM is comparable to DMLS, in which metal powder particles are selectively melted and fused using a laser. It is frequently used for intricately shaped high-precision metal components.	Medical implants, aerospace components, automotive	(Gibson et al., 2010; Kruth et al., 2011)
Laminated Object Manufacturing (LOM)	LOM entails utilising an adhesive or heat to layer and adhere sheets of material, most frequently paper or	Large-scale prototypes, architectural	(Deckard, 1988; Beaman et al., 1992)

	plastic. It is used to make inexpensive or large-scale prototype models.	models, low-cost models	

Greater design freedom provided by additive manufacturing makes it possible to produce extremely complex and optimised structures that were previously impossible to produce using conventional manufacturing techniques. Additive manufacturing enables the fabrication of things with exact geometry and customised material properties by layering materials and precisely depositing them (Bourell et al., 2016). This ability creates new opportunities for product innovation, expanded functionality, and better performance. However, there are still obstacles in the way of fully realising additive manufacturing's promise in the context of Industry 4.0. The need for better material selection and characterisation, process optimisation, and quality assurance are some of these difficulties (Gao et al., 2015). Furthermore, standards, interoperability, and intellectual property rights must be carefully taken into account when integrating additive manufacturing into already-existing supply chains and industrial ecosystems (Kumar et al., 2019). It is essential to undertake a thorough study of the existing status of the technology, identify gaps, and provide strategies for its successful deployment in order to address these issues and fully capitalise on the advantages of additive manufacturing in Industry 4.0. With a focus on its impact, difficulties, and potential facilitators, this study seeks to add to the body of knowledge by offering a thorough analysis of additive manufacturing in the context of Industry 4.0. The goal of this study is to offer insightful analysis and suggestions for future developments in additive manufacturing within the context of Industry 4.0 by reviewing the most recent research, papers, and case studies.

Manufacturers may construct goods with complex geometries with additive manufacturing, which is difficult or impossible to do using conventional production techniques. This makes it especially beneficial for sectors like aircraft, where delicate designs and lightweight construction are essential. Reducing waste and maximising resource consumption are two benefits of additive manufacturing in Industry 4.0. During the production process of traditional manufacturing techniques, extra material is frequently produced. With additive manufacturing, waste is reduced and material costs are reduced because only the material needed to make the product is used.

Additionally, additive manufacturing has a great deal of promise for on-demand production, which eliminates the need for significant completed goods inventories. A more responsive supply chain and lower storage costs may arise from this. Additive manufacturing can be used with other digital technologies like automation and artificial intelligence (AI) in Industry 4.0 (Figure 2) to produce manufacturing processes that are more effective and productive. Automation can handle monotonous operations like part removal and post-processing, while AI can be used to optimise designs for additive manufacturing.

It's important to remember that additive manufacturing is not a universal answer and might not be appropriate for all goods or uses. The method might not be economical for high-volume production runs and some materials might not be compatible with additive manufacturing procedures. Despite these drawbacks, additive manufacturing is a key technology in Industry 4.0 and is anticipated to grow in significance within the industrial sector over the next several years.

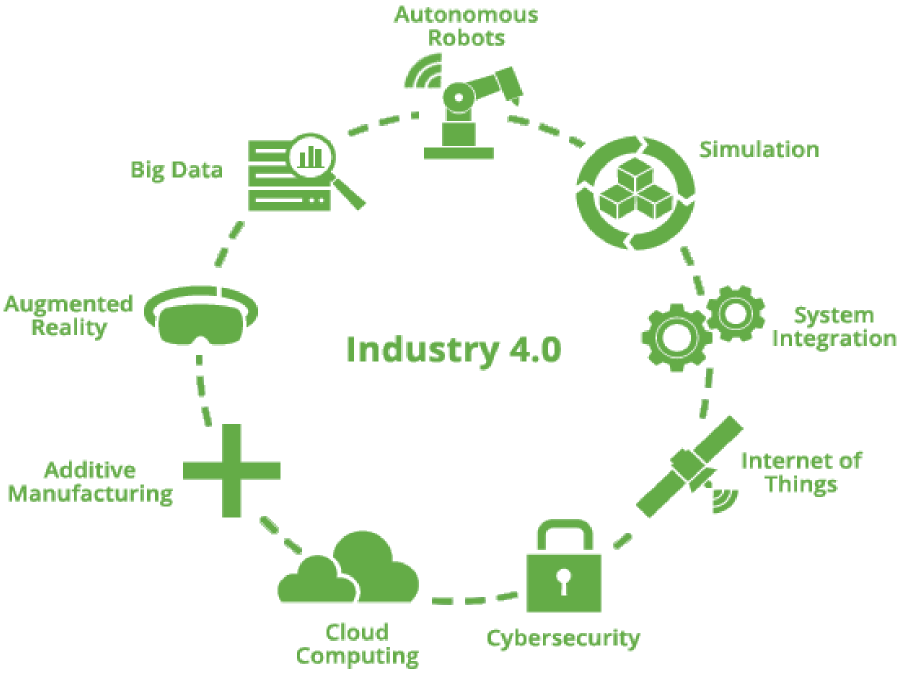


Figure 2 Industry 4.0
(Leap webadmin, 2023)

1.3 APPLICATION AREAS OF ADDITIVE MANUFACTURING

AM in various sectors and industries and facilitate the growth of Industry 4.0 also, a list of examples of various industries from each sector is given in **Table *2***:

- **Aerospace Sector:** The aerospace industry has embraced additive manufacturing as a game-changer in the production of aircraft and spacecraft components. Aerospace producers may produce sophisticated and complex parts with great structural precision by using 3D printing technology. This makes it possible to produce lightweight parts that improve overall performance and fuel economy (Sachs et al., 2012; Taminger, 2016). For example, GE Aviation has utilized additive manufacturing to produce fuel nozzles for jet engines, allowing for the production of intricate internal geometries that optimize fuel combustion and enhance engine performance (Wohlers Associates, 2019).
- **Automotive Sector:** The use of additive manufacturing in the automobile sector has grown significantly in recent years. The enormous potential of 3D printing technology for creating prototypes, customised components, and tools has been acknowledged by the auto industry. The design and development process has been expedited by the capacity to build parts quickly utilising additive manufacturing, allowing for quicker iterations and a shorter time to market (Berman, 2012; Kempton et al., 2018). Wheel rims, air intakes, and external mirrors are just a few of the components that automakers like BMW have produced using additive manufacturing to allow for customisation, better functioning, and design freedom (Weller et al., 2015).
- **Tooling and Manufacturing:** Additive manufacturing has found significant applications in tooling and manufacturing processes. The ability to produce customized jigs, fixtures, and molds using 3D printing technology has transformed the production landscape.

Manufacturers, such as Airbus, have adopted additive manufacturing to create complex molds for aircraft parts, enabling faster production cycles, reduced costs, and increased design flexibility (Weller et al., 2015; Pham et al., 2020).

- **Medical Sector:** With the introduction of additive manufacturing, the medical sector has experienced revolutionary improvements. The capacity to design implants, prosthesis, and surgical instruments specifically for patients has transformed patient care (Bose et al., 2013; Hollister et al., 2015). With the help of additive manufacturing, personalised medical equipment may be created that precisely match each patient's distinctive anatomy, leading to better treatment outcomes and patient comfort (Bibb et al., 2011). For patients who require medical interventions, businesses like Oxford Performance Materials use additive manufacturing to create cranial implants that are customised to each patient's unique needs. This increases surgical precision, shortens recuperation times, and improves patients' quality of life (Wohlers Associates, 2019).
- **Personalization Sector**: The consumer goods industry has embraced additive manufacturing as a means to unlock new possibilities in product design and customization. With 3D printing, manufacturers can create intricate and personalized products that cater to individual preferences and requirements (Campbell et al., 2011; Lu et al., 2014). Companies like Adidas have utilized additive manufacturing to produce custom shoes, leveraging precise measurements and unique designs, offering consumers a truly personalized experience (Weller et al., 2015).
- **Energy Sector:** The energy industry has recognized the potential of additive manufacturing to address specific challenges in power generation and renewable energy systems. By leveraging 3D printing technology, manufacturers can produce complex parts and components with improved efficiency and durability (Kanagarajah et al., 2016; Liu et al., 2019). Siemens, for example, has harnessed

additive manufacturing to produce gas turbine blades that exhibit superior strength and performance compared to traditional blades (Wohlers Associates, 2019).

- **Construction Sector:** Additive manufacturing has made inroads into the construction industry, revolutionizing the way buildings are designed and constructed. With the use of 3D printing technology, architects and builders can create intricate and unique components for walls, floors, and facades (Buswell et al., 2007; Khoshnevis, 2017). Winsun, a Chinese construction company, has successfully used 3D printing to construct buildings, including a five-story apartment complex (Wohlers Associates, 2019).
- **Jewelry Sector:** The jewelry industry has embraced additive manufacturing to push the boundaries of design and craftsmanship. Jewellers can now construct sophisticated and complex jewellery pieces using 3D printing that were previously challenging to produce using conventional production techniques (Campbell et al., 2011). Companies like Bulgari have utilized 3D printing technology to produce high-end jewelry designs, including a range of necklaces (Wohlers Associates, 2019).
- **Food Sector:** Additive manufacturing has found its way into the food industry, where it enables chefs and food manufacturers to create customized food designs and decorations. Using 3D printing technology, intricate and artistic food creations can be made, enhancing visual appeal and presentation (Caballero et al., 2017; Wohlers Associates, 2019). Companies like 3D Systems have developed food printers capable of producing customized chocolate designs, showcasing the potential of AM in the culinary world.
- **Military Sector:** The military sector has recognized the benefits of AM in addressing the challenges of maintaining and repairing military equipment. By leveraging 3D printing, military personnel can produce spare parts and components on-demand, reducing dependence on traditional supply chains and minimizing downtime (Hall et al., 2014;

Hood-Daniel & Kelly, 2015). The US Army, for example, has embraced additive manufacturing to produce spare parts for vehicles and equipment, ensuring mission readiness and cost savings.

Table 2 *Various Industrial Examples*

Sr. No.	**Industry**	**Company Name**	**Product Description**
1	Automotive	Tata Motors	Additive manufacturing is used to produce prototypes, custom tooling, and certain vehicle components. (Berman B., 2012)
		Mahindra & Mahindra	AM is utilized for rapid prototyping, tooling, and manufacturing of specialized automotive parts. (Kempton A. et al., 2018)
2	Aerospace and Defense	Hindustan Aeronautics Limited (HAL)	HAL employs AM for manufacturing complex aircraft components, including engine parts and structures. (Buswell R. A., 2007)
		Bharat Electronics Limited (BEL)	BEL uses AM to produce high-precision electronic housings and specialized defense equipment. (Pham et. al, 2020)
3	Healthcare and Medical Devices	Medtronic India	AM enables Medtronic to manufacture patient-specific medical implants and surgical instruments. (Bose S. et al., 2013)
		Sree Chitra Tirunal Institute for Medical Sciences and Technology	This institute utilizes AM for producing customized prosthetics & biomedical devices (Hollister S. et al., 2015).

4	Personalization Sector	Titan Company	Titan leverages AM for the production of intricate and customized jewelry designs. (Campbell I. et al., 2011)
		Fabindia	AM is employed to create unique home decor items and personalized fashion accessories. (Lu Y. et al., 2014)
5	Architecture and Construction	Apis Cor	Apis Cor specializes in 3D-printed construction, producing houses and building components. (Khoshnevis B., 2017)
		Tvasta Manufacturing Solutions	Tvasta utilizes AM for on-site printing of low-cost, sustainable housing solutions (Wohlers Associates, 2019)
6	Tooling and Manufacturing	Godrej Tooling	Godrej employs AM for the production of complex tooling systems used in various manufacturing processes (Liu Z et al., 2019).
		Larsen & Toubro (L&T)	L&T utilizes AM to create intricate molds, fixtures, and jigs for precision manufacturing (Ngo T. D. et al., 2018).
7	Education and Research	Indian Institute of Technology (IIT) Bombay	IIT Bombay explores AM for research, innovation, and teaching, focusing on various application areas (Thakur V. et al., 2015).
		Vellore Institute of Technology (VIT)	VIT uses AM to develop prototypes, functional parts, and biomedical

			devices for research purposes (Jeevanantham A. K. et al., 2018).

AM enables the production of extremely customised items. For instance, the medical sector is utilising this technology to create individualised implants and prostheses that are tailored to each patient's needs. The percentages of AM applications in several global industry sectors are also shown in Figure 3.

