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Optimizing Efficiency and Sustainability in Advanced Manufacturing Systems: An Engineering Perspective

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Abstract

Sustainable manufacturing needs to take into account the social, environmental, and economic effects of product distribution and production at the same time. In essence, the execution, assessment, and response of sustainable manufacturing depend on comprehensive measurements, sophisticated choices, and legislation. This study examines current research on ideas, practices, and resources for sustainable manufacturing. Engineering research has tackled design, development, assessment, and process management challenges at the industrial level. Engineering research has also tackled issues with supply chain design, production scheduling and preparation, and facility management at the level of manufacturing systems. Manufacturing techniques and procedures continue to be associated with being hazardous, polluting, and ineffective, despite their economic importance. By focusing on sustainable systems and procedures, researchers from academia and industry are rethinking manufacturing as a source of creativity to fulfill the demands of society in the future. There are still a lot of challenges and possibilities in decision-making and process- and systems-level research, even with recent advancements. A number of these issues that are pertinent to research, design, execution, and teaching in manufacturing processes and systems are emphasized.

Keywords: *Optimizing Efficiency, Sustainability, Manufacturing Systems.*

Introduction

Sustainable Manufacturing System

A manufacturing system that is sustainable is one that minimizes the adverse effects of financial and environmental expenditures. Lean manufacturing techniques may help accomplish this in part by lowering operating costs, increasing production efficiency, and reducing output waste. However, the idea of lean methodologies ignores environmental aspects like energy usage and carbon dioxide emissions, which are crucial in today's world for creating a sustainable manufacturing system (Nujoom et al., 2018). Sometimes, the term "sustainable manufacturing" is used informally to refer to the processes involved in identifying and limiting the effects of manufacturing on the environment. However, the concept of sustainability encompasses much more than just evaluating and improving the ecological impact of production processes and systems. This conclusion is likely to be upheld despite this warning. When society uses resources and generates wastes faster than nature can convert wastes from industries into environmental nutrients and resources, manufacturing may be considered unsustainable. It is strictly true that only in the context of a closed system, like the one shown in Figure 1, can sustainability be debated. The components related to humans, the environment, and nature coexist with those related to manufacturing. Consequently, it is impossible to regard the idea of sustainable manufacturing as existing independently of larger natural and economic frameworks (Haapala et al., 2013).

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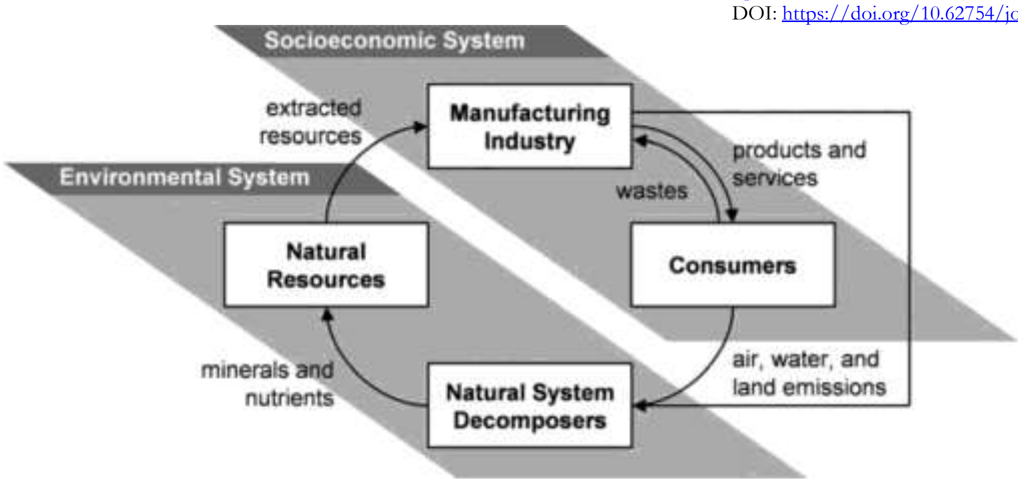

