EDUCATIONAL MODULE ON SUSTAINABLE ADDITIVE MANUFACTURING (AM)

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# Introduction

Science, technology, engineering, and mathematics (STEM) fields are changing rapidly due to many emerging global needs and challenges. Over recent decades, a growing global population has escalated the demand on materials and energy use, as well as the discharge of wastes and emissions. Engineers play a key role in managing economic security, quality of life, and natural resources. Manufacturing and sustainability are two key aspects of engineering that promote innovation and industrial competitiveness through science, technology, and standards. The integration of manufacturing and sustainability creates an effective and efficient infrastructure for academia and industry to strive towards sustainable production.

This joint advancement of human and environmental ecosystems was addressed in the term sustainable development, defined by the Brundtland report [1] as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” The context of sustainable development is varied, however, and not characterized entirely by environmental concerns. Rather, there exists an intricate relationship between environmental protection, economic development, and social welfare, which needs to be balanced, to represent sustainable development in a holistic worldview. These three independent, co-existing categories were reinforced as the three pillars of sustainability by the 2005 United Nations World Summit [2]. Advanced manufacturing has improved the performance of U.S. industry through innovation and technology to manufacture complex, yet reliable and affordable products. One of the emerging trends in advanced manufacturing is additive manufacturing (AM), which can be considered as a vehicle towards a sustainable future.

Thus, under this framework of sustainable development, the topics relating to, sustainable manufacturing, sustainable additive manufacturing and sustainability assessment of additive manufacturing are established in this educational module.

Manufacturing exists as a stronghold for continuous growth and development of countries in the global sphere, a trend that is likely to continue as demand for commodities grow. Manufacturing drives innovation and productivity in countries with advanced economic stability, as well as promoting economic development in developing nations. Industrialization since the early 1800s has driven world gross domestic product growth [3], leading to previously unimaginable enhancements to quality of life. Manufacturing plays an important role in modern socio-economic systems leading to dramatic changes in the world economy and to sustained increases in labor productivity and economic welfare [4], [5]. On the other hand, these same industrialization and manufacturing activities pose a significant demand on the environment. Economic and social development attributed to manufacturing leads to deleterious impacts for air quality, water pollution, resource depletion, and other indicators, which can pose a threat to human welfare. For example, manufacturing and economic growth in China has exposed 99% of its urban population to air quality much lower than the EU standard of 40µg/m3, and has reduced the average life expectancy of the people [3]. This pattern of growth and related impacts need to be mitigated through sustainable manufacturing principles that analyze and modify the economic, social, and environmental performance of manufacturing systems to promote sustainable development.

# Rationale: Improving AM for ensuring Sustainable Engineering

This educational module aims to improve understanding of sustainable manufacturing at the macro (system) and micro (process) levels and to bridge gaps between knowledge discovery and technology implementation. Training future engineers on issues related to the growing AM sector by focusing on different aspects of sustainability (e.g., life cycle assessment, energy monitoring and analysis, and socio-economic assessment methods) will reduce negative impacts of AM.

The synergy of sustainability and AM, the role of each in design and their benefits for society, various indicators and factors (e.g., energy consumption), and models for sustainability assessment of AM are considered. The module will be beneficial for teaching undergraduate and graduate students in product design and manufacturing engineering courses about the effect of product and process attributes on AM sustainability performance through process-based measurement and analysis of materials/energy use (environmental), production costs (economic), and worker health and safety (social). The objectives are: 1) to foster students’ learning and immerse them into the concept of sustainable AM by integrating instructional and active learning resources, 2) to create a student learning environment conducive to sustainable engineering, and 3) to provide pedagogical support for experimental process evaluations in the context of AM.

# Course Content: Theory, Methodology, and Applications

As defined by ASTM International [6], AM is a process of making objects from three-dimensional solid model data by joining materials, usually in a layer-by-layer fashion. While the most popular applications in AM still involve rapid prototyping for testing the form, fit, and function of a design, the technology is growing as a reliable method to design and manufacture functional products of value [7], [8]. A key aspect of AM and its future success is the ability of the technology to quickly produce parts at high volumes and produce components customized to application- or customer-specific needs. The layer-based process allows for the design of almost any geometry, a drastic expansion of the previously constrained design space.

