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Unique Instructional Delivery of Additive Manufacturing: A Holistic Review

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Abstract

Additive Manufacturing (AM), often referred to as 3D Printing (3DP), has emerged as a transformative technology compared to traditional manufacturing across industries such as aerospace, healthcare, and automotive. With this evolution, the demand for specialized education and training in AM is growing. This brief concept paper provides a condensed review of distinctive instructional delivery methods in the field of AM, reflecting the dynamic nature of STEM education. Moreover, it explores various dimensions of AM education, including innovative laboratories equipped with advanced 3D printers, remote laboratories to enable access from distant locations, curriculum development encompassing on-ground, online, and hybrid programs. Furthermore, this study examines AM software tools and simulations, industry certifications, and hardware and equipment used in educational settings. The paper also delves into educational pathways, collaborations between academia and industry, workforce demands, and the ethical and societal aspects of AM education, focusing on sustainability and equity. Overall, this study offers insights into the diverse and evolving landscape of AM education, emphasizing adaptability, innovation, and ethical considerations in preparing individuals for the challenges and opportunities presented by AM. The findings contribute to a deeper understanding of how AM education is evolving to meet the demands of the future.

Introduction

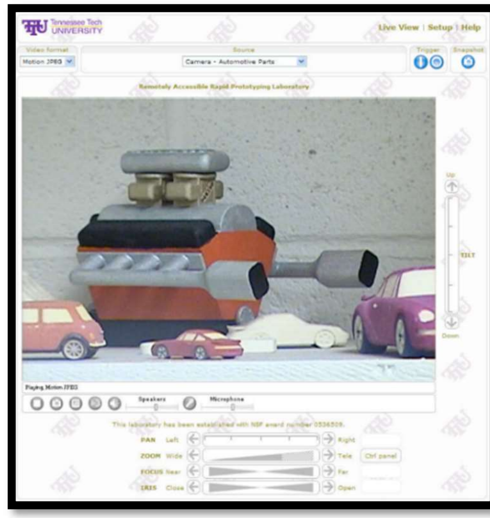
A concise overview of AM and its pivotal role in various global industries is imperative to establish the foundation for AM education [1]. AM is a sequential manufacturing process that produces parts in a layer-by-layer fashion [2][3]. AM has seven categories under its umbrella, however, only a few of those categories are suitable for AM education when considering operation complexity and cost [1][4]. Those are Material Extrusion (MEX), Stereolithography (SLA), and Powder Bed Fusion (PBF) [5]. AM is an attractive manufacturing method due to its versatility in producing components [6]. Additionally, research suggests that complexity is free with AM on the contrary to traditional manufacturing methods which are generally based on subtractive manufacturing method [7]. Design and manufacturing limitations are less than those of traditional manufacturing processes [8], which ultimately allow students to not withhold ideas when it comes to designing and manufacturing components.

The present review study seeks to deconstruct the multifaceted pieces of AM education. This includes an exploration of advanced laboratory facilities as well as the growing field of remote learning environments, designed to facilitate access and scalability [9]. The capacity to redefine production processes and product design highlight the vital need for specialized education and training in this domain. This research aims to conduct a condensed examination of innovative instructional delivery methods in the realm of AM [10]. Essential to our discussion is the crucial role of Open Educational Resources (OER), which include various resources like Massive Open Online Courses (MOOCs), YouTube tutorials, and academic websites [11]. It also encompasses an in-depth analysis of the software tools and simulations that play a central role in design and prototyping within the AM framework. Aligned with the evolving educational landscape, the study examines the certifications and training programs offered by institutions and organizations like Texas A&M University [12] and Tooling U-SME [13]. Furthermore, it analyzes the hardware and equipment employed within educational settings, which ranges from MEX to SLA and Selective Laser Sintering (SLS) systems.

