Environmental Impacts of Standardization Efforts in Additive Manufacturing

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Abstract – This paper focuses on the environmental effects of additive manufacturing (AM) and the need for critical evaluation techniques. The Life Cycle Assessment (LCA) methodology is emphasized as an approach to measure the ecosystem effect of AM over the whole lifespan of the product. The NSF-funded workshop on the environmental consequences of AM highlighted areas characterized by knowledge gaps and uncertainties, which will direct future research efforts in this domain. The paper highlights the significance of material selection in AM and presents a new mechanism for evaluating the environmental consequences of AM components. The research revealed that the use of materials in AM might lead to a substantial decrease in environmental consumption and energy consumption. Nevertheless, the research also emphasizes the problem of material waste in additive manufacturing techniques. The study advocates for the creation of standardized measuring methodology and sustainability characterisation methods for AM in order to encourage wider adoption and the implementation of sustainable manufacturing practices. ASTM International is an association dedicated to the advancement of standards for sustainable manufacturing and AM.

Keywords – Additive Manufacturing, Sustainable Manufacturing, Life Cycle Assessment, Sustainability Characterization, Standardized Measuring Methodology.

I. INTRODUCTION

The use of additive manufacturing (AM) is progressively expanding in the creation of novel items, including the stages of tooling, functional components, and conceptual design. AM, as defined by Edgar and Tint [1], encompasses various terms such as rapid manufacturing, rapid prototyping, freedom fabrication, additive fabrication, and 3D printing. It employs advanced techniques to construct parts by incrementally adding and bonding material layer-by-layer. AM is a swiftly growing technology that has shown potential in various applications, including medicinal implants, aerospace, and the automotive sector. Currently, the methods used for built ecosystem applications include of binder jetting and extrusion-based procedures. The use of AM methods in the construction sector as illustrated in **Fig 1**.

The capacity of additive manufacturing (AM) fabricates components directly from a digital model renders it a superior option in contrast to traditional manufacturing approaches such as injection molding, machining, and die-casting, particularly for the fast production of highly personalized parts. It is important to acknowledge that AM is particularly well-suited for creating items with intricate shapes in small quantities. However, it has also shown its ability to effectively speed up the manufacture of dies and tools used in high-volume producing processes. Additionally, it has the capability to expedite the manufacturing process of certain components by consolidating several pieces into a single unit. The range of raw products used in additive manufacturing (AM) are ceramic, composite, metallic, and plastic materials, which are available in various forms, including liquids, wires, or powders. The practical and geometrical characteristics of generated components may vary considerably due to the variances in additive manufacturing technologies and techniques.

Choosing appropriate AM elements, which meet performance guidelines necessitates a critical design process. AM can be employed in production to provide prompt planning and enhance efficiency [2]. However, more research is required to completely exploit the economic potential of additive manufacturing techniques by overcoming certification, regulatory and logistical barriers, for critical items such as automotive or aircraft parts. This study examines the environmental impact of additive manufacturing, also known as 3D printing. As shown by Lundy et al. [3], the life cycle analysis (LCA) strategy can be employed to evaluate the environmental effects of AM, such as every stage of manufacturing from raw material consumption to extraction.

However, 3D printing become more efficient, material selection becomes increasingly important due to environmental and human health implications. The study includes other current manufacturing industries and activities of sustainable and additive manufacturing. These endeavors include the creation of a structure for defining sustainability, the development of measurable criteria for sustainability, the improvement of indicators for sustainability, and the evaluation of additive manufacturing processes. The researchers emphasize the efforts of ASTM International in formulating standards for additive manufacturing (AM) and environmentally conscious production. They emphasize the significance of standards in the industrial sector.

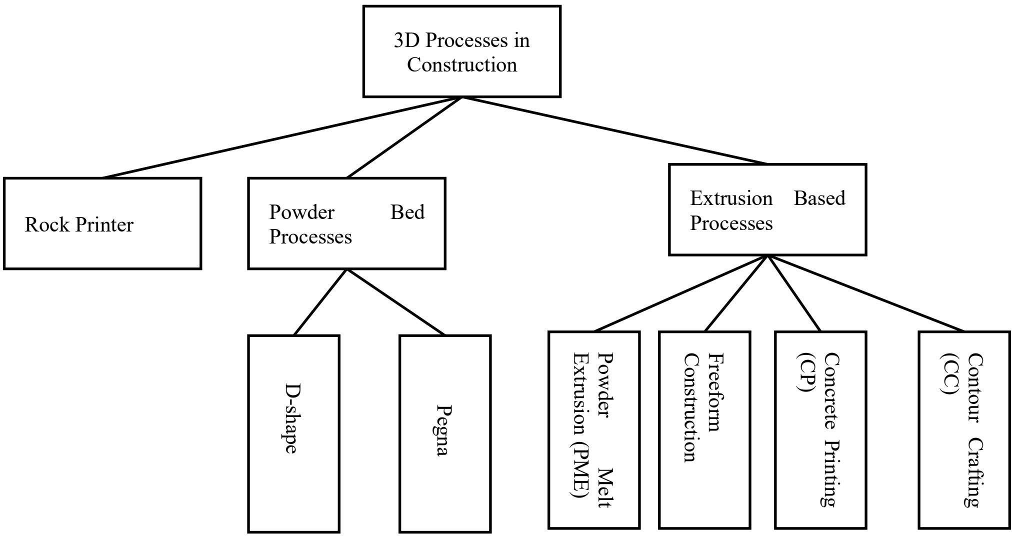

Fig 1. Additive manufacturing methods in the building industry

The rest of the paper is organized as follows: Section II presents a review of previous literature works on additive manufacturing; and sustainability and sustainable manufacturing. A discussion of the environmental effects of additive manufacturing has been provided in Section III. Section IV reviews the aspect of sustainability characterization, presenting a detailed methodology of it. Section V focusses on the relevant ASTM standards organizations, such as ASTM sustainable manufacturing, and ASTM additive manufacturing technology. Lastly, Section VI presents a summary of the environmental effects of additive manufacturing.

II. LITERATURE REVIEW ON ADDITIVE AND SUSTAINABLE MANUFACTURING

Additive Manufacturing

Additive Manufacturing (AM), or 3D Printing, is seen as a highly promising technology, which may significantly contribute to the creation and design of the built ecology. The prevalence of additive manufacturing may be attributed to its many benefits compared to conventional techniques, including rapid production, decreased labor expenses and waste materials, the capacity to fabricate personalized items, as well as improved precision and accuracy. Additive manufacturing technology can effectively and expeditiously meet housing demands in times of disaster. Moreover, these technologies allow the creation of distinctive and nonconformist structures that are unattainable by standard construction techniques. Developed countries have made significant investments in the robotization of the construction industry to tackle the shortage of skilled people and reduce dangers at construction areas. Even though additive manufacturing methods have been established for more than 30 years, the degree of automation in constructing applications has progressed at a sluggish pace. This barrier stems from the already inefficient additive manufacturing technology for direct application to a wider range of manufacturing processes.