AM helps realize low-cost, rapid manufacturing of high precision, tailored products, along with elimination of fixed assets (e.g., design restrictions and tooling) associated with subtractive manufacturing (SM) processes. Furthermore, AM technologies can provide significant benefits in the product design and manufacturing space. Some of the benefits include the ability of AM to reduce waste streams through design freedom and selective placement of material, and also to help reduce environmental impact of manufacturing systems with on-demand manufacturing, supply chain flexibility, and elimination of work-in-process. While the advantages provided by a reduction in material consumption, tooling, and harmful chemicals used in machining is well known, the benefits have been tempered by findings that additive processes tend to be energy inefficient and contain hidden wastes [6]. In reality, more efforts are required to fully understand the breadth of sustainability factors and improve the efficiency of additive techniques [7], [9]–[11].

AM processes involve the construction of a part that may consist of thousands of layers, and each may take several minutes to complete. Thus, production may require significantly more time than conventional manufacturing processes. AM requires a significant amount of energy, because the energy consumed per volume of material is high [12]. Nevertheless, the advantages of AM can contribute to improving the environmental impacts over the entire lifecycle of the product, as discussed above. The Advanced Manufacturing Office of the U.S. Department of Energy, for instance, claims that AM saves energy by eliminating distributed manufacturing processes and material waste [13]. Since energy savings are product-specific and vary extensively, it is not possible to map the energy utilization of the entire AM sector, and this conclusion cannot be generalized [14]. Thus, educating engineers about sustainable product design and manufacturing can benefit the AM sector and reduce impacts of production.

# Introduction to Sustainability and Engineering

The first section of the educational module establishes the concept of sustainability and sustainable design and manufacturing. Dr. Robert Frosch, former chair of the Committee on Industrial Environmental Performance Metrics (National Academy of Engineering and National Research Council) stated in this way [15]:

In thinking about sustainability, we must carefully balance our human desire to live as we please, with an increasing set of political, economic, social, and environmental constraints. We do not want to destroy, or even to damage severely or irrecoverably, valuable natural resources (e.g., animal and plant diversity, forests, and lakes). We depend on these for the materials (e.g., food, medicines, building supplies) and basic "services" (e.g., the regeneration of clean air and water) that make life on Earth possible and comfortable…The problems of the environment and of social and economic equity are interrelated, and their solutions are technological in nature. I believe that engineers and the National Academy of Engineering have a special role to play in this regard.

Under this context, we introduce the intersection of sustainability and manufacturing through the following concepts: sustainable development, sustainability principles, sustainable engineering, and sustainable design and manufacturing.

1. What is Sustainable Development?

Sustainable development has been defined as, “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1]. Thus, sustainability encourages us to take a broader view in making decisions and solving problems.

1. What are Sustainability Principles?

Sustainability principles have been defined in a number of ways. For example, Ben-Eli [16], defined five domains and underlying principles of sustainability as follows:

1. The material domain is the basis of our existence and “the basis for regulating the flow of materials and energy.” The underlying principle is: “Contain entropy and ensure that the flow of resources, through and within the economy, is as nearly non-declining as is permitted by physical laws.”
2. The economic domain is the “guiding framework for creating and managing wealth.” The underlying principle is: “Adopt an appropriate accounting system, fully aligned with the planet’s ecological processes and reflecting true, comprehensive biospheric pricing to guide the economy.”
3. The life domain is “the basis for appropriate behavior in the biosphere.” The underlying principle is: “Ensure that the essential diversity of all forms of life in the Biosphere is maintained.”
4. The social domain enables humans to interact socially. The underlying principle is: “Maximize degrees of freedom and potential self-realization of all humans without any individual or group adversely affecting others.”
5. The spiritual domain enables people to behave and act in a common, cohesive and ethical manner. The underlying principle is: “Recognize the seamless, dynamic continuum of mystery, wisdom, love, energy, and matter that links the outer reaches of the cosmos with our solar system, our planet and its biosphere including all humans, with our internal metabolic systems and their externalized technology extensions – embody this recognition in a universal ethics for guiding human actions.”
6. What is Sustainable Engineering?

Sustainable engineering can be viewed as part of the “design of human and industrial systems to ensure that humankind’s use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment” [17].

This concepts can be largely realized in the Twelve Principles of Green Engineering [18]:

Principle 1: Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.

Principle 2: It is better to prevent waste than to treat or clean up waste after it is formed.

Principle 3: Separation and purification operations should be designed to minimize energy consumption and materials use.

Principle 4: Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

Principle 5: Products, processes, and systems should be “output pulled” rather than “input pushed” through the use of energy and materials.

Principle 6: Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

Principle 7: Targeted durability, not immortality, should be a design goal.

Principle 8: Design for unnecessary capacity or capability (e.g., “one size fits all”) solutions should be considered a design flaw.

Principle 9: Material diversity in multicomponent products should be minimized to promote disassembly and value retention.

Principle 10: Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

Principle 11: Products, processes, and systems should be designed for performance in a commercial “afterlife”.