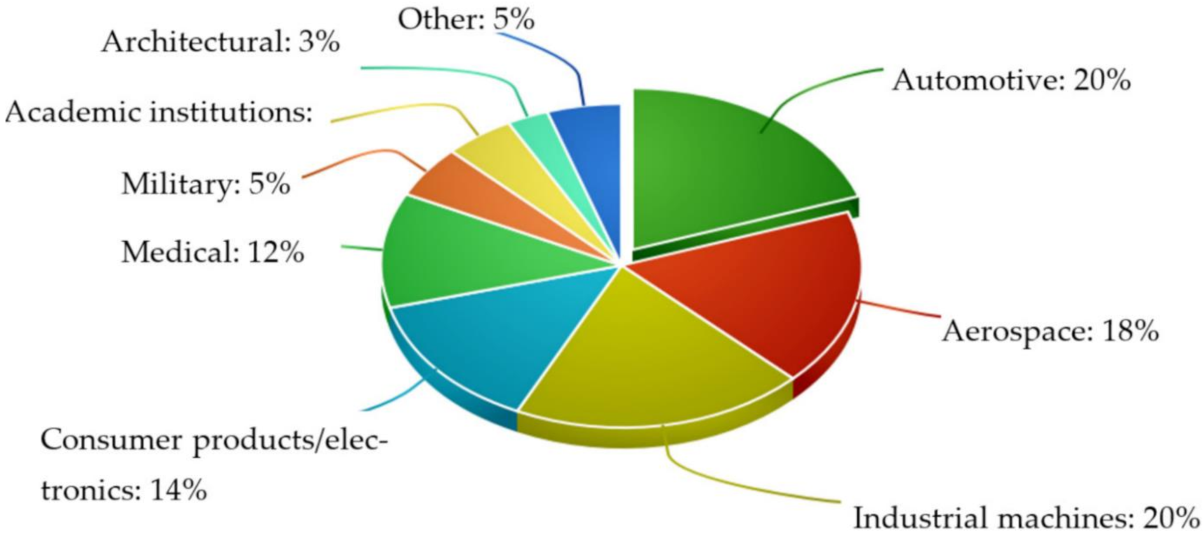


Figure 3 Pie Chart representing AM application in different sectors

(Vafadar, A et al., 2021)

The (Vafadar, A et al., 2021) pie chart represents the factual percentages where Additive Manufacturing is being used throughout the industrial sectors in which automotive and industrial machines leads with the most percentage of 20 percent, then is used in aerospace with 18 percent, and another thing to be noticed here is that Architectural firms , military are using least of the AM in their working with percentages of 3 percent and 5 percent respectively.

The environmental impact of production can be lessened using additive manufacturing. Traditional manufacturing processes frequently produce a lot of waste and use a lot of energy to create items. With additive manufacturing, waste and energy usage may be reduced, making manufacturing more environmentally friendly.

The management of the supply chain is also given new opportunities by additive manufacturing. Products can be produced locally or close to the point of consumption rather without having to travel long distances. As a result, the supply chain may be more responsive and delivery times may be shortened. Data analytics may be used more effectively by businesses thanks to the integration of additive manufacturing into Industry 4.0. By gathering and interpreting data from the additive manufacturing process, manufacturers may optimise the manufacturing process, lowering faults and raising overall product quality.

Large-scale building components have been produced with AM in the building sector. With the help of this technology, architects and engineers can produce intricate shapes and patterns that would be challenging or impossible to make using conventional construction techniques.Innovation in the industry is also being fueled by the creation of new materials created especially for additive manufacturing. These materials provide fresh options for product design and may enable the development of previously impractical goods.

Table 3 AM applications in various Industries

Sr. No.	**Industry**	**Additive Manufacturing Applications**	**Digital Technologies Incorporated**
1	Aerospace	- Rapid prototyping of complex aircraft components	- CAD software and simulation tools: Design and optimize complex components
		- Production of lightweight and high-performance parts	- Cloud computing: Utilize cloud-based design and collaboration

			platforms for seamless access to design data and resources
2	Automotive	- On-demand production of spare parts	- CAD software and simulation tools: Design and test custom car parts and components
		- Creation of complex engine components	- Internet of Things (IoT): Enable real-time monitoring and quality control of additive manufacturing processes
3	Healthcare	- 3D-printed patient-specific implants and prosthetics	- Medical imaging data: Create personalized medical solutions
		- Customized medical devices and instruments	- CAD software: Design and customize medical devices and instruments
		- Personalized pharmaceuticals and drug delivery systems	- Blockchain: Ensure traceability and security of supply chains for personalized pharmaceuticals and medical devices

5	Architecture	- Creation of intricate architectural models and prototypes	- CAD software: Design complex architectural structures
		- Construction of complex building components and facades	- Additive manufacturing: Implement IoT-enabled sensors for monitoring and maintenance of 3D-printed architectural elements
6	Personalization Goods	- Customized production of consumer products	- CAD software: Design and customize consumer goods
		- Optimization of product designs based on data analytics	- Data analytics: Analyze consumer preferences and trends to inform product customization and design decisions
			- Blockchain: Enable secure intellectual property protection and authentication for digitally distributed designs and customized products

7	Electronics	- Production of complex and miniaturized electronic components	- Additive manufacturing: Produce intricate electronic components
		- Design and optimization of circuit boards and housings	- CAD software and simulation tools: Design and optimize electronic components and housings
8	Energy	- Customized production of components for renewable energy systems	- Additive manufacturing: Produce optimized components for energy systems
		- Design and testing of energy-efficient parts and equipment	- CAD software and simulation tools: Design and test energy-efficient components and equipment

CHAPTER 2

LITERATURE REVIEW

The Fourth Industrial Revolution, or **Industry 4.0**, is the integration of cutting-edge digital technology into industrial processes to produce intelligent, networked, and highly automated systems. It includes, among other things, technologies like cloud computing, robotics, big data analytics, artificial intelligence (AI), and the Internet of Things (IoT). Since Industry 4.0 has the potential to transform manufacturing and whole industries, it has attracted a lot of interest. Industry 4.0, defined by the integration of physical and digital systems, signifies a paradigm shift in manufacturing, according to Baines et al. (2017). The authors stress that the incorporation of digital technology enables the development of intelligent factories that can adjust and react to changing demands in real-time, resulting in increased efficiency, flexibility, and production. Furthermore, Industry 4.0, according to Porter and Heppelmann (2015), has the ability to alter business models by opening up new avenues for value creation and improving client experiences. The Internet of Things (IoT), which facilitates connectivity and communication between devices, goods, and systems, is one of the main forces behind Industry 4.0. IoT technology enable real-time data gathering, analysis, and decision-making, which improves operational efficiency and promotes predictive maintenance, according to Li et al. (2017). The authors stress the ability of IoT to personalise production, enhance product quality, and optimise supply chains.

The application of big data analytics and AI is a crucial component of Industry 4.0. The importance of big data in enabling data-driven decision-making and process optimisation is highlighted by Chen et al. (2019). They contend that the analysis of enormous volumes of data by AI algorithms may be used to spot trends, optimise production settings, and anticipate maintenance requirements, which will increase productivity and lower costs. The potential of AI in enabling cognitive manufacturing systems that can learn, adapt, and make autonomous decisions is further highlighted by Wang et al. (2018). Industry 4.0 also includes automation and robotics as essential elements. Pereira et al. (2017) claim that the combination of robotics and AI technologies paves the way for the creation of cooperative and autonomous robots that can cooperate with people in a flexible and adaptable way, ***Table 4*** summarizes the aspect technologies of industry 4.0.

In conclusion, Industry 4.0 is an innovative change in manufacturing that is made possible by the use of cutting-edge digital technologies. It promises to enable new types of value creation, optimise supply networks, and build smart factories. The potential of Industry 4.0 can only be realised with the help of the Internet of Things, big data analytics, AI, and robotics. By utilising these technologies, industries may boost production, adaptability, and efficiency, which will provide them a competitive edge in the global market.

Table 4 Industry 4.0 and including Technologies

Aspect	Description	Citation
Connectivity	Industry 4.0 relies on the Internet of Things (IoT) to enable connectivity and communication between machines, products, and systems.	Li, S., Da Xu, L., & Zhao, S. (2017)
Big Data Analytics	Big data analytics plays a crucial role in Industry 4.0 by analyzing large volumes of data to derive valuable insights for decision-making and process optimization.	Chen, Y., Zhang, Y., & Cai, Y. (2019)

Artificial Intelligence	Artificial intelligence (AI) technologies are utilized in Industry 4.0 to enable intelligent decision-making, automation, and adaptive systems.	Wang, L., Xu, L. D., & Xu, E. (2018)
Robotics and Automation	Industry 4.0 integrates robotics and automation to enhance productivity, flexibility, and safety in manufacturing environments.	Pereira, C. E., Romero, D., Molina, A., & Garcia-Sanchez, A. J. (2017)
Additive Manufacturing	Additive manufacturing, also known as 3D printing, is a key technology in Industry 4.0 that enables the production of complex and customized products with reduced lead times and costs.	Kusiak, A. (2018)
Cyber-Physical Systems	Cyber-physical systems (CPS) are the backbone of Industry 4.0, integrating physical and digital components to enable real-time monitoring, control, and decision-making.	Lee, J., Bagheri, B., & Kao, H. A. (2015)
Augmented Reality	Augmented reality (AR) technologies are used in Industry 4.0 to provide workers with real-time information, instructions, and visualizations,	Liu, D., & Benyoucef, L. (2017)

	enhancing productivity and accuracy in manufacturing processes.	
Cloud Computing	Cloud computing enables scalable and flexible data storage, processing, and sharing in Industry 4.0, facilitating access to resources, collaboration, and remote monitoring and control.	Xu, L. D., Xu, E., & Li, L. (2018)
Blockchain	Blockchain technology is increasingly applied in Industry 4.0 to ensure secure and transparent transactions, data sharing, and traceability in supply chains and manufacturing processes.	Zeng, S., Wen, J. T., & Du, X. (2019)
Virtual Reality	Virtual reality (VR) is utilized in Industry 4.0 for virtual prototyping, training, and simulation, allowing for immersive and interactive experiences that enhance design and manufacturing processes.	Radkowski, S., & Dampc, F. (2019)
Cognitive Computing	Cognitive computing combines AI, machine learning, and natural language processing to enable machines to understand and interact with humans, supporting complex decision-making and problem-solving in Industry 4.0.	Davari, S., & Soltanizadeh, H. (2019)

One of the key technologies of Industry 4.0, which is characterised by the integration of digital technology into production processes, is additive manufacturing (AM), also known as 3D printing (Ji et al., 2018). In comparison to traditional manufacturing methods, additive manufacturing (AM) has a number of benefits, such as the ability to produce highly complicated geometries with less waste and at a lower cost (Kumar et al., 2019). AM is anticipated to play a big part in Industry 4.0 by enabling product customisation and personalization as well as quick prototyping of novel concepts.

Additionally, the combination of Industry 4.0 and AM can result in new business models and sources of income. For instance, AM can enable mass customization, enabling businesses to provide consumers with personalised items on a massive scale (Berman, 2012). Additionally, AM can generate replacement components immediately, eliminating the requirement for large inventories and enhancing supply chain effectiveness (Lindemann et al., 2017). To fully realise AM's promise in Industry 4.0, various issues must be resolved. These difficulties include the necessity for standardisation of additive manufacturing (AM) methods and materials as well as the shortage of skilled workers who can run and maintain AM equipment (Chua et al., 2017).

Collaboration between business, academia, and government organisations to address difficulties and advance R&D is an enabler for integrating AM with Industry 4.0 (Kumar et al., 2019). Additionally, the creation of open standards and norms for AM can aid in ensuring compatibility and interoperability between various machines and systems. Furthermore, funds and resources for research and development are available, which may hasten the implementation of AM in Industry 4.0.

The integration of AM with other I4.0 technologies offers even more significant potential for innovation and efficiency in manufacturing (Zheng et al., 2019). For example, the combination of AM and robotics can enable the automated production of highly complex products with minimal human intervention. Similarly, the integration of AM with the Internet of Things (IoT) can enable real-time monitoring of the production process and the optimization of manufacturing parameters (Tang et al., 2020). Another critical area of collaboration between AM and Industry 4.0 is using digital twins, virtual models of physical products or systems (Huang et al., 2020). Digital twins can simulate and optimize the manufacturing process, reducing the need for costly physical prototyping and testing. The combination of AM and digital twins can enable the rapid iteration and optimization of product designs, leading to faster time-to-market and increased competitiveness.