Although there have been recent developments in additive manufacturing (AM) technologies and processes, there are still significant requirements and research issues, which must be address. The issues include the need for emerging technologies and materials that can be used in non-environmental construction applications, and the advancement and integration of robustness in additive manufacturing structures. This requires advancements in computer modeling techniques, system conditioning, and the design of the most effective types of structures. A number of scholars have attempted to employ traditional construction materials to manufacturing systems using additive manufacturing methods. In contrast, other materials have been investigated by other researchers, including recycled materials, geopolymer concrete, building materials enhanced with waste materials, and natural fiber-reinforced composites.

Although additive manufacturing (AM) approaches have been improved to satisfy the requirements of construction, there remains a necessity to design materials, which can replace traditional products in the marketplace and can be easily included into the processes described above. Optimizing process parameters in AM poses challenges due to the need for the material to be fluidic for distribution, while also requiring quick curing to maintain structural integrity. Şahin and Mardani-Aghabaglou [4] reviewed several aspects related to 3D printing, including the capacity to extrude and create structures, the design of printer nozzles, the speed and direction of printing, the sizes of aggregates used, the ideal composition of mixes, and the incorporation of supports into the material. However, the level of development in AM standardization procedures in the building industry is insufficient for commercialization.

In this paper, we enhance and refine the prior reviews by conducting a comparative, systematic, and comprehensive, examination of the available literature, as outlined in the following paragraphs. This study evaluated original research papers and review papers from reputable journals to identify the limits and obstacles in the use of AM techniques in the construction industry. While there are several review papers available in this sector, a significant number of them lack a comprehensive and in-depth analysis. The articles by Ngo et al. [5] and Bai et al. [6] specifically focused on the material science aspects of the procedure, without delving into detailed data about process advancement. However, Utela et al. [7] did not thoroughly address the challenges associated with implementing materials into 3D printing procedures, although providing detailed explanations of the processes. The evaluations by De Castro and García-Ayuso [8] are now obsolete since there have been considerable improvements in techniques and materials in the area in recent years. Craveiro, Duarte, Bártolo, and Bártolo [9] conducted a comprehensive analysis of the three most well-known AM techniques (D-shape, concrete printing (CP), and contour crafting) in the construction industry. The study reported on potential uses, cost analysis, and other advantages compared to conventional building methods.

Bos et al. [10] emphasized the 3D CP facility at Eindhoven University of Technology, along with other established printing techniques. The study primarily addressed design, geometry, and process parameter concerns, while also investigating potential research avenues. Quah et al. [11] performed a thorough assessment of articles released in 2023 in their research. This article aims to investigate the progress achieved in three processes of computer-aided manufacturing at the 3D printing facility in Singapore. Kovler-Roussel [12] carried out a comprehensive study of materials with concrete and mortar conditions initially including geometric measurements of structures. They also examined the effect of these characteristics on mechanical features. In their study, D'Ambrisi et al. [13] thoroughly examined cementitious and polymeric building materials. In addition, they investigated the environmental and socioeconomic impacts of additive manufacturing processes in the building sector. Gradesi and Labonot [14] thoroughly examined the practice of additive manufacturing (AM) in the construction industry, and proposed possible improvements in the application of AM technology. Rehman and Kim [15] thoroughly examined the technical characteristics and features of 3D printed materials.

Aguirre-Guerrero et al. [16] conducted a study to establish a strong relationship between the demands for 3D printed cement products and the growth in this industry. Chen et al. [17] conducted a research that presented a thorough analysis of the applications of Additive Manufacturing (AM) in the construction sector. The authors outlined the several stages included in contemporary building and deliberated on the existing materials as well as the prospective ones for future use. Ghaffar, Corker, and Fan [18] have completed a thorough examination of additive manufacturing techniques and technology in the construction sector. In their study, Vafadar et al. [19] conducted a comprehensive literature analysis on the use of metal AM technologies, with a particular focus on their applications in the construction industry. Marchisotti and Zappa [20] conducted a feasibility analysis of several drone-based technologies for the practical building of masonry structures. Wakisaka et al. [21] conducted a thorough examination of the progress of automation in the building industry for high-rise buildings. They also analyzed the market in relation to academic research. Three primary disparities were discovered among the robotics industry, academia, and construction sector, along with suggestions to resolve these disparities.

A scient metric visualization and study of literature pertaining to artificial intelligence in construction, engineering, and architecture was conducted by Pan and Zhang [22] conducted a thorough examination of the use of unmanned aerial systems for inspecting automated structures in the built environment. They also presented a case study to verify the suggested framework. In their publication, De Schutter et al. [23] focused on addressing technical challenges associated with concrete 3D printing, while also highlighting the environmental and economic benefits that this technology offers. In a recent publication, Yu et al. [24] conducted research on the process features and qualities of 3D printed cement-based composites in both their hardened and fresh states.

In their work, Panda, Unluer, and Tan [25] conducted a similar investigation on extrusion-based techniques. However, their focus was primarily on discussing the mechanical characteristics of cementitious composite materials in more depth. Bos et al. [26] released a comprehensive review study specifically examining the application of reinforcement in 3D printed concrete structures. The review article given by Kondepudi et al. [27] compiled existing material to determine the necessary rheological specifications for concrete printing. Given the deficiencies in existing research, it is necessary to identify and tackle interdisciplinary concerns so as to effectively use AM operations. In order to include AM processes in the construction industry, it is necessary to have a comprehensive understanding of the most advanced methods now available. This will help identify and emphasize the limitations and challenges associated with these techniques. The focus of this review is on four specific areas: AM processes commercialization in built ecosystem, AM processes, AM process constraints, and construction materials for AM. This review aims to help researchers from various backgrounds, such as sustainability, manufacturing, designers, and material science, to identify future research directions.

Sustainability and Sustainable manufacturing

Essentially, sustainability refers to the capacity to persist or withstand, and this has substantial consequences. Sustainability refers to the long-term production and variety of biological structures from an ecological standpoint, as well as the possibility for long-term wellbeing from a human viewpoint. The latter is contingent upon the welfare of the natural environment, which encompasses the prudent use of natural resources and proper waste management. Sustainability entails establishing a stable and harmonious connection between humankind and our planet. Undertaking such a task is arduous, given the intricate nature of both the planetary system and the human system. Sustainability, within the context of ecosystem stewardship and human progress, encompasses ideological, political, ecological, and economic aspects. It is primarily understood as a derivative of the concept of sustainable advancement. Sustainability encompasses three main dimensions: social (like political), economic, and environmental aspects (refer to **Fig 2**). To achieve sustainability, multi-dimensional indicators and an advanced strategy are necessary to establish connections between a community's economy, society, and ecosystem.