This study explores the various academic programs, extending from associate degrees to advanced doctoral studies, which are aligned with the domain of AM. The paper also delves into the pivotal collaborations between academia and industry, bearing witness to the symbiotic relationship fostering innovation, research, and real-world application. In addressing the demands of the workforce and the essential competencies required for success in the AM domain, the study identifies the expanding need for skilled professionals in sectors, including aerospace, automotive, and healthcare [14]. Lastly, the research underscores the ethical and societal dimensions of AM education, with a particular focus on sustainability, equity, and the responsible deployment of technology. In summation, this study embarks upon an intricate exploration of the evolving landscape of AM education, shedding light on its dynamic and adaptive character, thereby illuminating the path for future advancements [15].

Innovative AM Laboratories and Remote Laboratories

Innovative AM laboratories represent the vanguard of experiential education in the realm of 3DP technology. These state-of-the-art facilities, strategically positioned within educational institutions, serve as crucibles for hands-on exploration and skill development. Equipped with a range of AM tools and technologies, these laboratories provide students with immersive learning experiences, fostering a profound understanding of AM processes and their real-world applications. Such laboratories often feature cutting-edge 3D printers, advanced scanning equipment, and post-processing stations, providing students with comprehensive access to the entire AM workflow [16]. These in-person laboratories serve as essential bridges between theoretical knowledge and practical proficiency. In parallel, the emergence of remote laboratories presents an intriguing dimension within AM education. By harnessing technological advancements, remote laboratories enable students to access and operate AM equipment from disparate locations, overcoming geographic limitations [17]. This promotes accessibility and scalability, making it feasible for learners to engage with AM technology regardless of their proximity to a physical lab facility. Consequently, innovative AM laboratories and remote learning environments play a crucial role in teaching students' practical skills and understanding AM processes and technologies. Some of the remote labs are shown in Figure 1.



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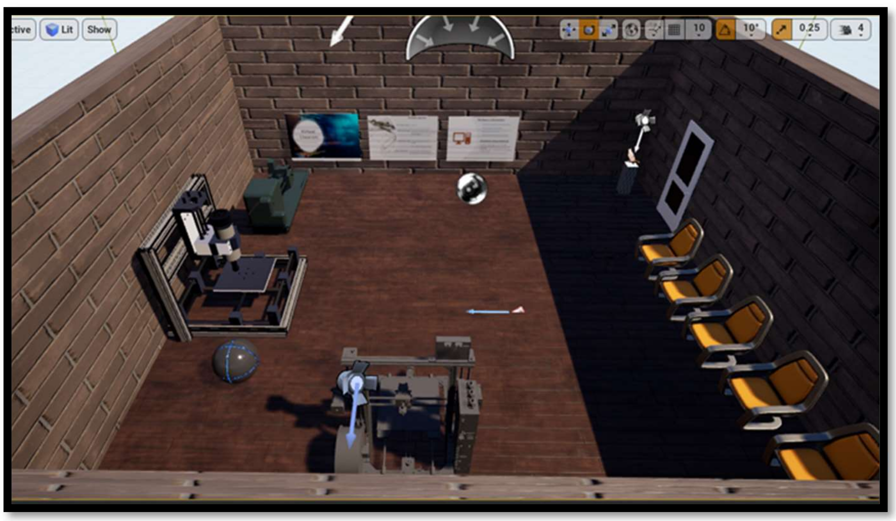

C)

Figure 1: Three Innovative AM labs, A) Network camera accessible AM laboratory [18], B) Remotely accessible AM laboratory [19], C) Remote laboratory with 3D printers and fabricated parts