2.1 ADDITIVE MANUFACTURING IN COLLABORATION WITH VARIOUS OTHER TECHNOLOGIES OF INDUSTRY 4.0 AND FUTURE SCOPE

Certainly, additive manufacturing can be used in collaboration with another technology in Industry 4.0 for further development in the industry and by using additive manufacturing in conjunction with other Industry 4.0 technologies, researchers can improve the product development process, creating more efficient products, higher quality, and better suited to meet the needs of customers:

- Additive manufacturing and artificial intelligence (AI) can be collaborated to improve the efficiency and effectiveness of the product development process. For example, researchers could use AI algorithms to generate and optimise complex designs for additive manufacturing, resulting in functional and aesthetically pleasing products. Once a design has been created, additive manufacturing can produce the product, with sensors installed to collect data on the manufacturing process. This data can be used to refine the manufacturing process, reduce defects, and improve product quality. The data collected can also be fed back into the AI algorithms, improving their ability to generate optimised designs for future products (Heiden B. et al., 2021).
- Additive manufacturing and 3D scanning: 3D scanning can capture and digitise physical objects, which can be used as the basis for additive manufacturing. For example, researchers can scan an existing part and use the resulting 3D model to create a new version of the part that is optimised for additive manufacturing (Wang, R. et al., 2021).
- Additive manufacturing and Cloud Computing: Cloud computing can store and analyse data collected during additive manufacturing. This data can optimise the

manufacturing process, identify potential issues, and improve product quality. Additionally, cloud computing can enable remote collaboration between researchers, allowing for real-time collaboration and communication (Haghnegahdar, L. et al., 2022).

- Additive manufacturing and Nanotechnology: Nanotechnology can create new materials specifically designed for additive manufacturing. For example, nanoparticles can be added to traditional materials to improve their properties, such as strength, flexibility, or thermal conductivity (Deshmukh K. et al., 2022).
- Additive manufacturing and Robotics: Robotics can automate the additive manufacturing process, reducing the need for human intervention and improving production efficiency. Additionally, robotics can perform post-processing tasks, such as cleaning or finishing, reducing the need for man power (Pinar Urhal et al., 2019).

Industry 4.0 relies heavily on additive manufacturing because it enables producers to efficiently produce intricate, highly personalised items. This technology is expected to play a bigger role in manufacturing as it develops, opening the door to the development of whole new goods and industrial processes that were previously unachievable.Using artificial intelligence (AI) and machine learning to improve the manufacturing process is a crucial area of cooperation between AM and Industry 4.0 (Kim et al., 2020). The application of additive manufacturing in smart factories is depicted in the figure. AI algorithms can find trends in the data collected from sensors and other sources and forecast how well AM machines will operate. This can help to optimize the manufacturing process and reduce the risk of errors and defects.

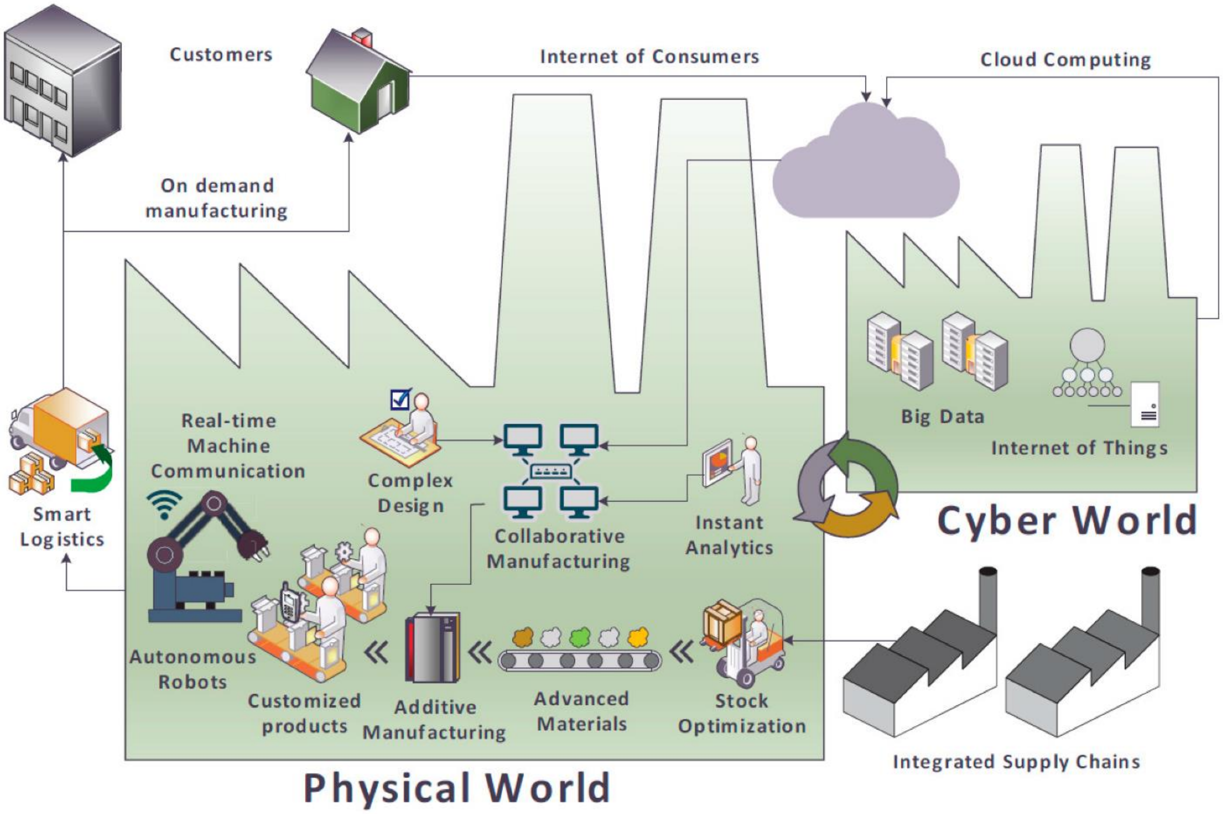


Figure 4 Role of Additive Manufacturing in a Smart Factory under Industrial 4.0 (Mehrpouya, M, 2019)

Distributed manufacturing is one of the main advantages of additive manufacturing in the context of Industry 4.0 (Wuest et al., 2016). AM can be spread out around the globe, connected to one another via the internet, and controlled from a single location. As a result, a decentralised production network may be established, which is more adaptable and responsive to changes in demand. Additive manufacturing can be extremely important for sustainable production in addition to its potential for distributed manufacturing. Compared to conventional production methods, additive manufacturing (AM) can save waste and energy by using only the materials required to make a product (Huang et al., 2021).

2.2 ENABLERS

Enablers are elements or factors that make it easier or promote the achievement of a particular result or objective. They are essential to improving or facilitating a certain process, project, or system's success. Resources, techniques, technology, tactics, or any other powerful elements that support the efficacy, efficiency, and successful completion of a particular undertaking are examples of enablers. Depending on the particular domain or environment, enablers can take on many shapes. Advanced software, hardware, or infrastructure that promote innovation, automation, and digital transformation are examples of enablers in technology-driven fields. Enablers in organisational settings can include strong leadership, transparent channels of communication, a welcoming culture, and availability of required resources. Enablers in the context of personal development could be methods, strategies, or networks of assistance that aid in learning, development, and goal-achieving.

Enablers found out from thorough researching the available published works of various renowned researchers, which could be used for various decision-making techniques, to know which one is most affecting in encouraging additive manufacturing in industry 4.0, The Analytic Hierarchy Process (AHP), a method for making decisions, can be used to prioritise and assess options based on a variety of criteria. These enablers can be used as criterion for this process. The goal of AHP is to rank alternatives according to their relative relevance by first organising complex decisions into a hierarchy of criteria and alternatives, and then comparing the alternatives pairwise. In the AHP hierarchy, the enablers can serve as the top-level criteria from which sub-criteria and alternatives can be formed depending on the particular situation and decision-making goals. The Analytic Hierarchy Process (AHP), a method for making decisions, can be used to prioritise and assess options based on a variety of criteria. These enablers can be used as criterion for this process. The goal of AHP is to rank alternatives according to their relative relevance by first organising complex decisions into a hierarchy of criteria and alternatives, and then comparing the alternatives pairwise. In the AHP hierarchy, the enablers can serve as the top-level criteria from which sub-criteria and alternatives can be formed depending on the particular situation and decision-making goals.

Table 5 shows list of enablers with their supporting citations:

2.2.1 Triple Helix

Collaboration between industry, academia, and government agencies: Triple helix is a term that relates the collab of academia, government agencies and industries (Asad et al., 2018). Collaboration between stakeholders is crucial for successfully integrating additive manufacturing in Industry 4.0. Studies have demonstrated that cooperation can result in the creation of new technologies, standards, and laws that can help with additive manufacturing's issues, such as the requirement to standardise procedures and materials (Kagermann et al., 2013; Lefebvre et al., 2019). Collaborative efforts can also facilitate the sharing of resources, knowledge, and expertise, leading to accelerated innovation and adoption of additive manufacturing technologies (Jia et al., 2020).

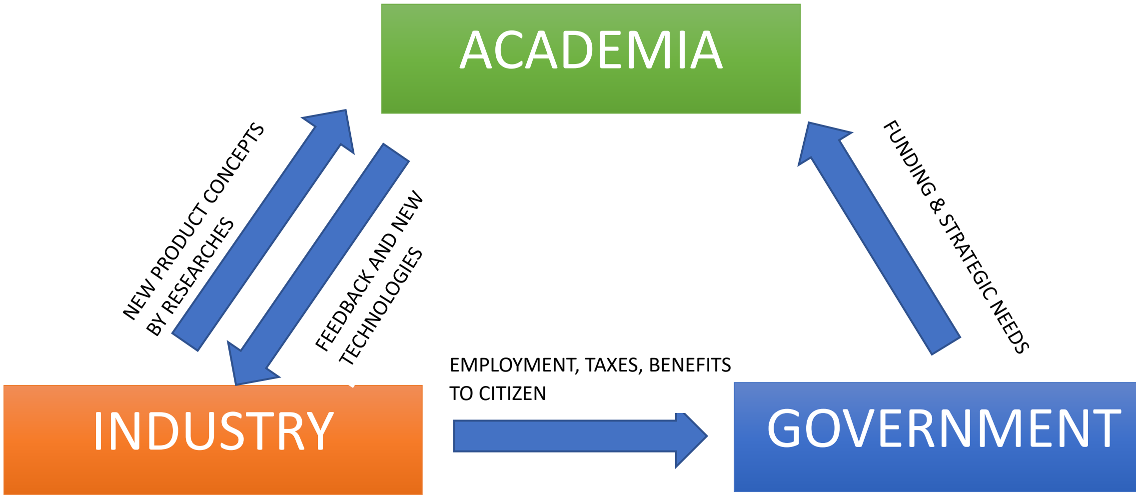


Figure 5 Triple helix

(Dezhina, Irina et al., 2023)

2.2.2 Accessibility

Development of open standards and guidelines for additive manufacturing: Open standards and guidelines can help to ensure interoperability and compatibility between different systems and machines. This can make additive manufacturing more widely used in Industry 4.0 and encourage innovation. In order to foster interoperability, enhance quality, and lower costs, open standards and norms for additive manufacturing have been emphasised in prior research (Mäntyjärvi et al., 2017; Mazzoleni et al., 2020). The development of open standards can also support global collaboration and the development of a common language for additive manufacturing (Klein et al., 2017).

2.2.3 Capitalization

Research and development funding and resource availability: Adequate funding and resources are required to support additive manufacturing research and development. The use of additive manufacturing technologies could be accelerated as a result, encouraging innovation. Investment in research and development related to additive manufacturing can potentially result in the emergence of new markets, businesses, and sources of income (Weller et al., 2015). For the advancement of additive manufacturing, financing and resources are crucial, especially in the fields of material science, process development, and system integration (Jia et al., 2020; Zhang et al., 2020).

2.2.4 Resource Material

Creation of new materials suitable for additive manufacturing: The technology's potential applications may increase with the creation of new materials suitable for the process. The development of new materials for additive manufacturing, including biocompatible materials, high-performance polymers, and advanced composites, has been the subject of prior study (Zhang et al., 2016; Jamshidinia et al., 2018). New materials can lower production costs, enabling the production of complicated geometries, and improve product functioning (Gao et al., 2019).

2.2.5 Suffusing Labor

Trained personnel who can operate and maintain additive manufacturing machines, Suffusing labor implies to the skilled personnel, who are necessary to operate and maintain additive manufacturing machines successfully. Previous studies have emphasized the importance of training programs for personnel in additive manufacturing, covering topics such as design, material science, process engineering, and quality control (Roberson et al., 2016; Zeghmati et al., 2020The use of additive manufacturing may be made more widely available and its quality and consistency of parts can be improved with the development of a qualified workforce (Wits et al., 2018).