Sustainable manufacturing encompasses the involvement of companies in the productive sector, whereby the entire production system, including the supply chain, should adhere to certain principles. These principles include ensuring economic viability, avoiding pollution, conserving natural and energy resources, providing creative and social rewards for all workers, maintaining safety and fair treatment of consumers, communities, and workers. Several legislation and standards have been suggested to regulate and guarantee sustainable production. Some of them include: Accountability is measured using the AA 1000 framework, while social accountability is assessed using the AS 8000 standard.

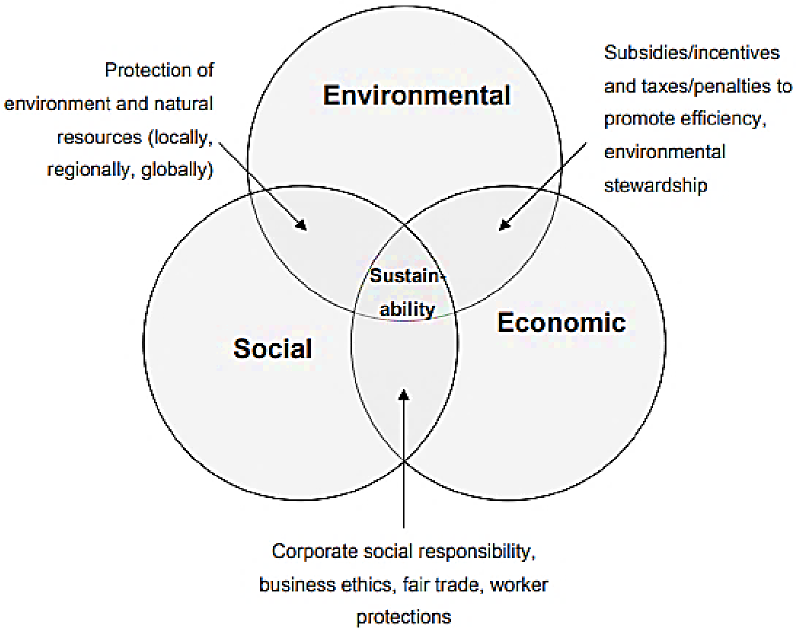

Fig 2. The concept of sustainability as the point where its three main components meet

The Global Reporting Initiative (GRI) provides guidelines for reporting on sustainability. Environmental management standards are outlined in the ISO 14000 series. The SR ISO 26000 offers international guidelines for social responsibility. The Commission on Sustainable Development is an organization dedicated to promoting sustainability. The Triple Bottom Line (TBL) or 3BL concept emphasizes the importance of environmental, economic, and social factors. The sustainability performance (SP) of companies is measured by the Dow Jones Sustainability Index (DJSI) [28]. ETHOS is an organization focused on promoting social responsibility. The Corporate Sustainable Index BOVESPA (ISE BOVESPA) [29] is a sustainability index in Brazil.

Multiple measurement suggestions for sustainable manufacturing have been identified, each with distinct methodologies. It is important to note that no one concept can be deemed universally valid. However, it is worth mentioning that the metrics exhibit a more comprehensive approach towards business sustainability. Furthermore, this does not hinder its use in assessing the sustainability of a company's manufacturing system. To effectively meet the requirements of a manufacturing measurement application, it is necessary to adhere to many components of the economy, environment, and society. This may be achieved via the use of specialized sub-indicators related to manufacturing. Hence, data will be gathered from the production system to validate the sustainability of this specific manufacturing process. In AM, verification may be conducted using two different methods, as is the case with various other technologies. One may assess the production metrics in the environmental, economic, and social dimensions of each technology in additive manufacturing. The alternative method involves comparing and organizing them in a systematic manner to identify similarities that may establish the equality of these indicators in all respects. Therefore, this relationship would establish a conformity among all metrics for the various additive manufacturing methods.

III. ENVIRONMENTAL EFFECTS OF ADDITIVE MANUFACTURING

The study pertaining to environmental implications is centered upon life cycle assessment (LCA), as seen in **Fig 3**. In contrast to other ecosystem impact assessment methodologies like Design for Environment or Carbon Assessment, the LCA Table approach allows for precise quantification of the ecosystem effect of a comprehensive system using many criteria. The quantification technique has been identified by institutions, such as UNEP (United Nations Environment Programme), according to the ISO Standard 14044 [30]. To achieve maximum realism, a life cycle study must be comprehensive and thorough. It is important to consider each stage of the whole life cycle (LC) of a product, starting from the raw materials removal to the last stage of disposal, which includes the production process. Nonetheless, the most recent step indicated is often disregarded. Indeed, there are only a limited number of approaches that can accurately assess the environmental consequences of current manufacturing processes. It is important to acknowledge that the use of energy linked to producing components may be substantial, and it is vital to acknowledge that not all manufacturing techniques have an equivalent environmental impact.

Norgate and Haque [31] emphasize the need of doing a comprehensive evaluation of the environmental impacts at the manufacturing stage. The NSF provided funding for a workshop dubbed the NSF Environmental Impacts of AM, which aimed to comprehensively examine the ecological impacts of AM [32]. The workshop performed an extensive examination of the existing studies on the environmental impacts of AM, particularly with regards to energy use and embodied energy. It also identified areas where there is a lack of knowledge and uncertainties, which can guide future research on the ecosystem impacts of AM. Additionally, the workshop aimed to broaden the research community's focus on energy use and environmental concerns in additive manufacturing. The majority of the existing research mostly concentrate on energy use. LCI information about resource use and both indirect and direct and process emissions are mostly unavailable. Typically, the particular energy values stated for AM unit procedures are 10 to 100 times greater than those for traditional machining and injection molding techniques.