Curriculum Development: On-ground, Online, Hybrid

Curriculum development in the context of AM education is a multifaceted process that has adapted dynamically to the diverse learning needs of students. A well-developed curriculum is a must for a successful delivery of AM content modules [20]. In the traditional on-ground setting, educational institutions have tailored their curricula to provide comprehensive AM instruction, integrating theoretical foundations with practical hands-on experiences in physical laboratory settings [21]. This approach ensures the acquisition of fundamental knowledge and the development of essential skills. In contrast, online education in AM has flourished in recent years, catering to a global audience seeking flexible learning options. Online curricula are thoughtfully designed to deliver theoretical content, often enriched with multimedia resources, simulations, and virtual labs that simulate real-world AM processes [22]. The inherent advantage of asynchronous learning, where students can pace themselves, renders online education an accessible conduit for remote and diverse learners. Furthermore, the hybrid model harmoniously merges on-ground and online components, providing a flexible and integrated approach. Hybrid curricula feature a blend of in-person interactions, practical hands-on experiences, and virtual learning modules, offering the best of both worlds [23]. Consequently, this section underscores the evolving nature of AM curriculum development, considering the distinctive requirements of on-ground, online, and hybrid instructional modes to empower learners with the knowledge and skills essential in navigating the multifaceted landscape of AM. Some current courses focusing on AM are listed in Table 1.

Table 1: Some of the courses developed and implemented by the institutions

Name of the course	Name of the institution	Type of the curriculum
Additive manufacturing for innovative design and production	MIT	Online [24]
Additive Manufacturing: Materials, Processing And Applications	University of Washington	In person [25]
Additive Manufacturing - Microelectronics	ASU	Online [26]
Additive Manufacturing	UMICH	Online [27]
3D Printing and Additive Manufacturing Specialization	RIT	Online [28]
3D Printing and Additive Manufacturing Specialization	University of Illinois	Online [29]
Design for Additive Manufacturing	ASU	Hybrid [30]
Generative Design for Manufacturing Applications	Autodesk	Online [31]
The 3D Printing Revolution	Illinois University	Online [32]
Additive Manufacturing	University of Maryland	On-ground [33]
Introduction to Additive Manufacturing	The Ohio State University	On-ground [34]
Introduction to Additive Manufacturing	University of Pittsburgh	On-ground [35]

In the on-ground AM practices, students benefit from face-to-face interactions with instructors and peers. This direct engagement allows for immediate feedback, collaborative problem-solving, and hands-on learning experiences, which are particularly beneficial for mastering practical skills in AM, such as operating AM machines and troubleshooting technical issues. Additionally, access to physical laboratory equipment and resources facilitates a more immersive learning environment, enabling students to gain a deeper understanding of the AM process and materials.

Online AM learning offers flexibility and accessibility, allowing students to engage with course materials and lectures at their own pace and from any location with an internet connection. Through online platforms, students can access a wealth of multimedia resources, including video tutorials, simulations, and virtual laboratories, which can enhance their understanding of AM concepts and techniques. However, online learning may present challenges in providing hands-on experiences and real-time interactions, potentially limiting opportunities for practical skill development and collaborative learning.

The hybrid practices combine the elements of both on-ground and online learning, offering a balance between flexibility and hands-on engagement. In a hybrid AM course, students may participate in lectures and discussions online while attending in-person laboratory sessions or workshops for practical application and experimentation. This approach maximizes the benefits of both learning modalities, providing students with the convenience of online resources combined with valuable hands-on experiences in a physical laboratory setting. Additionally, hybrid learning can promote self-directed learning and time management skills, as students navigate between online and on-ground components of the course.

Open Educational Resources (OER)

OER tools have emerged as a pivotal cornerstone in the democratization of knowledge and the accessibility of AM education. In an era characterized by the digitalization of learning materials, OER plays an instrumental role in offering comprehensive, cost-effective, and readily accessible resources to students and enthusiasts worldwide. MOOCs, YouTube tutorials, academic websites, and open-access textbooks are essential constituents of the OER landscape within AM education [36]. These resources not only provide learners with foundational AM knowledge but also facilitate skill development and practical insights, creating an inclusive learning environment unbound by geographical constraints and financial barriers. As the adoption of OER thrives, it underscores the educational sector's commitment to the spreading AM expertise widely, allowing learners from diverse backgrounds to engage in the innovative world of 3DP, thereby contributing to the democratization of educational opportunities in the field of AM [37]. Figure 2 presents the YouTube videos developed by MIT.