Principle 12: Material and energy inputs should be renewable rather than depleting.

Additionally, however, sustainable engineering must encompass the economic and societal aspects of technical problems. Broadly, these are encompassed by three principles with 17 underlying actionable engineering functions, as described by Boyle and Coates [19]:

Principle 1: Maintaining the viability of the planet

Principle 2: Providing for equity within and between generations

Principle 3: Solving problems holistically

1. What is Sustainable Design and Manufacturing?

Diegel et al. [20] described sustainable design as “design which aims to achieve triple-bottom line ideals by striving to produce products that minimize their detriment to the environment while, at the same time, achieving acceptable economic benefits to the company and, wherever possible, having a positive impact on society.”

Sustainable manufacturing has been defined as, “The set of systems and activities for the creation and provision of manufactured products that balance benefits for ecological systems, social systems, and economic systems” [21]; where:

“Creation” includes the design of products and manufacturing systems, and the manufacture of physical products. “Provision” includes delivery and recovery of products, through remanufacturing, recycling, and other activities. “Balanced benefits” shows that the benefits cannot be optimized for each subsystem, but a balance point can be reached to bring positive benefits to society and economy. This assumes there is a cost born by ecological system (the benefit usually is negative).

Figure 1 indicates a view of the interrelationship between sustainable design and manufacturing.



Figure 1. Sustainable Design and Manufacturing

Several key product/process parameters impact sustainable design and manufacturing, which are material, geometry, and application in product design, and materials, geometry, and process in manufacturing. Understanding supply chain, production, and process requirements, inputs, and outputs, and their relationships supports sustainable design and manufacturing.

# Introduction to AM

The second part of the module focuses on educating the students on AM processes, principles, sustainability performance of AM, and sustainability assessment of AM at the macro and micro level.

The module progresses by answering key questions about AM presented below. Answering these questions will provide students an overview of what AM is, what approaches are used, what are the possible applications, and what are the limitations of the technology.

1. What is AM?

ASTM committee F42 defined AM as “a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Synonyms: additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication” [22].

AM or AM processes have also been referred to as follows:

* Layered manufacturing
* Direct CAD (computer-aided design) manufacturing
* Solid freeform fabrication
* Rapid prototyping and manufacturing
* 3D printing

1. What are the different AM processes and how are they classified?

AM systems are capable of utilizing polymers, ceramics, metals, composites, and various other materials. The three main types of AM are as follows:

* Liquid-based: Liquid monomers that are cured layer by layer into solid polymers
* Solid-based: Solid sheets that are laminated to create the solid part
* Powder-based: Powders that are aggregated and bonded layer by layer

ASTM defines seven key processes that form the set of technologies know as AM [22].

Binder jetting, n—an additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.

Directed energy deposition, n—an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

Material extrusion, n—an additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.

Material jetting, n—an additive manufacturing process in which droplets of build material are selectively deposited.

Powder bed fusion, n—an additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

Sheet lamination, n—an additive manufacturing process in which sheets of material are bonded to form an object.

Vat photopolymerization, n—an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

1. What are various classes/approaches within AM processes?

Figure 2 shows the multiple AM approaches, for various materials, technologies, and applications.



Figure 2. AM approaches

1. What are the limitations of parts produced by AM when compared to traditional manufacturing?

The main limitations of parts produced by AM include: non-conformity to dimensional specifications, and surface finish, part strength, thermal properties, build time (speed), and cost.

1. What are the key contributors to sustainability performance of AM processes?

The elements that make AM an advantageous method compared to traditional subtractive and formative processes are compatible with the principles of sustainability. The elimination of tooling, the ability to manufacture complex geometries, and the selective placement of material only where necessary, contribute to a reduction in waste and an increase in process efficiency [6]. AM allows the production of multiple components in a parallel manner, without the need for tooling [23], [24]. It inherently offers opportunities for reducing waste. The single-step nature of AM also provides transparency to the energy utilized in the process. Equipment often has peripheral devices; thus, basic power consumption and processing time are the two main considerations in energy consumption calculations [25]. It has been shown that the ability to update, repair, and remanufacture tooling presents an opportunity for significant reductions in energy consumption, emissions, and costs [2]. AM, therefore, has the potential to impact the life cycle of products by both directly and indirectly reducing the burden placed on the environment by manufacturing processes [4].

Despite the demonstrated success of AM, sustainability evaluation is a challenging but necessary task [25]. The joint efforts of design and manufacturing engineers with environmental scientists are essential in understanding the fundamental impacts of newer technologies and materials. Evaluation of the extent of the impact of these processes and their resulting products is required to define regulations and the spatial distribution that will enable the control and prevention of the potential harm, along with estimates of the cost required to deal with related issues.