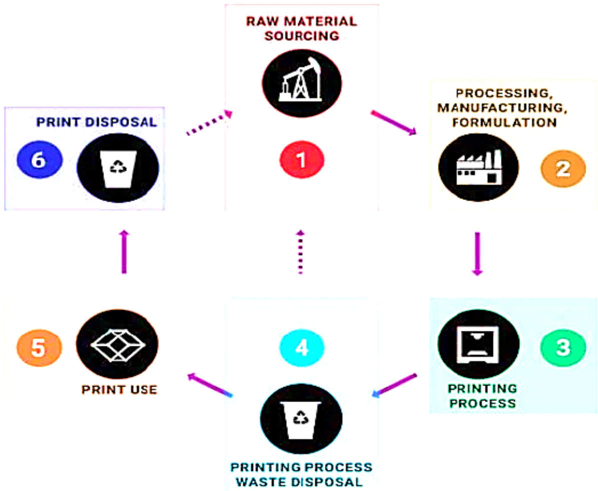

Fig 3. A six-step process for additive manufacturing

Several scholars have dedicated their efforts to addressing this problem over the last decade and a half. In their extensive assessments, examined these and other significant aspects of ECM (environmentally conscious manufacturing), citing over 300 references. While the ecosystem consequences of tooling and AM were not specifically addressed, the discussion included some ideas that are pertinent to the topic. Collection and disassembly, environmentally conscious production (ECP), product recovery and remanufacturing, materials recovery, and recycling, as well as environmentally conscious design (ECD), all contribute to the product LC processing through the use of tooling and rapid prototyping (RP) technologies. Nevertheless, the complete quantification of the environmental consequences associated with the various phases of processing product`s lifecycle has not yet been accomplished.

Hoepner [33] conducted a comprehensive evaluation of the most advanced environmental impact assessment (EIA) methods for AM. Several techniques were evaluated for assessing environmental effect, including life-cycle analysis (LCA), design for environment (DFE), and environmental impact scoring systems (EISS). It was found that the absence of thorough study and rapid growth of this technology led to several unresolved issues. The authors suggest a cooperative initiative including environmental experts, process control engineers, and designers, to evaluate the implication. Recent studies on the environmental consequences of AM [34] have investigated the claim that this initiative may minimize the carbon footprint of products by decreasing logistics and supply chain activities.

Burgess and Brennan [35] provide a significant study on the utilization of Life Cycle Assessments (LCAs) for determining the environmental consequences of sourcing chemicals in a broad sense. The majority of these research mainly concentrate on energy use or other related variables. In [36], Buranská et al. observed the various sorts of significant effects by contrasting AM to the process of machining the hollowed-out thermoplastic components. This monitoring was done from the beginning to the end of the life cycle. The study's primary finding was that, contrary to previous ideas, the environmental effects of transportation, disposal, and material considerations were far less significant compared to the energy consumption of printers. Therefore, the most crucial aspect to enhance the sustainability of AM would be to optimize the energy efficiency of 3D printers.

However, as printers improve in efficiency, the significance of materials choices in terms of ecological consequences and human health becomes more relevant. Therefore, it is crucial to analyze and compare the implications associated with distinct materials. To do LCA, it is advisable to adhere to the International Organization for Standardization (ISO) Standards, namely ISO 14044:2006and ISO 14040:2006, since they provide guidelines for completing such studies [37]. AM has the ability to decrease carbon emissions by optimizing design and reducing material waste (MW). The ATIKINS study determined that an ideal design might provide material and weight savings of about 40% [38]. According to their calculations, decreasing the weight of a long-range aircraft by 100 kg leads to a cost reduction of 2.5 million dollars in fuel and a decrease of 1.3 million metric tons of CO2 emissions during the aircraft's lifespan. Additional investigation is necessary to comprehensively analyze the environmental impacts of AM.

In order to get a complete understanding of the benefits and possible disadvantages of implementing additive manufacturing (AM), it is essential to implement a comprehensive plan that covers the whole life cycle of the AM-produced component(s), from its inception to its disposal. The components that are particularly formulated to utilize the unique weight-saving capabilities of additive manufacturing have the greatest potential for reducing environmental impact. Egle et al. [39] provide an innovative method for evaluating the impact on the environment, together with a thorough examination of the technical and economic factors. This methodology is employed in various additive manufacturing techniques and functions as a tool for producers to make decisions on the selection of a production process, taking into account multiple criteria. The authors conducted a study where they generated and evaluated new materials for paste extrusion printing. Additionally, they also examined materials that were created by other researchers. Testing conducted a LCA to compare the overall ecosystem consequences of their whole system with the typical ABS extrusion. Additionally, testing evaluated the material cost, printability, and strength.

The energy required for printing was decreased by 75%, resulting in a reduction from 160 to 40 Wh per component. Additionally, the environmental effects associated with the materials used were decreased by 83%, from 6.5 to 1.21 REHM per component [40]. The overall effects per component were decreased by 79% (from 28 to 7 REHM), which includes the embedded effects of the printer itself, in the scenario where maximal utilization is achieved. The use of AM is believed to reduce material waste, however, it has been shown that the actual amount of material waste may exceed initial expectations. This discrepancy may be attributed to mistakes made by either humans or the printer itself [41]. The amount of support material in FDM is determined on the orientation of the part and other printing variables. Inadequate preheating time, improper component geometry, human mistake, or printer problems may all lead to failures. This research gathered MW from commercial printers of FDM that use ABS material in a highly used open shop. The data about the weight of both the prints and the support material that did not meet the required standards were systematically documented as time progressed.

Furthermore, the unsuccessful prints were categorized into nine distinct groups and evaluated based on the causes of their failure. The statistics were analyzed and revealed that approximately 35% of plastics utilized in open studio was squandered. In view of the unsuccessful prints as the additional quantity of material used in real-life situations, the amount of material wasted due to failure is about two times more than what would be expected in a controlled process research. Combining the energy usage and materials waste data would result in a fuller LC inventory of the commercial FDM printer.

IV. SUSTAINABILITY CHARACTERIZATION

Recently, the business and academics have openly speculated on the sustainability advantages of AM. However, in order to encourage the widespread application of the technology, it is fundamental to provide scientific data using well-established measuring methodologies [42].

Previous research has documented efforts to evaluate the effectiveness of additive manufacturing methods, as seen by studies such as [43][44]. Specialized benchmark components have been developed to evaluate the performance of AM processes and systems, and provide valuable data to aid in decision-making. Multiple benchmark works have been published to ascertain the attainable levels of surface quality and dimensional accuracy using current AM technologies. In addition to the method and material, several elements, such as the architectural style and particular process parameters, might potentially impact the precision and surface quality of the component. In order to accomplish sustainable manufacturing, it is fundamental to create and standardize measurement science methodologies for AM. These methods will enable the assessment and quantification of the sustainability implications of AM.

Sustainability Characterization Methodology

Currently, industrial firms are compelled to produce and distribute high-quality goods while simultaneously reducing their negative influence on the environment. Transitioning industrial organizations' environmental operations from a human-centered approach to science-based approaches may be accomplished by using science-based endurability classification. This classification will include data on several presentation indicators, which will be critical in assessing the sustainability of a unit manufacturing process (UMP). UMPs refer to the discrete stages in which raw materials are converted into a final product by the application of energy.