2.2.6 **Interoperability** and **compatibility** between different systems and machines

Interoperability and compatibility between different additive manufacturing systems and machines are necessary to produce complex parts efficiently. Previous research has focused on ensuring interoperability between machines from different vendors is a crucial aspect of achieving industrial-scale additive manufacturing (IAM) (Barnes et al., 2017). The lack of standards for data exchange between machines and software systems has been a significant barrier to the efficient implementation of IAM (Kempton et al., 2017) and developing interoperability standards and protocols for additive manufacturing (Bai et al., 2016; Wits et al., 2018). Developing open standards and guidelines for additive manufacturing can help ensure that machines and software systems from different vendors are interoperable and can exchange data seamlessly, reducing the need for manual intervention.

2.2.7 Optimization

The quality of the products can be increased while production time and cost are decreased by streamlining the additive manufacturing process. Prior research has concentrated on improving several areas of additive manufacturing, such as part design, material choice, and process parameter control (Lindemann et al., 2017). Using sophisticated modelling and simulation tools is one method of process optimisation. Modelling and simulation can assist in identifying and optimising the crucial process variables, such as temperature, pressure, and print head speed, that affect the part's quality (Chiu et al., 2018). In-situ monitoring and feedback systems can also aid in flaw detection and correction in real-time, lowering the requirement for post-processing and increasing the process' overall efficiency (Zhou et al., 2020; Tzeng et al., 2020).

2.2.8 Artificial Intelligence

Using artificial intelligence and machine learning to streamline the manufacturing process: The effectiveness and precision of the additive manufacturing process can be increased by implementing machine learning and artificial intelligence. Prior studies have concentrated on applying machine learning and artificial intelligence to a variety of additive manufacturing applications, including part design, process planning, and quality control (Meng et al., 2018; Tsou et al., 2021). Machine learning can help optimize the process parameters by learning from previous production runs and adjusting the parameters for the next run to achieve better quality and productivity. Artificial intelligence can be used to optimize the design of the part by analyzing data from the production process and identifying design features that affect the quality of the part (Lee et al., 2018). In addition, artificial intelligence can be used to detect defects in real-time, reducing the need for post-processing and improving the overall efficiency of the process.

2.2.9 Entrepreneurship

On the basis of additive manufacturing, new business models and revenue streams can be created, such as on-demand creation of spare parts and mass customisation. The potential of additive manufacturing for new business models and revenue streams has been recognised in earlier research (Berman, 2012; Gao et al., 2019). Small batch sizes can be produced with additive manufacturing, which eliminates the need for significant stocks and storage facilities. Additionally, additive printing can make it possible to create intricate shapes and geometries that are either impractical or impossible to make using conventional manufacturing processes, creating new possibilities for product differentiation and personalization.

2.2.10 Personalization

Promotion of mass customisation and on-demand manufacture of spare parts: Additive manufacturing makes it possible for mass customization and inventory-saving on-demand production of spare parts. The difficulties associated with traditional manufacturing, such as the requirement for high production volumes and lengthy lead times, may be addressed in this way. Healthcare, aerospace, and the automotive sectors are just a few of the sectors where personalization through additive manufacturing is growing in popularity (Choi et al., 2018; Luo et al., 2020). For instance, with 3D printing, customised implants and prostheses can be made to fit each patient's individual anatomy and increase comfort and mobility (Van Noort, 2012). Additive manufacturing is utilised in the aerospace sector to create lightweight, intricate, and high-performance components that are challenging or impossible to manufacture using conventional manufacturing methods (Craeghs and Van Genechten, 2018). Additionally, the production of replacement components on demand using additive manufacturing in the automobile sector lowers lead times and costs for manufacturers (Gebhardt et al., 2019). To fully utilise the promise of additive manufacturing for mass customisation and spare part production, there are still issues that need to be resolved.

The lack of 3D printable materials with the required qualities for functional parts is one of the difficulties (Rengier et al., 2010). To solve this problem, it is essential to create new materials and material processing methods that are compatible with additive manufacturing. To assure the quality and dependability of the printed parts, it is necessary to optimise design and process parameters (Lindemann et al., 2017). The design and process parameters for additive manufacturing can be optimised using machine learning and artificial intelligence approaches, allowing for the production of high-quality and dependable parts at a lower cost and with shorter lead times (Tsou et al., 2021).

The Analytic Hierarchy Process (AHP), a method for making decisions, can be used to prioritise and assess options based on a variety of criteria. These enablers can be used as criterion for this process. The goal of AHP is to rank alternatives according to their relative relevance by first organising complex decisions into a hierarchy of criteria and alternatives, and then comparing the alternatives pairwise. In the AHP hierarchy, the enablers can serve as the top-level criteria from which sub-criteria and alternatives can be formed depending on the particular situation and decision-making goals.

Table 5 *Enablers that facilitates the impact of Additive manufacturing in Industry 4.0*

Sr. No.	**Enabler**	**Description**	**Supporting Citations**
1.	Triple Helix	Collaboration between stakeholders can lead to the development of new technologies, standards, and regulations, facilitating the sharing of resources, knowledge, and expertise, leading to accelerated innovation and adoption of additive manufacturing technologies.	Kagermann et al., 2013; Lefebvre et al., 2019; Jia et al., 2020; Lu et al., 2021; Mishra et al., 2021
2.	Accessibility	Open standards and guidelines can help ensure interoperability and compatibility between different systems and machines, facilitating the adoption of additive manufacturing in Industry 4.0 and promoting innovation.	Mäntyjärvi et al., 2017; Mazzoleni et al., 2020; Klein et al., 2017; Yen et al., 2021; Kim et al., 2021
3.	Capitalization	To promote research and development in additive manufacturing, adequate money and resources are required. This will speed up the adoption of additive manufacturing technology, encourage innovation, and result in the creation of new employment, businesses, and revenue streams.	Jia et al., 2020; Zhang et al., 2020; Hidayat et al., 2021; Nguyen et al., 2021; Horta et al., 2022
4.	Resource Material	The development of new materials compatible with additive manufacturing can expand the range of applications for the technology, enabling the production of complex geometries, improving product functionality, and reducing production costs.	Zhang et al., 2016; Jamshidinia et al., 2018; Gao et al., 2019; Chen et al., 2021; Liu et al., 2021
5.	Suffusing labor	To improve the quality and consistency of items created by additive manufacturing and to make the technology more widely used, skilled	Roberson et al., 2016; Zeghmati et al., 2020; Zhang et

		employees are required to run and maintain the machines.	al., 2020; Wu et al., 2021; Kostov et al., 2022
6.	Interoperability and Compatibility	Interoperability and compatibility between different additive manufacturing systems and machines are necessary to produce complex parts efficiently, achieved by developing interoperability standards and protocols for additive manufacturing, ensuring that machines and software systems from different vendors are interoperable and can exchange data seamlessly.	Bai et al., 2016; Wits et al., 2018; Barnes et al., 2017; Kempton et al., 2017; Abeyrathna et al., 2021
7.	Optimization	By improving many components of the additive manufacturing process, such as the design of the parts, the choice of materials, and the control of the process parameters, one may increase the quality of the parts produced as well as cut down on production time and costs.	Lindemann et al., 2017; Tzeng et al., 2020; Chiu et al., 2018; Zhou et al., 2020; Mousavi et
8.	AI	The effectiveness and precision of the additive manufacturing process can be increased by putting machine learning and artificial intelligence to use.	Meng et al., 2018; Tsou et al., 2021; Lee et al., 2018
9.	Entrepreneurship	Mass customisation and the creation of replacement components on demand are two examples of the new business models and revenue streams that additive manufacturing might offer.	Berman, 2012; Gao et al., 2019;
10.	Personalization	Additive manufacturing enables mass customization and on-demand production of spare parts, which reduces lead times and inventory costs.	Choi et al., 2018; Luo et al., 2020; Van Noort, 2012;

			Craeghs and Van Genechten, 2018

2.3 BARRIERS

The term "barriers" describes the difficulties or impediments that prevent the acceptance or application of Industry 4.0 technology and practices. These obstacles may be caused by a variety of elements, including organisational, cultural, technical, and economic aspects. For Industry 4.0 and additive manufacturing to be successfully implemented and integrated, it is essential to recognise and address these obstacles.

The following barriers outline the issues that must be resolved for the broad adoption of additive manufacturing as part of Industry 4.0,

Table 6 summarizes the list of barriers altogether with their supporting citations:

2.3.1 Lack of Standardization

Lack of standardisation is one of the major obstacles preventing the widespread use of additive manufacturing in Industry 4.0. The absence of standardized processes, materials, and design guidelines hinders the seamless integration and compatibility of additive manufacturing technologies across different industries and sectors. This lack of standardization poses several challenges, such as ensuring consistent part quality, promoting interoperability between different additive manufacturing systems, and facilitating material selection for specific applications (Gibson et al., 2015; Kietzmann et al., 2018). Addressing this barrier requires collaborative efforts from industry stakeholders, regulatory bodies, and research institutions to develop and establish widely accepted standards that can promote the reliable and efficient implementation of additive manufacturing technologies.

2.3.2 Financial Steepness

The high costs associated with the technology are a significant deterrent to the widespread adoption of additive manufacturing in Industry 4.0. The initial cost of purchasing the necessary equipment for additive manufacturing, as well as recurring costs for supplies, upkeep, and expert labour, can be high. These expenses may make implementing additive manufacturing less feasible and accessible, particularly for small and medium-sized businesses (SMEs) with limited financial resources (Kang et al., 2016; Kamran et al., 2018). To lower the financial barriers and make additive manufacturing more accessible to a wider range of industries and enterprises, it is critical to develop cost-effective solutions, such as enhanced manufacturing processes, optimised material utilisation, and affordable equipment options.

2.3.3 Limited Material

Adopting additive manufacturing in Industry 4.0 is significantly hampered by the scarcity of suitable materials. While there are more material options accessible with additive manufacturing than with traditional production methods, the selection of materials that are suited for particular purposes is still constrained. According to Berman (2012) and Wong et al. (2019), the majority of materials used in additive manufacturing are polymers, which limits the technology's potential usage in sectors that need materials with particular characteristics, such as high strength, temperature resistance, or biocompatibility. In order to realise the full potential of additive manufacturing and solve its material limits, significant research and development efforts are needed to increase the spectrum of materials that are compatible with it, including metals, ceramics, and composites.

2.3.4 Intellectual Property and Legal Issues

Significant obstacles to additive manufacturing's adoption in Industry 4.0 include IP concerns and legal challenges. Concerns concerning copyright infringement, unauthorised replication of protected designs, and trade secret protection are brought up by the digital nature of additive manufacturing methods. To further ensure the safety and caliber of additive made items, product liability and regulatory compliance are significant factors (Lopez-Galindo et al., 2019; Tham et al., 2019). To promote trust and confidence in the additive manufacturing ecosystem, it is necessary to build strong IP frameworks, precise rules for legal obligations and liabilities, and efficient enforcement mechanisms.

2.3.5 Quality and Safety Concerns

Adoption of additive manufacturing in Industry 4.0 is also significantly hampered by issues with its quality and safety. Even if customisation and unique design freedom are possible with additive manufacturing, maintaining consistent and dependable part quality is still a challenge. The structural integrity and functional performance of items made by additive manufacturing can be impacted by changes in material qualities, manufacturing conditions, and post-processing procedures. Additionally, the handling of powders and the usage of some hazardous compounds present safety issues that must be adequately handled (Kim et al., 2018; Mahamood et al., 2019). To get beyond these obstacles and inspire confidence in the dependability and safety of additive manufacturing, improved quality control systems, reliable testing and certification procedures, and the creation of thorough safety guidelines are crucial.

2.3.6 Lack of Skilled Labor

Adoption of additive manufacturing in Industry 4.0 is significantly hampered by the dearth of competent labor. Compared to conventional manufacturing methods, additive manufacturing technologies call for a diverse set of skills, including proficiency with CAD/CAM software, materials science, process optimisation, and equipment operation. The wider use of the technology is hampered by the lack of qualified employees with the expertise and training required to operate and maintain additive manufacturing equipment (Paraskevas et al., 2019; Snider et al., 2020). To overcome this obstacle, educational programs, training initiatives, and industry-academic partnerships must be established in order to create a skilled workforce capable of utilising additive manufacturing technologies.

2.3.7 Environmental Concerns

Another big impediment is the environmental issue around Industry 4.0's usage of additive manufacturing. Energy is utilised extensively during additive manufacturing processes, and it is important to manage the disposal of waste materials, such as support structures and wasted powders, to reduce the environmental impact. To reduce the environmental issues connected to the technology, additive manufacturing systems must be sustainable, which includes using eco-friendly materials, energy-efficient procedures, and recycling techniques (Lambert et al., 2017; Wang et al., 2020). Promoting environmentally responsible behavior and putting eco-friendly ideas into practice in additive manufacturing will help it gain widespread adoption and leave a smaller ecological imprint.