Figure 1. The Role of The Manufacturing Industry in A Sustainable System (Haapala Et Al., 2013)

Global growth and advancement have been greatly impacted by manufacturing, and this tendency is projected to keep going as the world's population grows and their standard of living rises. Thus, manufacturing is essential to modern socioeconomic systems and will continue to be so for many years to come, especially in developing nations where it will play a significant role in creating jobs and income. On the other hand, manufacturing operations can pose a serious environmental threat. For instance, in 2006, the manufacturing sector in the United States was responsible for 36% of the country's industrial sector's carbon dioxide emissions, although accounting for just $1.65x10^{12}$ (12.3%) of the industry's gross domestic product (*U.S. Carbon Dioxide Emissions and Intensities over Time: A Detailed Accounting of Industries, Government and Households*, 2010). The growth of sustainable manufacturing methods and procedures has drawn more attention in the last ten years as authorities around the world have been pressuring businesses to comply with ever-tougher environmental laws and regulations by encouraging low-emission and energy-efficient manufacturing practices. Hence, in addition to using conventional techniques to increase system efficiency and output, system engineers must also consider the adverse effects of the produced system by integrating environmental and economic restrictions into the development of their manufacturing systems (Lind-Kohvakka et al., 2008).

The Principles of Sustainable Manufacturing

Engineers are skilled in determining the financial worth of technological innovations used in production since manufacturing is a commercial activity. The duty of evaluating sustainability and social performance is more difficult for engineers and businesspeople. The tasks and procedures that manufacturing procedures and structures use to transform fuel and natural resources into useful goods have an impact on sustainability. Materials and fuel are essential entries into production chains and procedures; pollutants and carbon dioxide emissions, which are typically categorized as outcomes, are input into other industries and ecosystems, where they have an effect on the environment, economy, and society (Haapala et al., 2013).

Metrics

To assess and enhance the sustainability efficiency of manufacturing procedures and systems, both qualitative and quantitative measures are required. Improving decision-making criteria for improving procedure and system development is the primary objective of creating metrics for sustainable manufacturing. In order to pursue sustainability-based decision-making, it is necessary to identify and quantify the links and interactions between the three sustainability pillars (Haapala et al., 2013). Singh et al., (2012) provide an overview of various sustainability evaluation approaches. In their study, 41 sustainability indexes that have been put forth internationally are listed. He also restate that the majority of the studied indexes concentrate on just one sustainability pillar, with very few truly taking into account each pillar. Sala et al., (2012) also offer an overview of the development of sustainability examination, emphasizing the methodological, ontological, and epistemological components. The main ontology difficulty that

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characterizes the thoroughness of sustainability assessment when dealing with capital, principles, objectives, and tradeoffs was found by the review. The main obstacle for epistemology was determined to be stimulating innovations in knowledge through group projects and wider social learning.

There have been attempts to create techniques for manufacturing procedures and structures that concurrently address all three elements of sustainability. six key components that influence the sustainability of manufacturing processes were suggested based on the early research of Wannigarathne et al., (2004). Ecological effects, worker health, and worker security are among the other three that are more difficult to quantify. Of these, three are easily measured: production cost, energy usage, and handling of waste. General Motors states that sustainability measures should take into account the demands of all parties involved, promote creativity and expansion, align business units across various geographies, work with value-adding business systems, and work with associated measurement requirements (*General Motors Metrics for Sustainable Manufacturing - LABORATORY for SUSTAINABLE BUSINESS*). In a recent study, Eastlick et al., (2011) created an assessment tool for sustainable manufacturing that uses unit process-based simulation to estimate a wide range of variables. A demonstration of how sustainable manufacturing metrics relate to the manufacturing system that connects the process stage to the supply chain level is provided by (Graedel & Allenby, 2002). In order to lower the energy required in the manufacturing of cement, Chapparal Steel, for example, chose to supply gypsum and waste slag to cement producers. Metrics at the process level took energy conservation and residue reuse into account, while metrics at the management level took raw material and energy prices into account. Stakeholders in the production chain were also worried about the kinds and quantities of commodities exchanged. It is evident in this instance that several system elements highlight various facets of sustainable production. While every statistic used helped to assess sustainability, their relative significance differed depending on the production method and manufacturing system complexity.