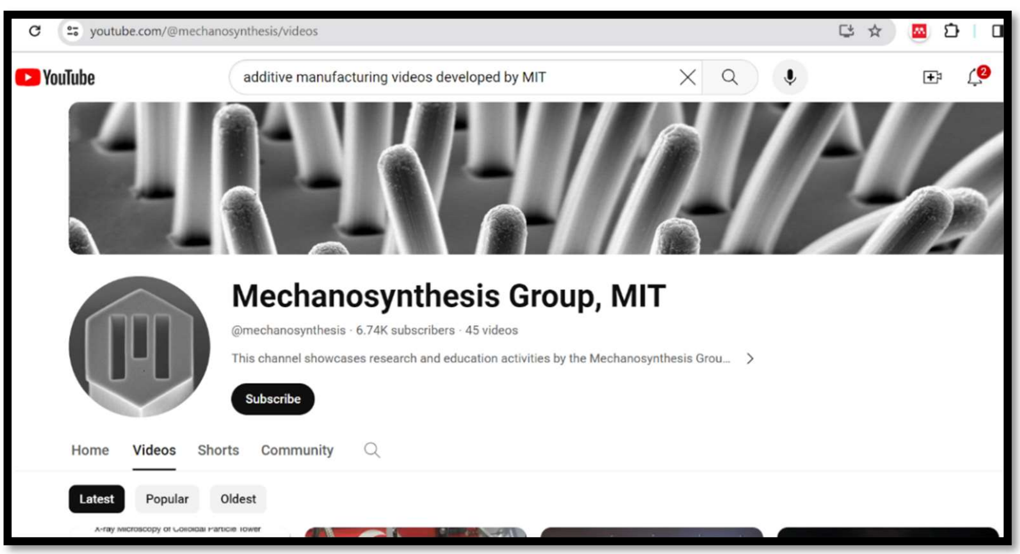

Figure 2: Additive Manufacturing Videos developed by MIT which are available on YouTube

AM Software Tools and Simulations

AM Software Tools and Simulations represent a crucial nexus in the pedagogical realm of AM education. These sophisticated software solutions, encompassing industry-standard programs like SolidWorks, Autodesk Fusion 360, and Ansys, empower students and practitioners with the capacity to digitally design, simulate, and analyze 3D printed objects. By bridging the theoretical and practical aspects of AM, these tools instill a comprehensive understanding of the intricacies of additive processes, material behavior, and design optimization as can be seen in Figure 3 [38]. Moreover, AM simulations enable learners to experiment with various scenarios, iterate designs, and predict the outcomes of real-world manufacturing with remarkable precision. In an educational landscape characterized by the imperative to cultivate practical expertise, AM software tools and simulations emerge as a pivotal conduit, equipping individuals with the competencies requisite for adeptly navigating the multifaceted terrain of modern 3DP technology [39].

Figure 3: AM software tools are used in a number of designs, analyses, and simulation studies

Certification and Training Programs

Certification and Training Programs hold a central position in the pedagogical spectrum of AM education. Institutions and organizations like SME (sme.org) and Tooling U-SME (earn.toolingu.com) offer structured pathways for learners to acquire recognized expertise in AM processes and technologies as can be seen in Figure 4 [40]. These programs provide students, professionals, and industry personnel with a well-defined framework for honing their knowledge and practical skills, ensuring they are well-prepared to meet the demands of a dynamic field. By addressing essential competencies, safety protocols, and the latest industry practices, certification and training programs substantiate the commitment to proficiency in AM. They bridge the gap between theoretical knowledge and hands-on application, fortifying the workforce with specialists equipped to contribute effectively to the ever-evolving landscape of AM. In doing so, they act as a catalyst for career advancement and industry innovation, aligning with the essential mission of AM education—to create a cadre of qualified individuals capable of harnessing the transformative potential of 3DP technology [41].