Thrust primarily deals with the analysis, evaluation, and combination of sustainable attributes of individual and collective processes, manufacturing facilities, and supply chains. This undertaking will provide the essential mathematical foundations for formulating process models that give priority to sustainability. The objective of the project is to produce a comprehensive set of metrics pertaining to materials, energy, and resilience. Furthermore, it will provide computational methodologies for computing these measures using process models. In the end, it will provide innovative approaches for integrating these metrics across all levels of the process. This initiative aims to conduct thorough assessments of manufacturing methods at the industry level with the goal of improving sustainable performance. It will do this by scrutinizing and delineating the specific manufacturing and assembly procedures, while also evaluating the competencies of suppliers. The research plan is formulated to implement the aforementioned technical principles. The content is divided into two primary focuses and six research initiatives (refer to **Table 1**).

Table 1. Projects for sustainable processes and resources

Project	Description
Sustainability of Unit Manufacturing Processes	This project aims to build analytical tools for assessing the sustainability of unit manufacturing processes. These tools will use computational methodologies to calculate several SP criteria.
Sustainable Metrics for Unit Assembly Processes	This project aims to provide the analytical tools required to assess the sustainability of unit assembly operations. It will include the use of several computational methodologies to calculate different sustainability performance criteria.
Integrated Production Processes	This project aims to provide a comprehensive methodology and computational strategy for combining sustainability parameters calculated at the individual unit and assemblage levels.
Supplier Characterization of Production Network	This project aims to provide sustainability characterizations and develop computational tools for the suppliers within the manufacturing network. This will include providers involved in the production and distribution of goods.
The Integration Infrastructure for Sustainable Manufacturing	Thrust primarily emphasizes the evaluation, analysis, and enhancement of sustainability indicators, and the enhancement of mathematical frameworks and strategies for optimization. The system will provide the necessary framework and organization to (1) calculate, declare, monitor, and share sustainability measurements, and (2) evaluate, and enhance the procedures responsible for generating those measurements.
Manufacturability Sustainability Metrics	This project will primarily address three fundamental components of the sustainability issue in relation to manufacturability: the establishment of clear criteria for energy and material information pertaining to sustainability and its integration with design specifications, the development of a systematic approach for evaluating energy and material usage in manufacturing processes, and the formulation of test methods for collecting data and calculating material and energy efficiency at the product level.
Sustainability Optimization and Modeling	This project aims to provide an integrated architecture that combines necessary technical information systems, computational instruments, and simulation software. The purpose is to assist in evaluating performance and making informed decisions at every level.

All researchers involved in the six previous initiatives are situated inside the Systems Integration Division (SID). The majority of individuals are located within the LC Engineering Group. The project descriptions within the Research Plan section provide a depiction of the interactions that occur between the team members and the projects. The Project Plans provide precise details on the Project activities coordination and the particular requirements for data sharing, including the kind and time, between Projects and external partners. External partnerships are crucial for the each project and program will create connections with the standards development organizations (SDOs), most relevant professional societies, and industry consortiums. Quarterly program meetings will be held, during which project leaders will provide updates on the state of work and the progress made towards milestones. Regular meetings with the Project leaders will provide a platform to identify possible issues or possibilities for collaboration with external organizations or inside NIST.

When assessing sustainability, it is crucial to thoroughly analyze all stages of the complete AM process, including post-processing, raw material preparation, real fabrication, pre-processing, and final component production. It is necessary to carefully select suitable measuring techniques to accurately evaluate sustainability. To gain insightful comprehension of the sustainability elements, it is necessary to conduct comparisons with proven processes, like powder metallurgy, which is regarded as sustainable due to its capacity to use recycled materials. A study is needed to provide a theoretical framework for evaluating sustainability in additive manufacturing. Prior research has shown the potential advantages of constructing theoretical frameworks to evaluate the sustainability of various industrial processes, especially those that depend on energy use.

Additive manufacturing (AM), being a disruptive technology, has potential benefits in the production of functional and critical components. Moreover, AM has the potential to improve the Social Media (SM) industry in terms of its social, economic, and environmental dimensions. AM is particularly advantageous for firms that experience economic advantages from mass customization, weight reduction of components, and optimization of the supply chain. This is mostly the case in sectors such as healthcare, dentistry, automotive, and aerospace.

V. RELEVANT ASTM STANDARDS ORGANIZATIONS

ASTM International develops standards that are relevant to both Additive Manufacturing (AM) and Sustainable Manufacturing (SM).

ASTM Sustainable Manufacturing

Multiple ASTM committees are now in the process of formulating standards for different facets of intelligent manufacturing procedures. ASTM's inclusive and progressive strategy allows stakeholders from growing sectors to proactively engage with ASTM in order to develop standards that promote the advancement of their respective industries. The standards for additive manufacturing, a process that constructs plastic or metal components by adding layers, are established by F42 on AM Technologies. F42 is accountable for establishing standards pertaining to several aspects of AM. These include defining requirements for metal mixtures used in fine particles bed fusion, providing guidelines for describing the characteristics of metal powders used in AM procedures, developing an AM file format, and establishing a method for reporting information related to AM specimens.

Aerospace engine components, such as combustion chambers and nozzles, produced using AM may exhibit distinct defects compared to parts built using traditional methods. Committee E07 on Nondestructive Testing is collaborating with F42 to establish standards specifically for this domain. "Our goal is to achieve a highly multidisciplinary outcome," said Dr. Jess Waller, a materials scientist working at the NASA White Sands Test Facility. He observes that E07 is developing cutting-edge non-destructive testing (NDT) protocols and organizing round-robin testing of samples with fault kinds that are exclusive to AM.

Computer-controlled equipment, such as driverless automated guided industrial vehicles (DAGIV), mobile robots, and unmanned ground vehicles, are significantly transforming the manufacturing industry due to their advanced capabilities. They possess the ability to transport goods or equipment from one location to another, as well as the skill to assemble various components. "Mobile manipulators, which consist of robot arms mounted on robot bases, are currently a subject of increasing interest for both researchers and robot manufacturers. They have the potential to revolutionize assembly line and agile manufacturing processes, as well as traditional methods of vehicle docking and navigation," states Roger Bostelman, a researcher at NIST and the chair of Committee F45 on DAGIV. Upon completion of two proposed ASTM standards, manufacturers and consumers will have the opportunity to assess the docking and navigation capabilities of devices.

Nanotechnology has led to the development of baseball bats with enhanced strength, textiles that are more resistant to wrinkles, and car coatings that are more durable. Additionally, it has the promise to advance illness treatment and more. The primary responsibility of ASTM's Committee E56 on Nanotechnology is to develop and establish a set of standards that define and evaluate nanomaterials, while also promoting the advancement of workforce education within the nanotechnology sector. According to Hong et al. [45], smart or digital manufacturing and nanotechnology are closely connected. He explains that as assemblies and components become smaller, more intricate, and more technologically improved, it is necessary to explore new directions and think creatively. He emphasizes that standards are crucial for the purpose of comparing and providing advice.