Table 6 *Barriers that restrict the impact of Additive manufacturing in Industry 4.0*

Sr. No.	**Barrier**	**Description**	**Supporting Citations**
1.	Lack of Standardization	The lack of standardization poses several challenges, such as part quality, interoperability, and material selection, among others.	(Gibson et al., 2015; Kietzmann et al., 2018; Reutzel et al., 2019; Koch et al., 2021; Arif et al., 2021)
2.	Financial Steepness	The cost of equipment, materials and skilled labour are some of the significant factors contributing to the high costs of additive manufacturing.	(Kang et al., 2016; Kamran et al., 2018; Gibson et al., 2019; Strano et al., 2020; Salehizadeh et al., 2021)
3.	Limited Material	Most of the materials available for additive manufacturing are polymers, which limits the applications of the technology.	(Berman, 2012; Wong et al., 2019; Liu et al., 2020; Lu et al., 2021; Cai et al., 2021)
4.	Intellectual Property and Legal Issues	These issues include copyright infringement, product liability, and patent infringement.	(Lopez-Galindo et al., 2019; Tham et al., 2019; Galasso

			et al., 2020; Gao et al., 2021; Zou et al., 2021)
5.	Quality and Safety Concerns	The quality of parts produced through additive manufacturing is still challenging, and safety concerns related to using hazardous materials in the process must be addressed.	(Kim et al., 2018; Mahamood et al., 2019; Cui et al., 2020; Zhang et al., 2021; Li et al., 2021)
6.	Lack of Skilled Labor	The technology requires a different skill set from traditional manufacturing processes, and there is a need for more skilled workers who can operate and maintain the equipment.	(Paraskevas et al., 2019; Snider et al., 2020; Qiu et al., 2021; Tabrizi et al., 2021; Zhang et al., 2021)
7.	Environmental Concerns	The process requires a significant amount of energy, and waste materials disposal is also a concern.	(Lambert et al., 2017; Wang et al., 2020; Zhang et al., 2021; Jiang et al., 2021; Mohd Hanafi et al., 2022)

2.4 ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP) was used to rank the enablers and barriers according to their significance in the context of additive manufacturing in Industry 4.0. The Analytic Hierarchy Process (AHP) was chosen as the decision-making technique in this study because it is appropriate for assessing and ranking many aspects or criteria. AHP is a method for multi-criteria decision analysis that is well known and frequently used, especially in settings where making decisions is difficult and subjective.

While there are other decision-making techniques available, each with its own advantages and limitations, AHP was deemed appropriate for this study based on its characteristics and applicability to the research objectives.

2.4.1 **Other techniques of decision making** which are commonly used for similar purposes include:

2.4.1.1 Multi-Attribute Utility Theory (MAUT):

Multi-Attribute Utility Theory (MAUT) is a decision-making technique that involves assigning utility values to different attributes or criteria and then combining them to determine the overall utility of different alternatives. MAUT is suitable for decision problems that have multiple attributes and require quantifiable utility values. In MAUT, each attribute is assigned a weight representing its relative importance, and a utility function is defined to measure the satisfaction or desirability of each attribute's value. The overall utility of each option is then determined by averaging the utility values using a mathematical model. MAUT offers a methodical method to assess and contrast options based on their utility scores, empowering decision-makers to make wise decisions.

2.4.1.2 Analytic Network Process (ANP):

Analytic Network Process (ANP) is an extension of the Analytic Hierarchy Process (AHP) that allows for the consideration of interdependencies and feedback among criteria. ANP is particularly useful when the decision problem involves a complex network of relationships and interactions between factors. ANP divides the decision problem into a hierarchy of clusters, elements, and criteria. It incorporates both pairwise comparisons and feedback loops to capture the interdependencies between criteria and their impact on the decision outcome. By considering the interactions between criteria, ANP provides a more comprehensive and accurate analysis of decision problems that involve complex relationships.

2.4.1.3 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS):

An alternative's distance from an ideal solution and a negative ideal solution is determined using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), a decision-making technique, based on a number of different factors. Based on how close each alternative is to the optimal choice, TOPSIS produces a numerical ranking. It entails creating a normalised choice matrix, figuring out the weighted normalised values for each alternative, and figuring out how far apart the positive and negative ideal solutions are from each other. The option that is closest to the ideal positive solution and farthest from the perfect ideal solution is deemed to be the most preferable. When decision-makers wish to assess alternatives based on how closely they resemble an ideal answer, TOPSIS is a helpful strategy.

2.4.1.4 Weighted Sum Model (WSM):

The Weighted Sum Model (WSM) is a simple and straightforward decision-making technique that involves assigning weights to different criteria and summing them up to obtain a composite score for each alternative. Weighted Sum Model (WSM) includes giving distinct criteria weights and adding them up to get a composite score for each possibility. When a decision problem involves a lot of quantitative criteria, WSM is frequently utilised. The composite scores offer a quantitative evaluation of how well the alternatives performed overall, and the weights reflect the relative relevance of each criterion. By allowing decision-makers to rank alternatives according to the weighted values of the criteria, WSM offers a clear and understandable method of decision-making.

Table 7 Decision Making-Techniques and their comparison with AHP

Technique	**Description**	**Advantage of AHP**	**Citation**
Multi-Attribute Utility Theory (MAUT)	Assigns utility values to attributes and combines them to determine overall utility of alternatives	AHP provides a more structured approach to decision-making, incorporating pairwise comparisons and a systematic evaluation process	Saaty, T. L. (1987).
Analytic Network Process (ANP)	Considers interdependencies and feedback among criteria	AHP allows for a simpler and more intuitive decision-making process compared to the complex network structure of ANP	(Saaty, T. L., 2005).
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	Ranks alternatives based on their similarity to an ideal solution	AHP incorporates a pairwise comparison approach, providing a more comprehensive and systematic evaluation of alternatives compared to	(Hwang, C. L., & Yoon, K., 1981).

		the similarity-based ranking of TOPSIS	
Weighted Sum Model (WSM)	Calculates a weighted sum of criteria to evaluate alternatives	AHP allows for a more flexible and adaptable weighting of criteria compared to the fixed weights used in the WSM	(Saaty, T. L., 1990).

While these techniques have their own merits, AHP was selected for this study due to its ability to handle both qualitative and quantitative data, its flexibility in accommodating subjective judgments, and its widely recognized applicability in multi-criteria decision analysis.

The fact that AHP can manage both qualitative and quantitative data is one of the main arguments for picking it. AHP enables the merging of expert and subjective judgements, which is frequently necessary in evaluating additive manufacturing-related aspects in the context of Industry 4.0. AHP permits the systematic evaluation of the relative relevance or priority of various aspects through the use of pairwise comparisons, offering a formal framework for decision-making.

2.5 RESEARCH GAP

I. A thorough analysis of the literature on additive manufacturing in the context of Industry 4.0 is required, with an emphasis on the advancements, challenges, and facilitators of this technology.

II. Additional study is required to fully comprehend the condition of additive manufacturing in Industry 4.0, including its developments, difficulties, and possible applications.

III. More investigation is needed to understand the advantages and disadvantages of using the Analytic Hierarchy Process (AHP) technique to make decisions for additive manufacturing in the Industry 4.0 environment.

2.6 RESEARCH QUESTIONS

I. What are the main factors facilitating and impeding the adoption of additive manufacturing within the context of Industry 4.0?

II. How do these enablers and barriers prioritize in terms of their impact on the successful adoption of AM in Industry 4.0?

III. How do the findings of our study compare with previous research conducted on the same topic?

IV. What are the limitations of our study that may affect the generalizability of the results?

V. *What are the future research opportunities and potential real-world applications based on the findings of our study?*

2.7 OBJECTIVES

The objectives of this study are:

I. This study is to examine the facilitators and hurdles that the Analytic Hierarchy Process (AHP) technique can utilise to help with decision-making for additive manufacturing in Industry 4.0.
II. To better understand the state of additive manufacturing in Industry 4.

CHAPTER 3

METHODOLOGY

A thorough literature research was done to determine the enablers and barriers of additive manufacturing in Industry 4.0 in order to meet the paper's objectives. Electronic databases like ScienceDirect, Scopus, and IEEE Xplore were searched, together with pertinent journals and conference proceedings, to conduct the literature review. "Additive manufacturing," "3D printing," "Industry 4.0," "enablers," and "barriers" were the search terms utilised. To guarantee the literature's applicability to the present state of the field, the search was restricted to publications published between 2016 and 2021.

The AHP technique compares criteria in pairs to establish their relative weight, and the results are displayed as a hierarchy. Based on the recommendations and knowledge of a panel of experts, the AHP study offers a structured and methodical approach to identifying the enablers and barriers of additive manufacturing in Industry 4.0. The analysis' findings can help with policy formulation and decision-making in the domain of additive manufacturing in Industry 4.0.

The AHP method made use of Expert Choice, a programme that is frequently used for setting priorities and making decisions. Using pairwise comparisons, the user of Expert Choice can establish a hierarchy of selection criteria and options, then give each one a weighted average. A group of specialists with experience and knowledge in additive manufacturing and Industry 4.0, including researchers, business people, and academics, carried out the AHP analysis.

Expert Choice: A decision-making tool called Expert Choice helps prioritise options based on a number of criteria and offers an organised approach to choice analysis. It provides a forum for stakeholders to work together to review possibilities, give weight to criteria, and determine the relative relevance of each criterion. To determine priorities and enable well-informed decision-making, the software applies the Analytic Hierarchy Process (AHP), a commonly used decision-making technique.

The usage of Expert Choice can construct decision hierarchies, which display the choice problem as a hierarchical structure of objectives, standards, and options. Users can compare each criterion or option to others in terms of relative importance using the software's pairwise comparison feature. The preferences or priorities of each element are then captured in numerical values based on these comparisons.

3.1 AHP ANALYSIS

The AHP analysis is performed in three stages:

3.1.1 Development of the hierarchy

The development of hierarchy is a fundamental step in the Analytic Hierarchy Process (AHP) as shown in Figure , a powerful decision-making technique used to analyze and prioritize multiple criteria and alternatives. In this initial stage of the AHP process, the aim is to create a well-defined hierarchy that represents the decision problem at hand.

The aim, criteria, and alternatives make up the hierarchy's three primary levels, which are organised in a hierarchical tree-like fashion. The goal, which stands for the ultimate aim or reason for the decision-making process, is at the top of the hierarchy. The objective is then broken down into a list of criteria that are important for achieving the objective. A hierarchical structure can be created by further subdividing these criteria into other criteria. The alternatives, which are the prospective options or solutions being considered, make up the lowest level of the hierarchy. Based on their relative importance, the enablers and barriers found in the literature review were arranged into a hierarchical framework. The hierarchy's principal purpose was at the top, followed by the criteria and sub-criteria.

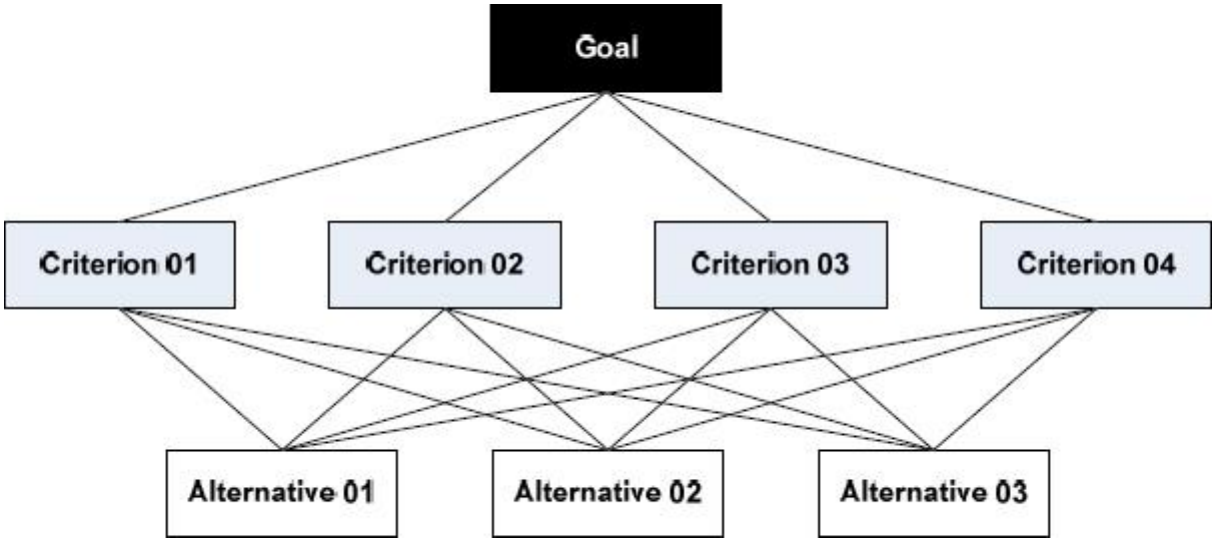


Figure 6 Hierarchical Structure for AHP technique (Schiavon, L.L.P et al., 2023)

3.1.2 Pairwise Comparisons

In the pairwise comparison step of the Analytic Hierarchy Process (AHP), criteria and options are systematically compared to ascertain their respective weights. By allocating numerical values based on the degree of preference or significance between items, this is accomplished. Here's an overview of the process:

i. Select two elements to compare.

ii. Use a scale (e.g., Saaty scale) to assign values representing relative importance as explained in **Table 8**.