Figure 4: Tooling U-SME is one of the most popular training and certification programs in AM

AM Hardware and Equipment in Educational Settings

The presence of AM hardware and equipment within educational settings serves as a key player in the pedagogical landscape, facilitating immersive learning experiences. Academic institutions, from technical colleges to research-intensive universities, are investing in an array of 3DP technologies. These encompass diverse AM processes such as MEX, SLA, and SLS systems, which span the spectrum of AM capabilities. This technology-rich environment empowers students to become adept at operating and understanding the underlying principles of various 3DP methods [42]. Figure 5 shows the diverse applications and utilizations of AM hardware and equipment tools. AM hardware and equipment are invaluable tools for translating theoretical knowledge into practical competence, fostering a new generation of experts well-versed in the intricacies of AM technology [43]. In essence, the presence of these advanced tools within educational institutions plays a pivotal role in shaping the next wave of AM professionals and innovators, establishing a bridge between educational institutions and the dynamic demands of contemporary manufacturing industries.

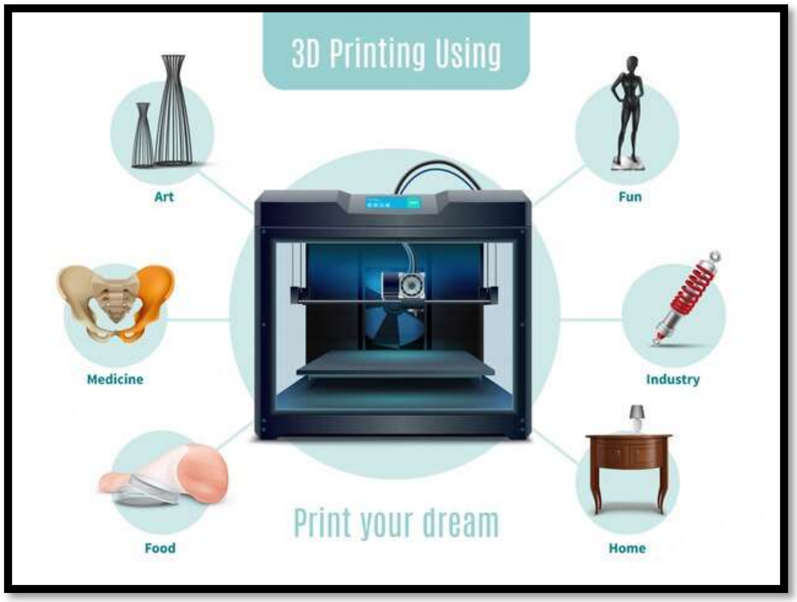

Figure 5: AM equipment is used to fabricate a number of objects you can imagine

Collaborations Between Academia and Industry

Collaborations between academia and industry in the domain of AM are a cornerstone of innovation, research, and practical integration of cutting-edge technology. These partnerships bridge the gap between the academic realm and real-world industrial applications, fostering an environment of mutual learning and advancement. Such collaborations often encompass a multitude of initiatives, including joint research projects that explore innovative AM materials, processes, and applications as can be seen in Figure 6. They facilitate internships and cooperative programs, enabling students to gain practical experience in industrial settings. Moreover, they frequently involve industry experts and professionals who share their insights through guest lectures and hands-on workshops, offering students a deeper understanding of the practical challenges and opportunities within the AM sector [44]. These synergistic efforts serve to enrich both academia and industry, fostering innovation, knowledge exchange, and a skilled workforce equipped to navigate the ever-evolving landscape of AM. In essence, collaborations between academia and industry form a critical component of AM education, enriching the educational experience and reinforcing the vital link between theoretical knowledge and its practical application.