# Sustainability Evaluation of AM

The third section of the module aims to introduce a methodology for engineers to evaluate the environmental, economic, and social performance of AM. The environmental responsibility of producing parts through AM is evaluated by introducing the concept of Design for Sustainable AM to reduce the energy footprint of AM, while costs and worker impacts are also introduced. The module progresses by answering the key questions as presented below.

1. What are the required steps to make a part using AM?

* Create a CAD model
* Export the CAD model in STL format
* Import the STL file to AM software for pre-processing:
* Convert the model into a computerized format that approximates its surfaces by facets (triangles or polygons) via tessellation
* Slice the model into closely-spaced parallel horizontal layers
* Download the processed file to AM machine and make the part
* Post process the part (process dependent)

1. How are the various process parameters defined in AM, such as part build time?

Time to complete a single layer is calculated by Eq. 1:

 (Eq. 1)

where Ti = time to complete layer i; Ai = area of layer i; v = average speed of the depositer (e.g., nozzle or beam); D = width of the deposited material (e.g., extrudate or beam); and Td = delay time between layers.

Once the Ti values have been determined for each layer (i), the total build cycle time is calculated using Eq. 2:

 (Eq. 2)

where Tc = build cycle time and ni = number of layers used to approximate the part.

1. How is the energy use in AM calculated?

A method for calculating the energy in AM process is by calculating the energy consumption rate (ECR), which is the energy consumed per mass of material used [10]. However, this value is difficult to calculate without having a clear understanding of the key contributors to energy consumption in AM. Translating process parameter behavior into a process model can reduce variability in the process and help control energy consumption. To achieve that goal, mapping the interrelationships of process energy consumption with environmental performance metrics, e.g., through energy modeling, is required. The fundamental concepts can be introduced in lecture, and then demonstrated in the laboratory exercise described later in the module.

# Future Directions for Sustainable AM

The module concludes by addressing the key challenges that exist in current AM technologies and discusses ways to bridge the gap between knowledge discovery and technology implementation in AM. The future studies should address existing challenges in sustainable AM through the following improvements:

* Improvements in surface finish
* Increase in detail rendition by thinner layers
* Improvements of material properties and range
* Elimination of rework
* Cut down of construction time
* Reduce the total cost

# Summary

The information above is provided as an overview with references for the instructor. Each topic is covered in a 20-30 minute lecture slideset. In addition, learning resources provide 20-25 minutes of in-class examples and a problem-based homework assignment. Two interlinked hands-on lab activities are discussed below, and involve a computer-based design laboratory and a machine-based manufacturing laboratory. These are included as supplementary material.

# Connections to Existing Core Curriculum

Introduction of sustainable design principles for AM can help us strive towards the above mentioned objectives related to improving the student learning environment, improving student learning of sustainable engineering, and supporting pedagogy for experimental evaluation of AM processes. This module will focus on introducing students to sustainability principles, AM principles, and the concept of design for sustainable AM. Thus, this module can be used across undergraduate and graduate curricula in disciplines such as industrial design, industrial engineering, manufacturing engineering, and mechanical engineering. Thus, students can learn about green design, sustainable manufacturing, energy analysis, cost analysis, and process throughput analysis through the lectures and activities in the module.

# Case Study

As mentioned above, AM is growing in popularity, and students will have the opportunity to use this process in their undergraduate curricula and their working careers for a variety of applications. Since AM can be material and energy intensive, especially when considering the upstream material impacts, it will be beneficial for them to gain exposure to design and analysis of additively manufactured products from a sustainability perspective. This module includes a case study in the form of a hands-on laboratory that will educate students about the use of CAD and CAM tools in AM, and about sustainability issues related to process time and energy use. The case study document includes the following information (see supplementary material):

1. Design of a product (keychain) and application of sustainability principles in analysis
2. Use of the fused deposition modeling (FDM) AM process
3. Calculation of the part build time and energy consumption
4. Design iteration to reduce cost, time, materials, and energy

# Problems

This module includes homework to scaffold the in-class learning (see supplementary materials).

# PowerPoint Presentations

This module provides a slide set with four topic areas. Each topic area is included as a slide subset, so instructors are free to select from among the four and/or rearrange the topic presentation order. Each subset includes coverage of the topic, as well as an in-class activity (e.g., an exercise or reflective question) to scaffold the concepts presented, and include (see supplementary materials):

1. Introduction to sustainable engineering
2. Introduction to AM
3. Energy analysis of AM
4. Future directions for sustainable AM

# References for Further Reading

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