Assessment of Manufacturing Environmental Performance

An Environmental Management System (EMS) is the method that producers most frequently utilize to enhance their commitment to sustainability. An EMS is a structure that enables a company to continually handle substantial environmental consequences, lower the risk of environmental accidents, guarantee adherence to applicable environmental laws, and continuously enhance its business activities. An internationally recognized guideline known as ISO 14001/14004 lays out the specifications needed to create, put into practice, and run an environmental management system (ISO, 2018). The ISO 14001 is merely a monitoring standard; it neither establishes nor supports any environmental performance requirements, nor does it indicate adherence to environmental policies or legislation. It does, however, provide a foundation for ongoing enhancement and allow attention to be drawn to environmental sustainability. The ISO 14001 is merely a monitoring standard; it neither establishes nor supports any environmental performance requirements, nor does it indicate adherence to environmental policies or legislation. It does, however, provide a foundation for ongoing enhancement and allow attention to be drawn to environmental sustainability.

Nowadays, the most popular technique for assessing the negative ecological effects of manufactured commodities is life cycle assessment or LCA. According to ISO 14040, life cycle assessment (LCA) covers the environmental factors and potential effects on the environment of a product's use, recovery from the end of its life, and disposal, including the consumption of resources and the resulting effects of discharges. Assessments of manufacturing systems and procedures are made more complex by compromises among various ecological effects (Curran, 2006).

A variety of techniques, including steelmaking, die casting, sand casting, milling, crushing, selective laser sintering, and injection molding, have shown recent work to support the idea that any choice that seeks to enhance the sustainability of a manufacturing process or system should be supported by LCA (Dahmus & Gutowski, 2004). A formal life cycle assessment (LCA) is comprised of four elements, as per the ISO 14040 standard: inventory analysis, impact evaluation, goal description and planning, and conclusion. Inputs (such as water, power, and resources) and outputs (such as air pollutants, solid material, and sewage) are recognized and measured during inventory analysis. Because gathering such information requires a lot of

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effort and money, life cycle inventory databases for basic products and processes have been created (Hischier & Weidema, 2010). Researchers in the United States and the European Union have recently suggested a method for creating the next generation of life cycle inventory databases for evaluating the environmental consequences of industrial operations (Kellens et al., 2011). According to some, life cycle inventory data needs to be gathered really quickly and has a few crucial features, like transparency, high-quality engineering, and the capacity to update when new data is gathered. The new database is supposed to enable a user to create a life cycle inventory of an element using only the most basic details about how a product might employ particular unit operations. For instance, in creating a unit process for drilling, it is important to take into account inputs such as the setup time, coolant characteristics, drill diameter, drilling duration, feed rate, and cutting speed of the workpiece. It is necessary to specify whether relationships are obtained from empirical equations or from basic concepts. The DIN 8580 standard has been implemented for process taxonomy. For the most part, the initial advancement was concentrated on machining procedures.

Major Manufacturing Impact Domains

Effective use of resources and pollution to the air, water, and land are two ways that manufacturing systems and procedures impact the financial and sustainability pillars. Numerous factors influence the social dimension, including as the physiological and psychological repercussions on workers, public opinion, community involvement, and loyalty to consumers. A few manufacturing-related sustainability factors are briefly discussed here.