Figure 6: Interaction between the AM industry and academic institutions is growing in developing and implementing high speed fabrication technologies

Skill Set Demands and Workforce Readiness in AM

The demands of the workforce in the realm of AM stand as a testament to the transformative potential of this technology. As industries across the spectrum, from aerospace to healthcare, increasingly embrace AM, there arises a commensurate demand for a skilled workforce equipped to harness its capabilities. AM professionals are required to possess a multifaceted skill set, encompassing proficiency in design for AM, knowledge of material science, an understanding of advanced software tools, and expertise in operating and maintaining 3D printers. Workforce readiness in AM necessitates not only technical competencies but also the ability to adapt to an ever-evolving field, with a keen eye for innovation, problem-solving, and collaboration [20]. Educational institutions and industry partnerships play a central role in nurturing this skilled workforce, ensuring that the next generation of AM professionals is equipped to address the dynamic challenges and opportunities presented by this disruptive technology [45][6]. In this context, workforce readiness and skill set demands converge to underscore the critical role of AM education in shaping a competent and forward-thinking workforce. Some of the skillsets of the future AM workforce are summarized in Figure 7.

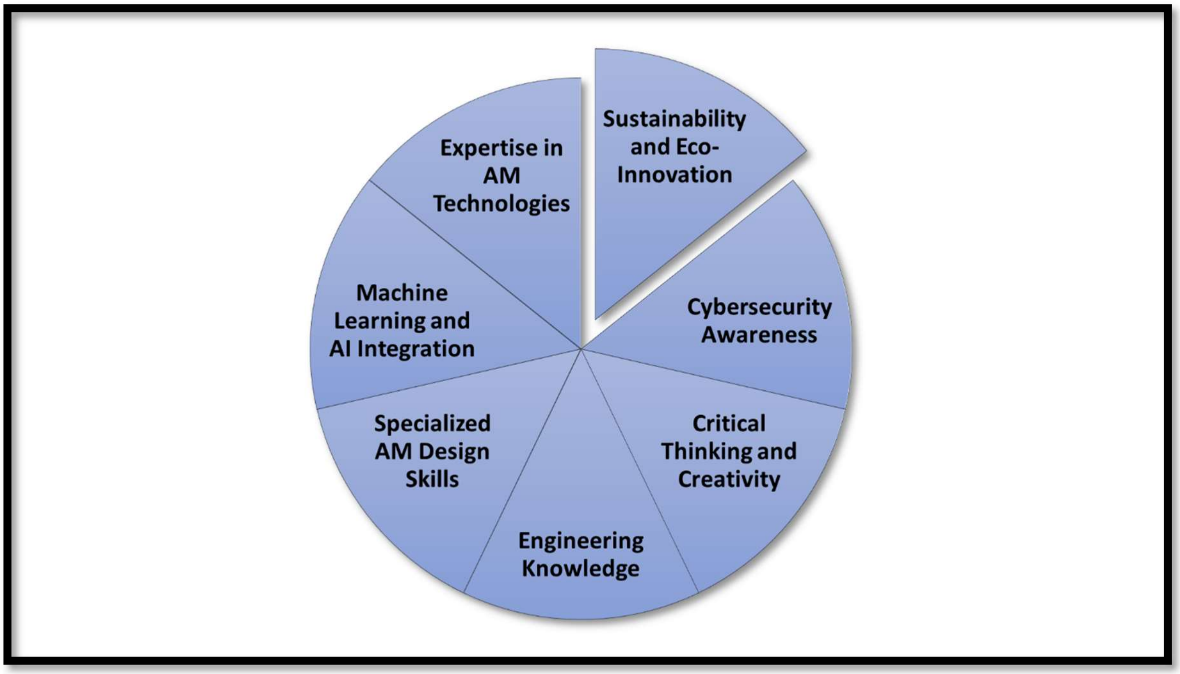

Figure 7: AM future skillset

Ethical and Societal Aspects of AM Education

The ethical and societal dimensions of AM education manifest a profound awareness of the responsibilities that accompany technological advancement. In the realm of sustainability, AM confronts questions concerning material usage, waste reduction, and the environmental footprint of 3DP. Ethical considerations extend to the responsible use of AM in fields such as healthcare, addressing issues of patient safety, data security, and equitable access to medical advancements [46]. Furthermore, the theme of equity weaves through the educational landscape, prompting discussions about accessibility, affordability, and inclusivity in AM education and its opportunities [47]. As AM technologies continue to advance, a responsible approach to education is imperative, ensuring that learners not only acquire technical skills but also grapple with the ethical implications of their work. In this context, AM education is a crucial arena for shaping ethical, responsible, and conscientious individuals who understand the societal impact of their actions in an age marked by rapid technological transformation.