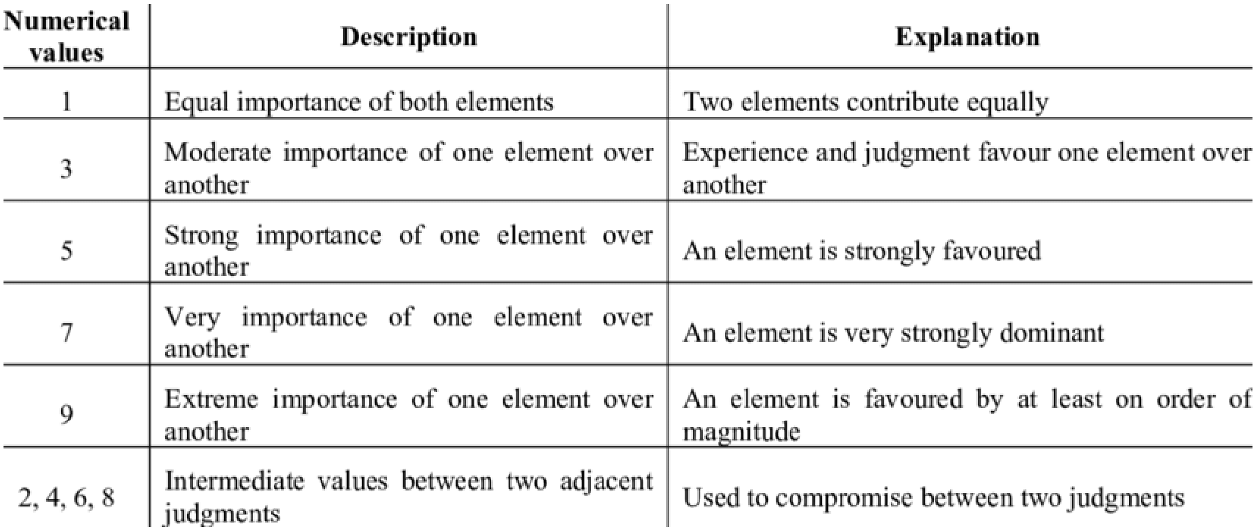
iii. Compare the elements and assign the appropriate value.

iv. Check for consistency using the consistency ratio (CR).

v. Repeat the process for all relevant pairwise comparisons.

vi. Aggregate the comparison values into matrices.

***Table 8** Explanation of each numerical value in Pairwise matrix*



Numerical values	Description	Explanation
1	Equal importance of both elements	Two elements contribute equally
3	Moderate importance of one element over another	Experience and judgment favour one element over another
5	Strong importance of one element over another	An element is strongly favoured
7	Very importance of one element over another	An element is very strongly dominant
9	Extreme importance of one element over another	An element is favoured by at least on order of magnitude
2, 4, 6, 8	Intermediate values between two adjacent judgments	Used to compromise between two judgments

By measuring the connections between the elements, pairwise comparisons aid in the hierarchy's establishment. They guarantee a disciplined and methodical approach to decision-making and offer insightful information about the relative weight of the various criteria and options. For our study, the experts were instructed to compare the criteria and sub-criteria pairwise based on importance. The experts assigned numerical numbers to each criterion to show its relative relevance when compared to all other criteria.

3.1.3 Weight calculation

Calculating weights is the last step in the Analytic Hierarchy Process (AHP). Following pairwise comparisons, weights are computed to identify the relative weights of criteria and alternatives. Here's a brief description of the weight calculation process:

i. Construct a matrix using the pairwise comparison values obtained in the previous stage.

ii. Normalize the matrix by dividing each element in a column by the sum of its column values.

iii. Calculate the average of each row in the normalized matrix to obtain the weight for each criterion or alternative.

NORMALIZED/SUM = WEIGHTS

And sum of all the weights should be equal to 1.

iv. A matrix known as the pairwise comparison matrix is created after the pairwise comparisons are finished. The comparisons done between each pair of criteria are contained in the square-shaped matrix. The matrix's elements depict the relative weights or preferences given to each pairwise comparison.

v. The pairwise comparison matrix is then used to create the choice matrix that is displayed in Tables 9 and 11. The pairwise comparison matrix is normalised to get this result, which guarantees that the weights of the criterion are correct. Calculating the geometric mean or average of the pairwise comparison matrix row- or column-wise is a step in the normalisation process. The weights or priorities of the criterion are represented by the normalised values that arise.

vi. The criteria are compared to the alternatives using the decision matrix as the framework. By creating a decision matrix, one can analyse alternatives based on a variety of criteria in a structured and methodical manner, enabling decision-making that is objective. Making educated and logical decisions is facilitated by carefully weighing numerous elements and their respective relevance. To determine the overall performance or desirability of each alternative, the weighted scores from the decision matrix are multiplied by the scores given to the alternatives for each criterion. This enables a thorough evaluation and ranking of the options based on the relative weights of the standards established through pairwise comparisons.

vii. Verify the consistency of the weights by computing the consistency ratio (CR) using a consistency index.

$CI = (\lambda_{max} - N)/(N-1)$ gives us the value of consistency index

CR = CI/Ri, where Ri = Random Index and depends on the order of the matrix ***Table*** 9 gives the values of Ri for each order of the matrix.

Table 9

Random Index for AHP

Random Index															
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ri	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

viii. If the CR is within an acceptable range (i.e., <10%), the weights can be considered valid. Otherwise, adjustments may be required.

ix. The calculated weights provide a quantitative measure of the relative importance of criteria and alternatives in the decision-making process.

Calculating weights enables you to rank criteria and options according to their importance. Based on the established hierarchy and relative importance of the elements, it enables decision-makers to manage resources, make educated decisions, and discover the most advantageous possibilities. Based on the numerical values provided by the experts in the pairwise comparisons, the weights were determined using the Expert Choice software. The results of the analysis were used to evaluate the relative importance of each criterion in the context of additive manufacturing in Industry 4.0. The weights were expressed as percentages.

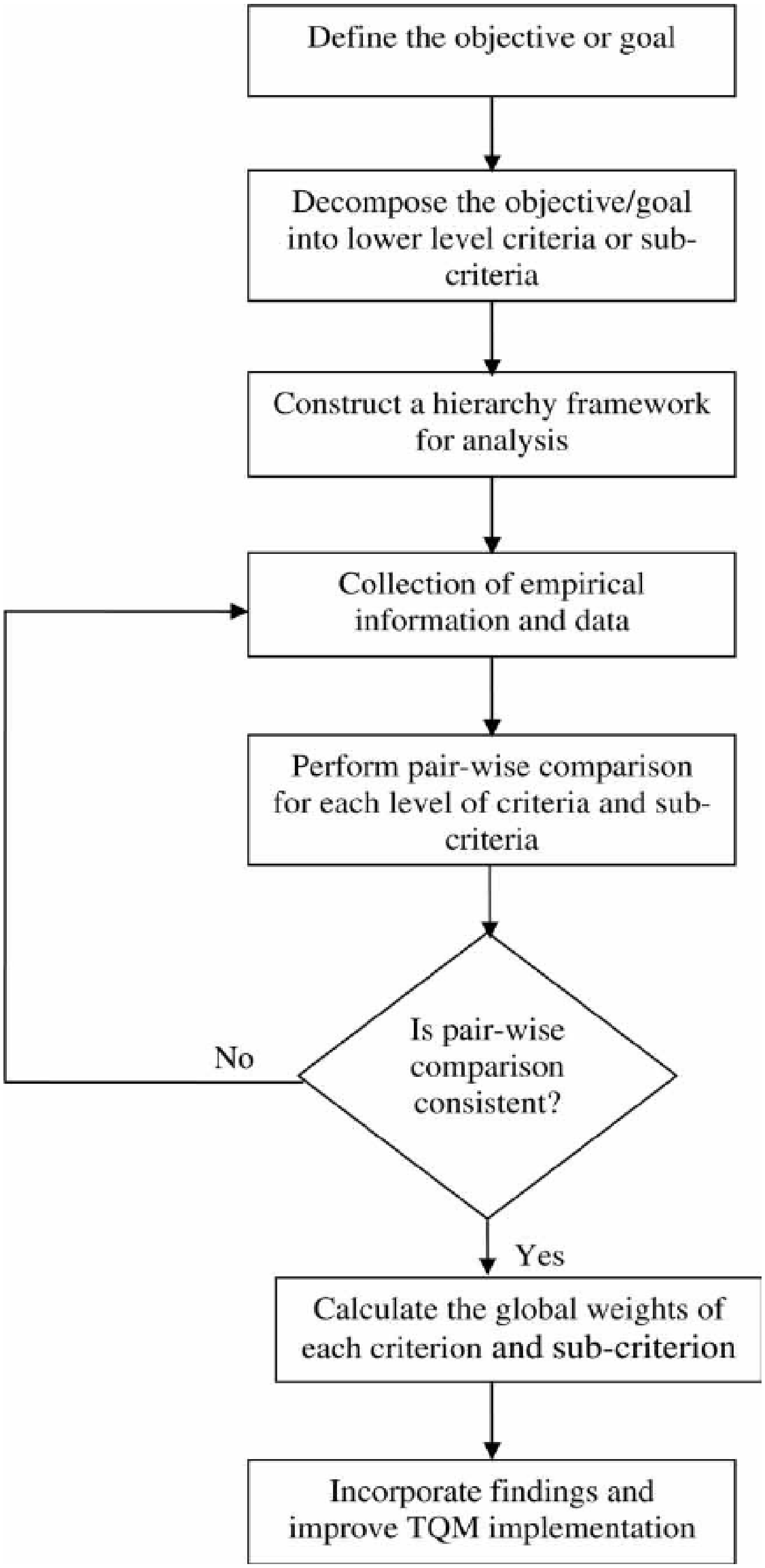


Figure 7 Process layout for my Methodology

CHAPTER 4

RESULTS & DISCUSSION

4.1 RESULTS

4.1.1 PRIORITY TABLE FOR ENABLERS

The priority table provides a structured framework for evaluating and ranking factors, enabling decision-makers to make informed choices based on the identified priorities and are ranked accordingly.

weights for the criteria that are produced as a result of pairwise comparisons:

***Table 10** Resulting weights based on pairwise comparison*

S. No.	Factors	Priority	Ranks
1	TRIPLE HELIX	27.4%	1
2	ACCESSIBILITY	21.8%	2
3	CAPITALIZATION	9.9%	3
4	RESOURCE MATERIAL	8.2%	5
5	SUFFUSING LABOR	8.8%	4
6	INTEROPERABILITY AND COMPATIBILITY	3.3%	10
7	OPTIMIZATION	6.8%	6
8	AI	4.3%	8
9	ENTREPRENEURSHIP	6.0%	7
10	PERSONALIZATION	3.5%	9

Number of comparisons = 45

Consistency Ratio CR = 7.6%

Principal eigen value = 10.957

Eigenvector solution: 5

iterations, delta =7.6E-8

4.1.2 Decision Matrix for enablers:

By creating a decision matrix, one can analyse alternatives based on a variety of criteria in a structured and methodical manner, enabling decision-making that is objective. Making educated and logical decisions is facilitated by carefully weighing numerous elements and their respective relevance. To determine the overall performance or desirability of each alternative, the weighted scores from the decision matrix are multiplied by the scores given to the alternatives for each criterion.