Energy Consumption

The Energy Information Administration (EIA) of the United States conducted an investigation on energy use in manufacturing in 2006. The survey included information on energy use during a five-year period for electrical power, heating fuels, and other industrial energy inputs like coal and coke. In the end, the manufacturing industry in the United States uses, on average, one-third of the energy that is delivered (U.S. Energy Information Administration, 2022). But it's crucial to remember that most energy use occurs when a product is being utilized, not when metals are processed into final goods, or when plastics or semiconductors are made for application in products. This suggests that the various effects manufacturing has on the environment and society should be taken into consideration when weighing opportunities to cut energy use. For example, switching from solvent-based paints to powder coatings frequently results in an increase in overall electricity usage, but also lower pollution levels in the air and water, as well as better working conditions. These trade-offs are frequently avoided when energy-saving measures complement other aspects of sustainability, such as worker learning, equipment and generator efficiency, HVAC efficiency, process heating and cooling efficiency, and reusing, and remanufacturing procedures (Rajemi et al., 2010).

Airborne Pollutants

Sutherland et al., (2007) examined the causes and consequences of airborne emissions from production procedures, paying particular attention to particulate matter's effects at work. The health impacts that were reported included lung, throat, and urinary tract cancer, as well as silicosis, allergies, and pneumonia. We've already covered US regulations that establish acceptable exposure limits to airborne contaminants during production. There are numerous and diverse sources of airborne emissions in the manufacturing industry. Among the notable procedures are those that produce fumes and nanoparticles during welding, metal particulates, chemical mists from machining and crushing, microparticles and organic chemicals from casting, hazardous and greenhouse gasses from electronics manufacturing, and fugitive particulates and toxic organic exposure from polymer production.

Water Consumption and Wastewater

Many industrial processes use a lot of water, and the amount used in those that use agricultural feedstocks is significantly higher. For example, the creation of a single newspaper uses 950 liters of water, whereas the

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production of an automobile uses 380,000 liters of water—a disproportionate amount of water relative to mass. There is always an opportunity to increase the efficiency of the water used in production procedures related to washing, quenching, air conditioning, and process chemical delivery. Quantifying the direct and indirect water consumption of industrial processes and finished goods has been attempted as a starting point (Chen et al., 2015).

Solid Waste and Resource Recovery

Solid wastes, which include everything from leftover cartons and packing materials to machine chips, are unavoidable consequences of most manufacturing processes. Zero-waste manufacturing has advanced significantly as a result of tighter landfilling regulations and rising commodity prices. A number of companies, including Honda, Xerox, and Proctor & Gamble, are working toward or have already achieved zero-waste or landfill-free production plants. Zero-waste operations often employ the advantages of lean manufacturing techniques to enhance environmental performance by consuming fewer resources and producing less trash (Moreira et al., 2010). Prioritizing waste reduction, most businesses seek to find ways to recycle trash that cannot be avoided. Waste is turned into energy if it can't be reused or removed. Since it does not enhance the value of a product but is required for transportation and protection, packaging material has been a solid waste stream of special care. In the meantime, the European Union has been implementing regulations since 1994 to limit the quantity of packaging materials that end up in the trash stream. General Motors has used recycled cardboard shipping materials into automotive sound absorbers (European Commission, 1994). The goal of zero-waste manufacturing plants is to only release clean emissions and the finished good. While not regarded as waste when they are shipped, products may produce waste both while they are being used and when their end of life (EoL) approaches. In order to attain a zero-waste manufacturing process, environmentally responsible decisions on use-life design and resource recycling activities are necessary.

Planning and Decisions Making

The goal of sustainable production and growth depends on sustainable manufacturing, however it's important to remember that the ecological consequences of a certain product are mostly decided upon during the design phase. This is comparable to product costs, where 70–80% of the entire cost is fixed by decisions made during the design phase (Ullman, 2018). Consequently, it is ideal to adopt design choices that support production that is sustainable. New manufacturing methods and procedures have always been developed with the goals of reducing costs and boosting efficiency in mind. In order to account for sustainable production during the design phase, common financial success metrics like net present value, total life cycle cost, internal rate of return, payback period, and benefit-to-cost ratio must also be included, along with the metrics and assessment techniques covered above.