Social Impact of AM

A growing number of companies and individuals are using AM in there new business models as AM is emerging process with high number of invention going to have this technology more approachable and accessible in rapid manufacturing, in social aspect this technology is used by two groups of companies those uses low cost and low end technology and those that use high end tech in cutting edge mass sectors, such as biomedical sectors, nanomanufacturing or bioprinting or newly developed 4D Printing [48]. AM in customized healthcare sector used to improve the population health and quality of life it also helps to reduce the environmental impact for sustainable manufacturing [46]. AM streamlines the supply chain to improve efficiency and responsiveness in meeting demand [47]. Figure 8 shows different social impact of AM in various categories.

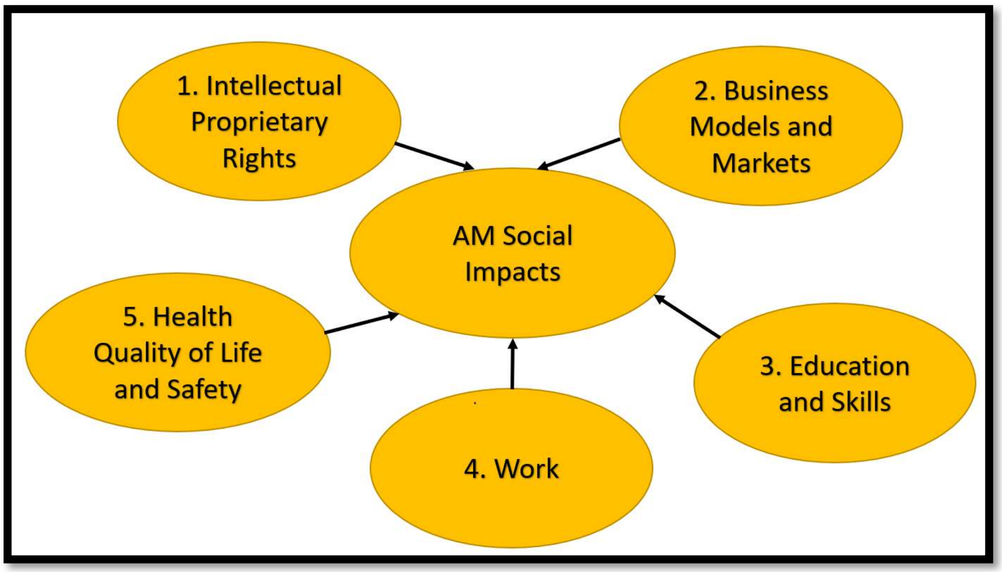

Figure 8: Social impacts of AM

1. Social impact of AM in intellectual proprietary rights

As AM gains popularity, protecting intellectual property on design models becomes crucial for content creators and providers. This is particularly important as companies and individuals increasingly adopt these technologies. Such wide object information, which is represented in a variety of file formats, is easily copied and reproduced without loss of quality, just like other digital media [49]. This data sets combined direct streaming of machine code instructions (G Code) for 3DP with digital watermarking of actual 3D printed objects. Replicating the object became challenging since the user was no longer in possession of a digital model of the item that needed to be printed [50].

2. Social impact of AM in business models and markets

Additively manufactured products in current industrial interest are divided in two categories. The first called as automation driven industry 4.0 paradigm, which consist of idea of small scale, localized data driven factors with resource efficient on demand capabilities [51]. The second is business model paradigm deals with selling physical products with a service that is product-based service system. Both models suggest that the technology in AM has potential to make AM technology impactful in various business models and different social markets [52][53].