Packaging plays a crucial role in smart manufacturing by not only safeguarding items during transportation, but also serving additional functions. Intelligent packaging has the capability to regulate temperature, check the state of freshness, and provide tracking, among several other advantages. The standards established by Committee D10 pertain to both the constituent materials of a package and its performance characteristics. Single use systems provide a more intelligent approach to pharmaceutical and biopharmaceutical production by minimizing the risk of contamination for vaccines and pharmaceuticals. The product safety will be supported by the standards being created by Committee E55. Practices will aid in assessing the integrity of equipment and systems during manufacturing, among other things. The standards established by ASTM Committee E57 are propelling the advancement of 3D imaging systems by promoting uniform and precise language, hence enhancing user trust in system functionality [46]. Methods for assessing the efficiency of 3D imaging systems with greater capacities, often used in construction, aerospace, and other industries, are already accessible. Additionally, there is a suggested standard for evaluating the performance of systems used to monitor items in manufacturing facilities.

Enhancing the sustainability of manufacturing involves considering social, environmental, and financial aspects and using resource-efficient strategies. These elements are in line with smart manufacturing since they facilitate more efficient operations, decrease energy usage, and so on. The ASTM Subcommittee E60.13, which is part of the Committee E60 on Sustainability, is presently engaged in the creation of standards that seek to establish clear definitions and classifications for sustainable manufacturing processes. These standards will also address the proper handling of waste materials, including carbon dioxide emissions and energy consumption. Additionally, the subcommittee aims to provide guidance for policy implementation based on the findings of this study (E2986).

ASTM International's Committee on Sustainability E60 [47] has established a new subcommittee, E60.13, focused on sustainable manufacturing (SM). The primary objective of this subcommittee is to advance and streamline environmentally friendly manufacturing processes. The subcommittee E60.13 is currently developing four standards: WK38312, which focuses on new comments and actions related to facilities waste classification; WK35702, which introduces new guidelines for evaluating biological sustainability in process analysis; WK35705, which provides new guidelines for defining long-lived MP; and WK35703, which presents a new glossary of standard terms in SM. NIST is assuming a key role in the initiatives of the E60.13 subcommittee.

ASTM AM Technology

The F42 committee, focused on additive manufacturing technologies, consists of individuals from several sectors including startups, established enterprises, trade organizations, academia, and government. The organization has convened since 2009, coinciding with the emergence of the extensive prospects for additive manufacturing [48]. The committee's founders acknowledged the need for strong global standards in this rapidly expanding domain. They have established criteria that facilitate the implementation and acceptance of additive manufacturing for a wide range of materials and techniques. These standards provide a universally recognized framework, widely accepted criteria for AM materials, guidelines for these emerging technologies, and other benefits. ASTM International's additive manufacturing standards, including both existing major standards and proposed standards, are continuously improving in terms of their strength, level of detail, and specificity to different applications.

Consequently, companies worldwide are manufacturing components and goods with ever higher standards of excellence and performance. ASTM International facilitates cooperation among all stakeholders of standards by offering physical meeting spaces, internet tools, discussion places, and balloting options that are available 24/7. The purpose of ASTM's AM Technology standards is to enhance understanding of the industry, foster research, and promote the use of technology. ASTM Committee F42 is responsible for developing standards that include nomenclature, performance measurement of various manufacturing processes, quality assurance of final products, and calibration methods for AM machines. The ASTM F42 complex subcommittees are now focused on developing standards for many aspects including processes and materials, nomenclature, data and design formats, and test methods [49][50]. NIST takes an active role in leading some initiatives within the ASTM F42 subcommittee. ASTM and ISO International have recently entered into an agreement to enhance collaboration in the joint development of International Standards for AM.

VI. CONCLUSION

When discussing, comprehending, and implementing SM, it is crucial to possess information about sustainability and its corresponding measures. Sustainability is a multifaceted term that has been subject to many definitions and interpretations among individuals. The sustainable advancement concept was popularized by the Brundtland Commission, which defined it as the kind of advancement that ensures the satisfaction of current demands without jeopardizing the capacity of upcoming generations to accomplish their needs. Additive manufacturing is a very promising method for constructing intricate forms, personalized components, or limited quantities of items. This technique eliminates the need for producing molds or using machining processes, which may be inefficient and time-consuming. Further endeavors are required to expedite the development of additive manufacturing technologies for crucial components and large-scale production. The sustainability features of AM may provide firm with benefits to use this technology. However, presently there is an insufficiency of measurement science to fully comprehend the sustainability of additive manufacturing. Consequently, in this research, we first provided relevant material about the environmental consequences of AM. Subsequently, we presented a framework for a sustainability characterization guide that can be used as a point of reference by the community to evaluate AM procedures in terms of sustainability. The guide is currently in the process of being officially established and is currently an active project within the ASTM E60.13 committee. Ultimately, we provided a depiction of pertinent ASTM standards groups.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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Competing Interests

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References

[1]. J. Edgar and S. Tint, "'Additive Manufacturing Technologies: 3D printing, rapid prototyping, and direct Digital manufacturing', 2nd edition," Johnson Matthey Technology Review, vol. 59, no. 3, pp. 193–198, Jul. 2015, doi: 10.1595/205651315x688406.

[2]. D. R. Eyers and A. T. Potter, "Industrial Additive Manufacturing: A manufacturing systems perspective," Computers in Industry, vol. 92–93, pp. 208–218, Nov. 2017, doi: 10.1016/j.compind.2017.08.002.

[3]. D. Landi, F. C. Zefinetti, C. Spreafico, and D. Regazzoni, "Comparative life cycle assessment of two different manufacturing technologies: laser additive manufacturing and traditional technique," Procedia CIRP, vol. 105, pp. 700–705, Jan. 2022, doi: 10.1016/j.procir.2022.02.117.

[4]. H. G. Şahin and A. Mardani-Aghabaglou, "Assessment of materials, design parameters and some properties of 3D printing concrete mixtures; a state-of-the-art review," Construction and Building Materials, vol. 316, p. 125865, Jan. 2022, doi: 10.1016/j.conbuildmat.2021.125865.

[5]. T. Ngo, A. Kashani, G. Imbalzano, K. Nguyen, and D. Hui, "Additive manufacturing (3D printing): A review of materials, methods, applications and challenges," Composites Part B: Engineering, vol. 143, pp. 172–196, Jun. 2018, doi: 10.1016/j.compositesb.2018.02.012.