Table 11 *Decision Matrix for Enablers*

	1	2	3	4	5	6	7	8	9	10
1	1	3.00	5.00	3.00	3.00	7.00	3.00	5.00	3.00	7.00
2	0.33	1	3.00	3.00	3.00	7.00	5.00	7.00	5.00	3.00
3	0.20	0.33	1	3.00	1.00	5.00	1.00	3.00	1.00	3.00
4	0.33	0.33	0.33	1	1.00	5.00	1.00	3.00	1.00	3.00
5	0.33	0.33	1.00	1.00	1	5.00	1.00	3.00	1.00	3.00
6	0.14	0.14	0.20	0.20	0.20	1	1.00	1.00	1.00	1.00
7	0.33	0.20	1.00	1.00	1.00	1.00	1	2.00	2.00	1.00
8	0.20	0.14	0.33	0.33	0.33	1.00	0.50	1	2.00	2.00
9	0.33	0.20	1.00	1.00	1.00	1.00	0.50	0.50	1	3.00
10	0.14	0.33	0.33	0.33	0.33	1.00	1.00	0.50	0.33	1

4.1.3 PRIORITY TABLE FOR BARRIERS

The table provides a structured framework for evaluating & ranking according to the weightage of the barrier’s effects.

weights for the criteria that are produced as a result of pairwise comparisons:

***Table 10** Resulting Weights based on pairwise comparison*

S. No.	Factors	Priority	Ranks
1	Lack of Standardization	16.8%	3
2	Financial Steepness	10.5%	4
3	Limited Material	5.0%	6
4	Intellectual Property and Legal Issues	38.4%	1
5	Quality and Safety Concerns	20.9%	2
6	Lack of Skilled Labor	3.3%	7
7	Environmental Concerns	5.1%	5

Number of comparisons = 21

Consistency Ratio CR = 7.9%

Principal eigen value = 7.611

Eigenvector solution: 6 iterations, delta = 2.9E-9

4.1.4 Decision Matrix for barriers:

By creating a decision matrix, one can analyse alternatives based on a variety of criteria in a structured and methodical manner, enabling decision-making that is objective. Making educated and logical decisions is facilitated by carefully weighing numerous elements and their respective relevance. To determine the overall performance or desirability of each alternative, the weighted scores from the decision matrix are multiplied by the scores given to the alternatives for each criterion.

Table 12 *Decision Matrix for barriers*

	1	2	3	4	5	6	7
1	1	3.00	5.00	0.50	0.33	4.00	3.00
2	0.33	1	3.00	0.20	1.00	3.00	2.00
3	0.20	0.33	1	0.25	0.25	2.00	1.00
4	2.00	5.00	4.00	1	4.00	7.00	8.00
5	3.00	1.00	4.00	0.25	1	5.00	6.00
6	0.25	0.33	0.50	0.14	0.20	1	0.33
7	0.33	0.50	1.00	0.12	0.17	3.00	1

4.2 DISCUSSION

Here in this study, we performed AHP technique with the help of the software Expert Choice, and found out that the ranking of enablers as well as the barriers are same in both the cases and further discussions are done as under:

4.2.1 Consolidated result for enablers:

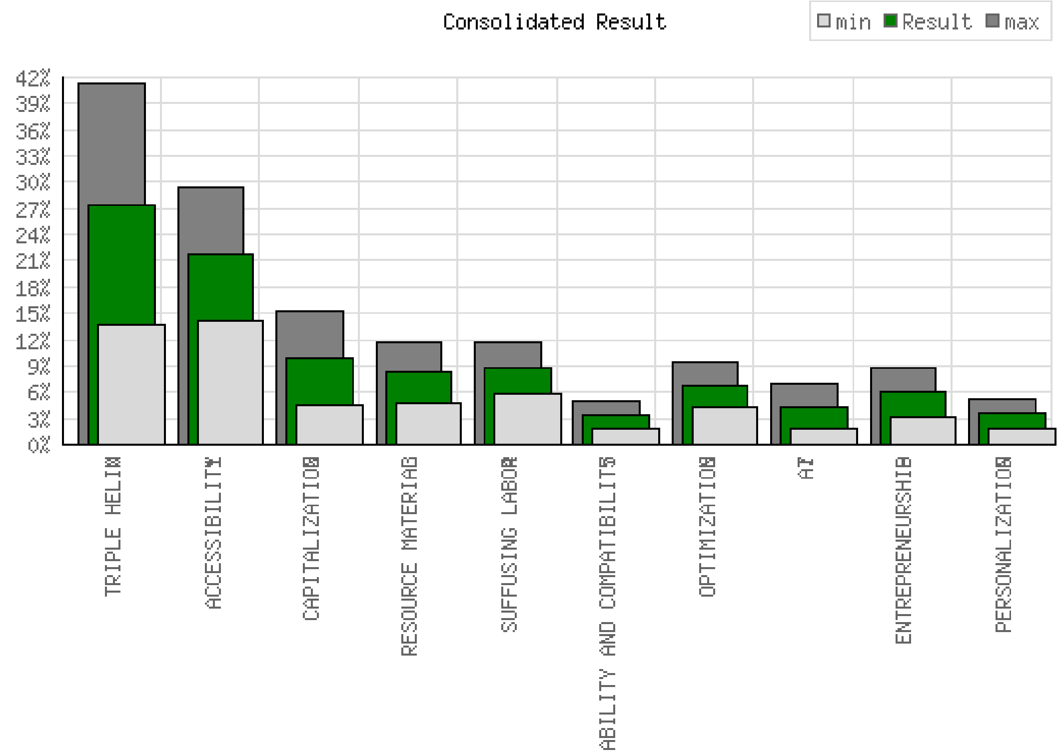


Figure 8 Bar Graph representing the consolidated result for enablers

After careful analysis and discussion, the priority matrix for the enablers of the decision-making problem is as follows:

1 Triple Helix: With the highest priority ranking of **27.4%,** the Triple Helix concept, which emphasizes collaboration between academia, industry, and government, is considered crucial for fostering innovation and driving economic development. The high priority given to the Triple Helix concept reflects its substantial impact on fostering collaboration and innovation. In the real world, this collaborative

approach has led to the establishment of innovation clusters, research partnerships, and knowledge exchange platforms. By bringing together academia, industry, and government, the Triple Helix model has resulted in groundbreaking advancements in various fields, driving economic growth, job creation, and societal progress.

2 Accessibility: Ranking second with a priority of **21.8%,** accessibility refers to the ease of access to resources, information, and opportunities. Ensuring accessibility enables wider participation and inclusivity, promoting sustainable growth and progress. The prioritization of accessibility acknowledges its significant impact on promoting inclusivity and equal opportunities. In the real world, efforts to improve accessibility have led to the development of digital platforms, infrastructural enhancements, and policy frameworks that ensure equitable access to resources, education, and services. Enhancing accessibility empowers individuals and communities, reduces disparities, and enables broader participation in economic and social activities.

3 Capitalization: Ranked third at **9.9%**, capitalization signifies the availability of financial resources and investments. Adequate capitalization is vital for funding research and development activities, supporting entrepreneurship, and fueling technological advancements. The prioritization of capitalization highlights its profound impact on fueling innovation and growth. Adequate capitalization facilitates research and development investments, venture capital funding, and access to financial resources for entrepreneurs and businesses. In the real world, sufficient capitalization has enabled the commercialization of novel technologies, the establishment of start-ups, and the scaling of innovative solutions, driving economic prosperity and technological advancement.

4 Suffusing Labor: With a priority of **8.8%,** suffusing labor focuses on the availability and integration of skilled workforce and human resources. By nurturing a skilled labor pool, organizations can enhance productivity, innovation, and competitiveness. The prioritization of suffusing labor recognizes the critical role of a skilled workforce in driving innovation and productivity. In the real world, efforts

to nurture and develop human resources have led to educational reforms, vocational training programs, and initiatives to bridge the skills gap. A well-equipped and skilled labor force enhances competitiveness, supports the growth of industries, and drives technological advancements in various sectors.

5 Resource Material: Ranked fifth at **8.2%,** resource material represents the availability of essential materials, infrastructure, and technological resources necessary for research, development, and implementation. Sufficient resource material ensures smooth operations and supports the innovation process. The prioritization of resource material acknowledges its tangible impact on research, development, and implementation. In the real world, the availability of essential materials, infrastructure, and technological resources has driven breakthroughs in manufacturing, construction, healthcare, and other industries. Access to resource material ensures smooth operations, accelerates innovation cycles, and enables the realization of novel ideas and designs.

6 Optimization: With a priority of **6.8%,** optimization emphasizes the use of efficient processes, technologies, and strategies to maximize output, minimize waste, and enhance overall productivity. Optimization techniques contribute to better resource allocation and improved decision-making. The prioritization of optimization highlights its practical impact on improving efficiency and productivity. In the real world, optimization techniques have revolutionized supply chain management, manufacturing processes, and service delivery systems. By streamlining operations, eliminating waste, and maximizing output, optimization contributes to cost savings, resource conservation, and enhanced customer satisfaction.

7 Entrepreneurship: Ranked seventh at **6.0%**, entrepreneurship highlights the significance of fostering a culture of innovation, risk-taking, and entrepreneurial spirit. Encouraging entrepreneurship drives economic growth, job creation, and the development of new products and services. The prioritization of entrepreneurship signifies its transformative impact on job creation, economic growth, and innovation. In the real world, entrepreneurship has led to the establishment of start-

ups, the introduction of disruptive technologies, and the creation of new markets. Encouraging entrepreneurship fosters a culture of innovation, risk-taking, and value creation, driving economic development and societal progress.

8 Artificial Intelligence (AI): With a priority of **4.3%**, AI represents the integration and utilization of intelligent systems and algorithms to enhance decision-making, automate processes, and drive innovation in various domains. The prioritization of AI reflects its profound impact on decision-making, automation, and innovation. In the real world, AI technologies have revolutionized various sectors, including healthcare, finance, transportation, and manufacturing. AI-enabled systems offer predictive analytics, process optimization, and intelligent automation, leading to improved efficiency, personalized experiences, and data-driven insights.

9 Personalization: Ranking ninth at **3.5%**, personalization emphasizes tailoring products, services, and experiences to individual needs and preferences. Personalization enhances customer satisfaction, engagement, and loyalty, contributing to business success. The prioritization of personalization acknowledges its significant impact on customer satisfaction and business success. In the real world, personalization strategies have transformed marketing, e-commerce, and service industries. By tailoring products, services, and experiences to individual preferences, personalization enhances customer engagement, loyalty, and revenue generation.

10 Interoperability and Compatibility: With the lowest priority ranking of **3.3%**, interoperability and compatibility refer to the seamless integration and compatibility of different systems, technologies, and platforms. Ensuring interoperability fosters collaboration, data sharing, and efficient operations. The prioritization of interoperability and compatibility highlights their crucial impact on seamless integration and collaboration. In the real world, interoperability and compatibility standards have facilitated data exchange, system integration, and cross-platform compatibility. By enabling interoperability, organizations can

leverage synergies, share information, and drive efficient operations in complex and interconnected environments.

In conclusion, the prioritization of enablers through the AHP technique provides valuable insights for decision-making. The high priority given to factors such as the Triple Helix, accessibility, and capitalization underscores the importance of collaborative innovation ecosystems, inclusivity, and adequate financial resources. The matrix also emphasizes the significance of skilled labor, resource availability, optimization, entrepreneurship, AI integration, personalization, and interoperability for driving success in the decision-making process. By considering these priorities, decision-makers can focus their efforts and resources on the most critical factors to achieve desired outcomes and promote sustainable development.