Sustainable Manufacturing Systems

The two primary focuses of environmentally sustainable manufacturing techniques have historically been (1) designing ecologically friendly production processes and (2) creating closed-loop distribution systems that take into account a product's life cycle from birth to door. Energy audits, sustainable planning and scheduling, and sustainable supply chains are the three essential components of creating a sustainable manufacturing system that is covered in this section. Figure 2 shows how production methods and sustainable manufacturing structures interact. Plant-level activities that affect system-level elements including the scheduling of production, process planning, the forward and reverse supply chains, and inspection/disassembly are manufacturing, reprocessing, and inspection/disassembly. Energy auditing is a system-level component that interacts with other system and process level components, even if it isn't mentioned specifically in Figure 2.

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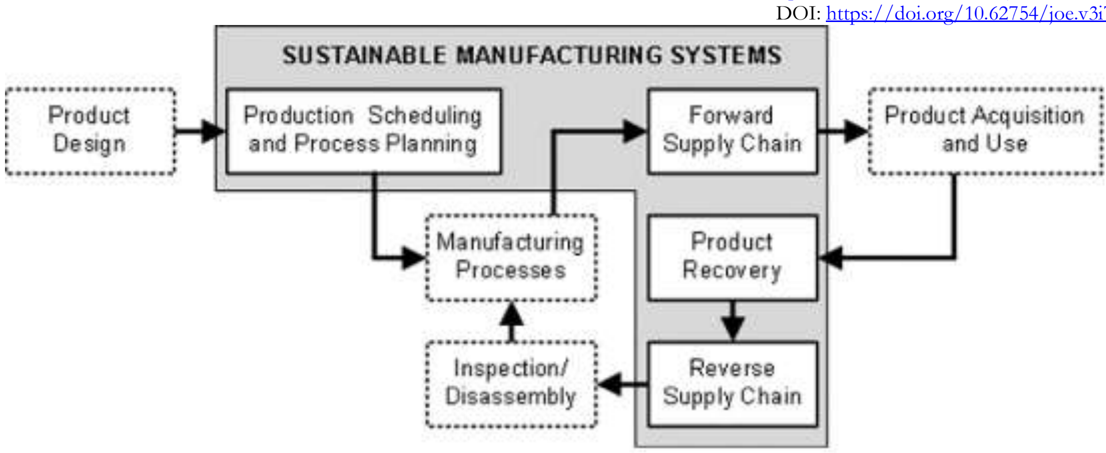

Figure 2. Important Components of a Sustainable Manufacturing System (Haapala Et Al., 2013)

Energy Auditing

Engineers must meet a variety of requirements while designing life cycle facilities, which include budgetary constraints and accounting for sustainability goals throughout the building, operating, and disposal phases (Pearce et al., 2000). In order to assess a facility's total degree of sustainable manufacturing, which is typically quantified with LCA and energy audits, Management in Energy and Environmental Design (LEED) certification has been helpful. Manufacturing businesses have traditionally utilized energy auditing as a facility-level strategy to lower their energy usage and related expenses (Krarti, 2011). Numerous manufacturing operations also frequently undergo energy audits. When compared to the underlying operations required for the functioning of manufacturing equipment, the total energy required for the active modification and extraction of material is often very little. Energy-saving initiatives that just concentrate on modernizing specific equipment or procedures are insufficient; instead, system-level strategies may provide larger advantages (Zhu, 2006).

Planning and Scheduling

The activities in manufacturing systems that are planned and scheduled determine which production processes are carried out, as well as how frequently, when, and in which sequence. When sustainability criteria are factored into production schedules and process plans, production procedures can become more sustainable. The following section discusses research on sustainability in manufacturing systems with reference to process execution and production management.