[6]. G. Bai, W. Li, G. Ma, J. Sanjayan, and M. Bai, "3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates," Cement and Concrete Composites, vol. 120, p. 104037, Jul. 2021, doi: 10.1016/j.cemconcomp.2021.104037.

[7]. B. Utela, D. W. Storti, R. Anderson, and M. A. Ganter, “A review of process development steps for new material systems in three dimensional printing (3DP),” Journal of Manufacturing Processes, vol. 10, no. 2, pp. 96–104, Jul. 2008, doi: 10.1016/j.jmapro.2009.03.002.
[8]. M. D. L. De Castro and L. E. García-Ayuso, “Soxhlet extraction of solid materials: an outdated technique with a promising innovative future,” Analytica Chimica Acta, vol. 369, no. 1–2, pp. 1–10, Aug. 1998, doi: 10.1016/s0003-2670(98)00233-5.
[9]. F. Craveiro, J. P. Duarte, H. Bártolo, and P. Bártolo, “Additive manufacturing as an enabling technology for digital construction: A perspective on Construction 4.0,” Automation in Construction, vol. 103, pp. 251–267, Jul. 2019, doi: 10.1016/j.autcon.2019.03.011.
[10]. F. F. Bos, R. Wolfs, Z. Z. Ahmed, and T. T. Salet, “Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing,” Virtual and Physical Prototyping, vol. 11, no. 3, pp. 209–225, Jul. 2016, doi: 10.1080/17452759.2016.1209867.
[11]. T. K. N. Quah, Y. Tay, J. H. Lim, M. J. Tan, T. N. Wong, and K. H. H. Li, “Concrete 3D Printing: process parameters for process control, monitoring and diagnosis in automation and construction,” Mathematics, vol. 11, no. 6, p. 1499, Mar. 2023, doi: 10.3390/math11061499.
[12]. K. Kovler and N. Roussel, “Properties of fresh and hardened concrete,” Cement and Concrete Research, vol. 41, no. 7, pp. 775–792, Jul. 2011, doi: 10.1016/j.cemconres.2011.03.009.
[13]. A. D’Ambrisi, M. Mezzi, L. Feo, and V. P. Berardi, “Analysis of masonry structures strengthened with polymeric net reinforced cementitious matrix materials,” Composite Structures, vol. 113, pp. 264–271, Jul. 2014, doi: 10.1016/j.compstruct.2014.03.032.
[14]. K. Gradeci and N. Labonnote, “On the potential of integrating building information modelling (BIM) for the additive manufacturing (AM) of concrete structures,” Construction Innovation: Information, Process, Management, vol. 20, no. 3, pp. 321–343, Nov. 2019, doi: 10.1108/ci-07-2019-0057.
[15]. A. U. Rehman and J. H. Kim, “3D Concrete Printing: A systematic review of rheology, mix designs, mechanical, microstructural, and durability characteristics,” Materials, vol. 14, no. 14, p. 3800, Jul. 2021, doi: 10.3390/ma14143800.
[16]. A. M. Aguirre-Guerrero, R. M. De Gutiérrez, M. A. Villaquirán-Caicedo, and S. Delvasto, “3D printing with cementitious materials: Challenges and opportunities for the construction sector,” Automation in Construction, vol. 146, p. 104693, Feb. 2023, doi: 10.1016/j.autcon.2022.104693.
[17]. X. Chen et al., “Implementation of technologies in the construction industry: a systematic review,” Engineering, Construction and Architectural Management, vol. 29, no. 8, pp. 3181–3209, Jul. 2021, doi: 10.1108/ecam-02-2021-0172.
[18]. S. H. Ghaffar, J. Corker, and M. Fan, “Additive manufacturing technology and its implementation in construction as an eco-innovative solution,” Automation in Construction, vol. 93, pp. 1–11, Sep. 2018, doi: 10.1016/j.autcon.2018.05.005.
[19]. A. Vafadar, F. Guzzomi, A. Rassau, and K. Hayward, “Advances in Metal Additive Manufacturing: A review of common processes, industrial applications, and current challenges,” Applied Sciences, vol. 11, no. 3, p. 1213, Jan. 2021, doi: 10.3390/app11031213.
[20]. D. Marchisotti and E. Zappa, “Feasibility Study of Drone-Based 3-D measurement of defects in concrete structures,” IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1–11, Jan. 2022, doi: 10.1109/tim.2022.3170969.
[21]. T. Wakisaka, N. Furuya, Y. Inoue, and T. Shiokawa, “Automated construction system for high-rise reinforced concrete buildings,” Automation in Construction, vol. 9, no. 3, pp. 229–250, May 2000, doi: 10.1016/s0926-5805(99)00039-4.
[22]. Y. Pan and L. Zhang, “Roles of artificial intelligence in construction engineering and management: A critical review and future trends,” Automation in Construction, vol. 122, p. 103517, Feb. 2021, doi: 10.1016/j.autcon.2020.103517.
[23]. G. De Schutter, K. Lesage, V. Mechtcherine, G. Habert, and I. Agustí-Juan, “Vision of 3D printing with concrete — Technical, economic and environmental potentials,” Cement and Concrete Research, vol. 112, pp. 25–36, Oct. 2018, doi: 10.1016/j.cemconres.2018.06.001.
[24]. K. Yu, W. McGee, T. S. Ng, Z. He, and V. C. Li, “3D-printable engineered cementitious composites (3DP-ECC): Fresh and hardened properties,” Cement and Concrete Research, vol. 143, p. 106388, May 2021, doi: 10.1016/j.cemconres.2021.106388.
[25]. B. Panda, C. Unluer, and M. J. Tan, “Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3D printing,” Cement and Concrete Composites, vol. 94, pp. 307–314, Nov. 2018, doi: 10.1016/j.cemconcomp.2018.10.002.
[26]. F. F. Bos, Z. Z. Ahmed, R. Wolfs, and T. T. Salet, “3D Printing Concrete with Reinforcement,” in Springer eBooks, 2017, pp. 2484–2493. doi: 10.1007/978-3-319-59471-2_283.
[27]. K. Kondepudi, K. V. L. Subramaniam, B. Nematollahi, S. H. Bong, and J. Sanjayan, “Study of particle packing and paste rheology in alkali activated mixtures to meet the rheology demands of 3D Concrete Printing,” Cement and Concrete Composites, vol. 131, p. 104581, Aug. 2022, doi: 10.1016/j.cemconcomp.2022.104581.
[28]. M. V. López, A. Garcia, and L. A. Rodriguez, “Sustainable Development and Corporate Performance: A study based on the Dow Jones Sustainability Index,” Journal of Business Ethics, vol. 75, no. 3, pp. 285–300, Feb. 2007, doi: 10.1007/s10551-006-9253-8.
[29]. R. J. Orsato, A. S. Garcia, W. Mendes-Da-Silva, R. Simonetti, and M. Monzoni, “Sustainability indexes: why join in? A study of the ‘Corporate Sustainability Index (ISE)’ in Brazil,” Journal of Cleaner Production, vol. 96, pp. 161–170, Jun. 2015, doi: 10.1016/j.jclepro.2014.10.071.
[30]. F. L. Bourhis, O. Kerbrat, J.-Y. Hascoët, and P. Mognol, “Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing,” The International Journal of Advanced Manufacturing Technology, vol. 69, no. 9–12, pp. 1927–1939, Jul. 2013, doi: 10.1007/s00170-013-5151-2.
[31]. T. Norgate and N. Haque, “Using life cycle assessment to evaluate some environmental impacts of gold production,” Journal of Cleaner Production, vol. 29–30, pp. 53–63, Jul. 2012, doi: 10.1016/j.jclepro.2012.01.042.
[32]. C. L. Redman, J. M. Grove, and L. Kuby, “Integrating Social Science into the Long-Term Ecological Research (LTER) Network: Social Dimensions of Ecological Change and Ecological Dimensions of Social Change,” Ecosystems, vol. 7, no. 2, Mar. 2004, doi: 10.1007/s10021-003-0215-z.
[33]. T. Hoepner, “A procedure for environmental impact assessments (EIA) for seawater desalination plants,” Desalination, vol. 124, no. 1–3, pp. 1–12, Nov. 1999, doi: 10.1016/s0011-9164(99)00083-1.
[34]. Y. Li, G. Jia, Y. Cheng, and Y. Hu, “Additive manufacturing technology in spare parts supply chain: a comparative study,” International Journal of Production Research, vol. 55, no. 5, pp. 1498–1515, Sep. 2016, doi: 10.1080/00207543.2016.1231433.
[35]. A. A. Burgess and D. J. Brennan, “Application of life cycle assessment to chemical processes,” Chemical Engineering Science, vol. 56, no. 8, pp. 2589–2604, Apr. 2001, doi: 10.1016/s0009-2509(00)00511-x.
[36]. E. Buranská, I. Buranský, L. Morovič, and K. Líška, “Environment and Safety Impacts of Additive Manufacturing: A review,” Vedecké Práce Materiálovotechnologickej Fakulty Slovenskej Technickej Univerzity V Bratislave so Sídlom V Trnave, vol. 27, no. 44, pp. 9–20, Jun. 2019, doi: 10.2478/rput-2019-0001.
[37]. B. Turner, “International Organization for Standardization (ISO),” International Organizations, p. 47, Jan. 2003, doi: 10.1057/9780230271326_102.
[38]. C. D. Gardner et al., “Comparison of the Atkins, Zone, Ornish, and LEARN diets for change in weight and related risk factors among overweight premenopausal women,” JAMA, vol. 297, no. 9, p. 969, Mar. 2007, doi: 10.1001/jama.297.9.969.
[39]. L. Egle, H. Rechberger, J. Krampe, and M. Zessner, “Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies,” Science of the Total Environment, vol. 571, pp. 522–542, Nov. 2016, doi: 10.1016/j.scitotenv.2016.07.019.
[40]. K. Biswas, S. Shrestha, M. Bhandari, and A. O. Desjarlais, “Insulation materials for commercial buildings in North America: An assessment of lifetime energy and environmental impacts,” Energy and Buildings, vol. 112, pp. 256–269, Jan. 2016, doi: 10.1016/j.enbuild.2015.12.013.