3. **Social impact of AM in education and skills**

Introduction to AM represents a very important leverage in the preparation of young and entry-level engineers throughout the world, so they can be benefited from both personal preparation, learning, and refining skills that are integral part of advanced manufacturing process in all modern industries [54]. In this category, it is important to train the STEM educators with the latest trends and technologies of AM first. Then, the educators who are trained with these timely technologies will train the skilled workforce of future generation with the need of the industry in analysis, fabrication, testing, quality, control etc. The skill sets needed for these industries have been identified by several survey tools today. Now, there is a number of initiatives offered as apprenticeship, train-the-training program, and career readiness certification [55].

4. **Social impact of AM in work**

The effects of the fast change in traditional manufacturing systems on workforce, employment, and business models are still being felt in some spheres of society [56]. However, recognizing these trends enables a longer-term perspective, offering perceptions into more general social trends that aids in the anticipation and management of upcoming developments. In order to support the identification of the social impacts of AM in work, a proper understanding of tools and resources must be delicately provided to workers or stakeholders before implementing the overall AM as standard operating procedure [57]. Some barriers identified as follows:

- Initial cost of some AM systems is high. Such a high cost of the industrial units is a concern for the organizations.
- Training and professional development of the current staffing is an apprehension for the management since the environment with AM will bring a high-tech production environment for the traditional practices.
- Service and maintenance tasks of the AM resources will be continuously made by the experts. This task will be an extra burden for the practitioners considering the sensitive and precise nature of the AM equipment and machines,

5. **Social impact of AM in health quality of life and safety**

In the recent times, AM has been turnaround in the medical sector as a flexible and affordable way to produce geometrically complex healthcare products with less cost and better quality [58][59]. Moreover, AM technology is utilized in the creation of products such as joint replacements, heart valves, and dental implants as new materials has been invented that can be printed with medical benefits in the mind and will not react to blood cells or any human muscular system and will act neutral in this case [60]. This technology offers strong mechanical properties and creates a physical model directly from CAD models by layering on materials [61]. Overall, the advancements in the AM tools, techniques, supplies, and consumables increase the efficiency and effectiveness of their practices in daily life. However, it is evident that the safety and hygiene concerns of these advancements increase parallel to the improvement of the technologies.

Future Directions

The upcoming trends and directions of AM training and education are poised to be dynamic and interdisciplinary, reflecting the evolving landscape of this fabrication technology [62][63][64][65]. As the field of AM continues to expand across various industries, educational institutions will increasingly emphasize hands-on experience with cutting-edge AM technologies. This applied approach will involve not only operating AM machines but also understanding the entire steps of the production technologies, from design, simulation, material selection, and post-processing, to inspection and quality control.

Furthermore, the integration of AM education into traditional engineering curricula is expected to grow from technical courses to capstone projects [66][67]. Engineering and technology students will be exposed to processing principles early in their academic careers, allowing them to develop a comprehensive understanding of how this technology can be applied across different engineering disciplines. Moreover, as the demand for skilled professionals in AM grows, specialized degree programs and certifications tailored specifically to AM are likely to emerge, offering students in-depth knowledge and expertise in this rapidly growing field. These programs may encompass a wide range of topics, including advanced materials science, digital design, process optimization, and even techno-entrepreneurship in AM. By preparing students with the necessary skills and knowledge, these educational initiatives will play a crucial role in shaping the future workforce in AM and driving innovation in the years to come [68].

Conclusion

In conclusion, the dynamic field of AM workforce and education is driven by innovation, practicality, and a commitment to shaping a skilled and responsible workforce. The diverse instructional delivery methods, resources, and collaborative efforts underscore the adaptability of educational institutions to prepare individuals for the evolving landscape of AM and continue to reshape industries. This multifaceted education approach is poised to meet the demands of the future, empowering students to navigate the complex world of 3DP technology while considering ethical and societal implications.

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