4.2.2 Consolidated result for barriers:

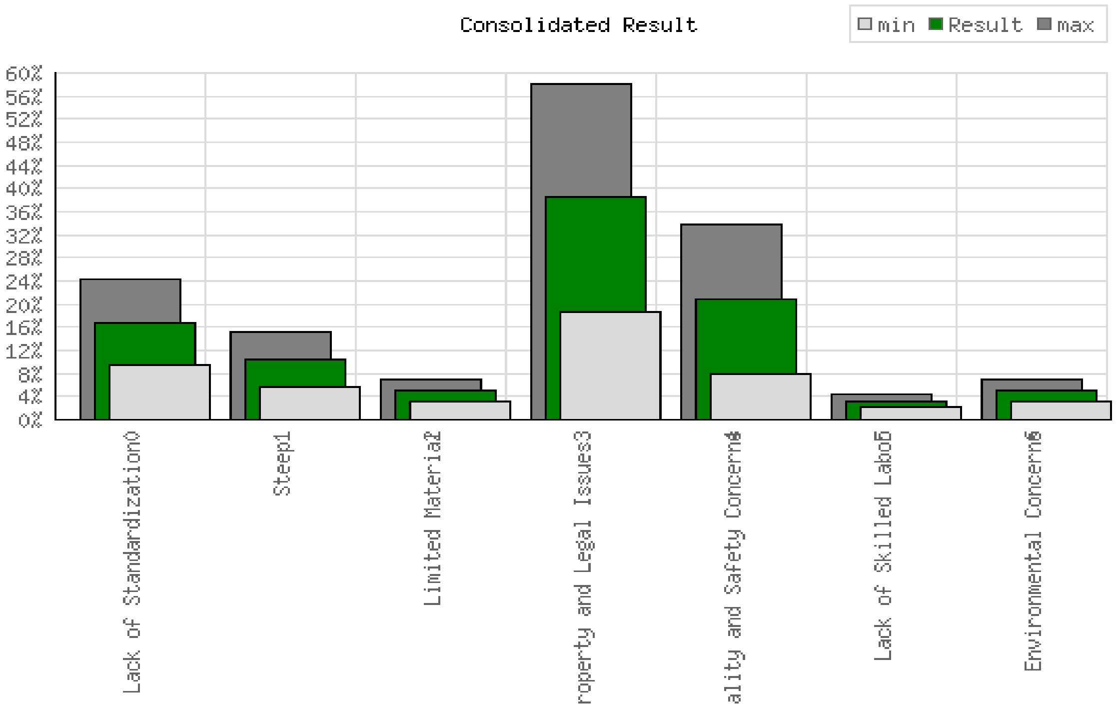


Figure 9 Bar Graph representing the consolidated result for barriers

1. Intellectual Property and Legal Issues (38.4%): The prioritization of intellectual property and legal issues as the top-ranked barrier with a percentage of 38.4% highlights the significant impact of protecting intellectual property rights and navigating legal frameworks. In the real world, these issues can create uncertainty, hinder innovation, and discourage investment. Adequate measures to address intellectual property concerns and establish clear legal frameworks are crucial for fostering a conducive environment for additive manufacturing.

2. Quality and Safety Concerns (20.9%): The prioritization of quality and safety concerns as the second-ranked barrier with a percentage of 20.9% acknowledges the importance of ensuring product quality and safety standards in additive manufacturing. In the real world, quality and safety concerns can impact consumer trust, regulatory compliance, and market acceptance. Addressing these concerns involves implementing rigorous quality control processes, adhering to industry standards, and continuously monitoring and improving safety protocols.

3. Lack of Standardization (16.8%): The prioritization of lack of standardization as the third-ranked barrier with a percentage of 16.8% highlights the challenges posed by the absence of consistent frameworks and protocols. In the real world, the lack of standardization hinders interoperability, compatibility, and collaboration among different stakeholders. Standardization efforts play a crucial role in facilitating seamless integration, ensuring quality control, and promoting efficient exchange of information and resources.

4. Financial Steepness (10.5%): The prioritization of financial steepness as the fourth-ranked barrier with a percentage of 10.5% acknowledges the significant financial barriers associated with implementing and adopting new technologies. In the real world, financial steepness can impede investment, research, and development efforts. It may limit access to capital, hinder scalability, and pose challenges for businesses, particularly startups or organizations with limited financial resources.

5. Limited Material (5.0%): The prioritization of limited material as the fifth-ranked barrier with a percentage of 5.0% highlights the constraint of availability and accessibility of specific materials required for additive manufacturing. In the real world, limited material can impact the production capacity and flexibility of manufacturing processes. It may result in delays, increased costs, or compromised product quality. Addressing this barrier involves ensuring a stable supply chain, diversifying material sources, and developing alternative materials suitable for additive manufacturing.

6. Environmental Concerns (5.1%): The prioritization of environmental concerns as the sixth-ranked barrier with a percentage of 5.1% recognizes the importance of sustainable practices in additive manufacturing. In the real world, environmental concerns focus on minimizing waste generation, reducing energy consumption, and adopting eco-friendly materials and processes. Addressing these concerns involves incorporating sustainable practices throughout the additive manufacturing lifecycle to minimize the environmental footprint.

7. Lack of Skilled Labor (3.3%): The prioritization of lack of skilled labor as the seventh-ranked barrier with a percentage of 3.3% highlights the challenge of

finding qualified professionals with the necessary expertise in additive manufacturing. In the real world, a shortage of skilled labor can impact the implementation, operation, and maintenance of additive manufacturing technologies. Addressing this barrier involves investing in training programs, educational initiatives, and workforce development to build a skilled workforce capable of leveraging additive manufacturing effectively.

The importance of addressing legal and regulatory obstacles in the adoption of additive manufacturing technology is highlighted by the high priority accorded to intellectual property and legal issues. Businesses must make sure that their intellectual property rights are safeguarded and that they adhere to all laws and requirements pertaining to additive manufacturing. Failure to resolve these problems may result in expensive legal disputes, harm to one's reputation, and a loss of competitive advantage. Concerns about quality and safety are another significant obstacle to the adoption of additive manufacturing technologies. To prevent product failures, recalls, and potential user harm, businesses must make sure that their additive manufacturing methods adhere to the necessary quality and safety standards. The results of the AHP research show how crucial it is for using additive manufacturing technology to overcome legal, regulatory, quality, and standardisation challenges. Companies may improve the adoption and integration of additive manufacturing technology and enjoy its advantages, such as greater productivity, cost savings, and product innovation, by overcoming these impediments.

CHAPTER 5
CONCLUSIONS

5.1 CONCLUSIONS

The results of the AHP analysis provide insight into the factors (both enablers and barriers) affecting Industry 4.0's adoption of additive manufacturing technology. Organisations and policymakers can design effective strategies for integrating this technology by taking into account both aspects and gaining a thorough grasp of the elements influencing or impeding its successful adoption.

The identified enablers, such as Triple Helix collaboration, Accessibility, and Capitalization, emphasize the importance of fostering strong partnerships between academia, industry, and government, ensuring easy access to Additive Manufacturing technologies, and providing sufficient financial resources for implementation. These facilitators act as fundamental building blocks in the development of an ecosystem that supports the adoption of additive manufacturing in Industry 4.0. By prioritizing these factors, organizations can leverage the transformative potential of Additive Manufacturing to drive innovation, enhance competitiveness, and achieve sustainable growth.

On the other hand, the identified barriers, including Intellectual Property and Legal Issues, Quality and Safety Concerns, and Lack of Standardization, highlight the issues that must be resolved to encourage wider use. Organisations must overcome major obstacles related to intellectual property and legal issues in order to safeguard their ideas and maintain compliance with applicable laws and regulations. Quality and Safety Concerns highlight the importance of maintaining rigorous quality standards and safety protocols to build trust in Additive Manufacturing processes and products. Lack of Standardization underscores the need for industry-wide collaboration to establish common frameworks and guidelines that ensure interoperability, consistency, and reliability across different applications and sectors.

By recognizing the significance of both enablers and barriers, organizations can develop holistic strategies that mitigate the identified challenges while capitalizing on the identified opportunities. Addressing barriers such as Intellectual Property and Legal Issues and Quality and Safety Concerns requires proactive measures, including the development of robust legal frameworks, quality control mechanisms, and industry-wide standardization initiatives. Progress in these areas depends on cooperation between stakeholders, including industry associations, regulatory bodies, and research organisations.

In terms of further studies and real-life implications, the results of this research provide valuable insights for researchers, industry practitioners, and policymakers. Future studies can build upon this foundation by exploring specific enablers and barriers in greater detail, examining their interdependencies, and assessing their impact across different industry sectors. The findings can inform the development of guidelines and best practices for organizations looking to adopt Additive Manufacturing technologies in Industry 4.0, helping them navigate potential challenges and maximize the benefits of this innovative approach to manufacturing.

Additionally, policymakers can utilize these findings to shape supportive policies and regulations that address the identified barriers and promote the widespread adoption of Additive Manufacturing. This may include initiatives to enhance intellectual property protection, establish industry standards, provide financial incentives, and support research and development efforts. By aligning policies and practices with the identified enablers, governments can foster an environment that accelerates the integration of Additive Manufacturing in Industry 4.0 and drives economic growth and technological advancement.

In summary, the combined analysis of enablers and barriers offers a thorough understanding of the variables impacting the adoption of additive manufacturing within the framework of Industry 4.0. Organisations may leverage the revolutionary power of additive manufacturing to revolutionise their processes, gain a competitive edge, and promote Industry 4.0 by proactively addressing these elements. To fully realise the promise of additive manufacturing in influencing the future of manufacturing, more research, industry collaboration, and policy development are necessary.

5.2 LIMITATIONS

While the study on additive manufacturing in the context of Industry 4.0 using the Analytic Hierarchy Process (AHP) provides valuable insights, it is important to acknowledge certain limitations:

- Sample Size:

  The study may have been conducted with a limited number of participants or experts, which could affect the generalizability of the findings. A larger and more diverse sample size would enhance the representativeness of the results.

- Subjectivity:

  The AHP method relies on subjective judgments and pairwise comparisons made by the experts. Individual biases or varying perspectives among the experts could influence the prioritization of factors, potentially introducing subjectivity into the analysis.

- Data Availability:

  The study's findings are based on the available data and information at the time of analysis. It is possible that some relevant data or research papers might have been missed, which could impact the comprehensiveness of the study.

- Time Constraints:

  The research might have been limited by time constraints, which could have affected the depth and breadth of the literature review. Some recent studies or developments in additive manufacturing in Industry 4.0 might not have been included in the analysis.

- External Factors:

  The study does not account for external factors such as economic conditions, policy changes, or technological advancements, which could have an impact on the implementation and outcomes of additive manufacturing in Industry 4.0. These external factors should be considered in future studies.

- Contextual Specificity:

  The study's findings may be specific to the particular industry or region under investigation. It is important to recognize that the factors, enablers, and barriers identified in this study may not be universally applicable and could vary across different industries or geographical locations.

- Future Research Opportunities:

  The study can serve as a foundation for further research on additive manufacturing in Industry 4.0. However, it is essential to acknowledge that this study does not provide an exhaustive analysis of all possible factors and their interrelationships. Future research can explore additional factors, conduct more in-depth case studies, and employ other decision-making techniques to enhance the understanding of additive manufacturing in the context of Industry 4.0.

By recognizing these limitations, future studies can address these gaps, refine the analysis methodology, and provide a more comprehensive understanding of additive manufacturing in Industry 4.0.

5.3 FUTURE SCOPE

The Analytic Hierarchy Process (AHP) study on additive manufacturing in the context of Industry 4.0 has a lot of potential for further investigation and real-world applications. Some potential avenues for future study and exploration include:

- Extended Analysis:

  The current study's main objective was to characterise the additive manufacturing-related drivers, enablers, and obstacles. Future studies can go deeper into each aspect, examining how they relate to one another and performing a more thorough analysis. This could involve employing advanced decision-making techniques, such as fuzzy AHP or hybrid methods, to enhance the accuracy and robustness of the analysis.

- Case Studies:

  While the study touched upon some case studies to illustrate the application of additive manufacturing in different sectors, future research can conduct more in-depth case studies. These case studies can explore the implementation challenges, outcomes, and lessons learned from real-world examples of additive manufacturing in Industry 4.0. This would provide valuable insights for practitioners and decision-makers.

- Impact Assessment:

Future studies can focus on assessing the impact of additive manufacturing in Industry 4.0 on various aspects, such as economic growth, sustainability, job creation, and supply chain optimization. Quantitative analysis and modeling techniques can be employed to measure and evaluate the benefits and drawbacks of adopting additive manufacturing technologies.

- Technological Advancements:

  Additive manufacturing is an evolving field, and new technologies, materials, and processes are continuously being developed. Future research can explore emerging trends, advancements, and innovations in additive manufacturing, and their implications for Industry 4.0. This would help identify new opportunities and challenges associated with the latest technologies.

- Policy and Regulatory Considerations:

  As additive manufacturing continues to advance; it is crucial to address the policy and regulatory aspects. Future research can investigate the legal and intellectual property frameworks, quality standards, safety regulations, and ethical considerations associated with additive manufacturing in Industry 4.0. This would provide guidance for policymakers, industry stakeholders, and legal experts in shaping the regulatory landscape.

- Global Perspectives:

  The current study may have focused on specific regions or industries. Future research can adopt a global perspective, examining the adoption and implementation of additive manufacturing in different countries and across diverse industries. This would enable a comparative analysis and facilitate the identification of best practices and success factors across various contexts.

- Collaborative Research:

Future research can foster cooperation between academics, business people, and politicians given the multidisciplinary character of additive manufacturing in Industry 4.0. Collaborative research projects can advance cross-sector relationships, boost information exchange, and make it easier to incorporate additive manufacturing into larger Industry 4.0 strategies.

The study can advance knowledge of additive manufacturing in relation to Industry 4.0 and aid in its successful application across diverse industries by addressing these topics of future research.

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