[41]. M. Javaid, A. Haleem, R. P. Singh, R. Suman, and S. Rab, “Role of additive manufacturing applications towards environmental sustainability,” Advanced Industrial and Engineering Polymer Research, vol. 4, no. 4, pp. 312–322, Oct. 2021, doi: 10.1016/j.aiepr.2021.07.005.

[42]. O. T. M. Bucheli, I. Sigvaldadóttir, and K. Eyer, “Measuring single-cell protein secretion in immunology: Technologies, advances, and applications,” European Journal of Immunology, vol. 51, no. 6, pp. 1334–1347, Apr. 2021, doi: 10.1002/eji.202048976.

[43]. T. Pereira, J. Kennedy, and J. Potgieter, “A comparison of traditional manufacturing vs additive manufacturing, the best method for the job,” Procedia Manufacturing, vol. 30, pp. 11–18, Jan. 2019, doi: 10.1016/j.promfg.2019.02.003.

[44]. S. a. M. Tofail, E. P. Koumoulos, A. Bandyopadhyay, S. Bose, L. M. T. O’Donoghue, and C. A. Charitidis, “Additive manufacturing: scientific and technological challenges, market uptake and opportunities,” Materials Today, vol. 21, no. 1, pp. 22–37, Jan. 2018, doi: 10.1016/j.mattod.2017.07.001.

[45]. J. Hong, A. B. Murphy, B. Ashford, P. J. Cullen, T. Belmonte, and K. Ostrikov, “Plasma-digital nexus: plasma nanotechnology for the digital manufacturing age,” Reviews of Modern Plasma Physics, vol. 4, no. 1, Jan. 2020, doi: 10.1007/s41614-019-0039-8.

[46]. P. K. Rachakonda, B. Muralikrishnan, M. Shilling, D. S. Sawyer, and G. S. Cheok, “An overview of activities at NIST towards the proposed ASTM E57 3D Imaging System Point-to-point Distance Standard.,” PubMed, vol. 12, no. 2, pp. 1–14, Jan. 2017, [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/31080845

[47]. X. Escoto, D. Gebrehewot, and K. C. Morris, “Refocusing the barriers to sustainability for small and medium-sized manufacturers,” Journal of Cleaner Production, vol. 338, p. 130589, Mar. 2022, doi: 10.1016/j.jclepro.2022.130589.

[48]. S. Yang and Y. F. Zhao, “Additive manufacturing-enabled design theory and methodology: a critical review,” The International Journal of Advanced Manufacturing Technology, vol. 80, no. 1–4, pp. 327–342, Mar. 2015, doi: 10.1007/s00170-015-6994-5.

[49]. J. Lee, A. P. Nagalingam, and S. H. Yeo, “A review on the state-of-the-art of surface finishing processes and related ISO/ASTM standards for metal additive manufactured components,” Virtual and Physical Prototyping, vol. 16, no. 1, pp. 68–96, Oct. 2020, doi: 10.1080/17452759.2020.1830346.

[50]. R. Kawalkar, H. K. Dubey, and S. P. Lokhande, “A review for advancements in standardization for additive manufacturing,” Materials Today: Proceedings, vol. 50, pp. 1983–1990, Jan. 2022, doi: 10.1016/j.matpr.2021.09.333.