Process Planning

Production planning based on changes to the product and process designs was aided by the use of a process modeling technique connected to life cycle assessment (LCA) (Haapala et al., 2013). Multi objective analysis in micro and macro planning can be used to provide robust process planning that incorporates environmental elements, as demonstrated by the work of Srinivasan and Sheng (1999). While macro planning looks at the interactions between features to find a globally optimal process plan, taking into account job scheduling, line balancing, facility planning, and related issues, micro planning takes into account the parameters, tooling, and related variables that are required to produce individual features only. They provided an example of their method for making small design adjustments to a machined product.

Production Scheduling

Organizing tasks in a workshop has historically been done solely based on throughput time, efficiency, delays, and associated indicators (Shen et al., 2006). However, there isn't a lot of study on scheduling that takes environmental goals into account. Mouzon et al., (2008) looked at the equipment-level scheduling problem of minimizing overall energy use for a single machine.

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They specifically examined the timetable of a CNC machine for a provider of tiny aircraft parts in a machine shop. Subai et al., (2006) integrated energy and waste considerations at the shop floor level into hoist scheduling issues related to surface treatment procedures. Liu et al., (2003) looked at the social elements of machine-workpiece coupling for noise reduction. The field of energy-aware scheduling is expanding (Irani & Pruhs, 2005). To cut down on energy usage at a car paint shop, Wang et al., (2009) specifically suggested the best scheduling method for vehicle sequencing. Paint quality might be increased and repaints could be decreased by choosing the right batch and sequence procedures, they discovered.

Supply Chains

The two main components of supply chain sustainability are turning production into a reverse supply chain and designing sustainable companies. In their definition of sustainable supply chain administration, Badurdeen et al., (2009) identified two key components: closing the production loop "through multiple life cycles with seamless information sharing about aU product life cycle stages between companies by explicitly considering the social and environmental implications to achieve a shared vision" and "the planning and management of sourcing, procurement, conversion and logistics activities involved during premanufacturing, manufacturing, use, and post-use stages in the life cycle." From traditional green supply chain management, which often concentrates on environmental considerations, sustainable supply chain management has developed.

To fully realize the sustainable manufacturing philosophy, a sustainable supply chain must be connected with sustainable production methods, designs, and technologies. Think about the production and reclamation of cars, which are the most recycled products ever. Ninety-five percent of all automobiles and about 80 percent of the material content are recovered by the automotive recycling system in the United States. However, in an attempt to lighten cars and lessen the environmental impact of the use phase, automakers are pursuing changes to vehicle design that include more aluminum and composites. However, these changes could have a negative impact on sustainability, threaten the financial stability of dismantlers, and raise the amount of ASR (automotive shredder residue). In their discussion of the difficulties facing the car industry facilities Kumar and Sutherland (2008) also provided a model for material flows and economic interactions along the whole automotive value chain. A follow-up paper stated that the only way to increase material recovery rates is to introduce new technologies, such as vehicle dismantling and plastic recycling, and that all stakeholders may need to share the financial burden of these technological advancements through regulatory measures (Kumar & Sutherland, 2009).

Conclusion

The assessment, planning, and performance evaluation of manufacturing systems frequently neglect environmental factors. In the past, engineers concentrated on system performance indicators in terms of results, resources, productivity, and other production-related factors. The creation of an optimization framework with multiple goals that support sustainable production-making decisions is reviewed in this paper. this multi-objective approach has three goals, that are designed to minimize the overall cost, the total energy consumption, and the quantity of CO2 emissions. Even with all of the recent advancements in engineering research, there are still possibilities and problems to be solved in the pursuit of sustainable manufacturing objectives. These requirements for research typically fit into one of four groups: (1) technology and manufacturing procedures; (2) production systems; (3) revolutionary changes in the life cycle of the product; and (4) education

Technology and Manufacturing Procedures

Both technological advancements and better understanding present opportunities with regard to manufacturing procedures and apparatus. In terms of technology, research must go on to create new production techniques and machinery that leave fewer footprints on the planet, with environmental life cycle assessments serving as a guide for choosing options. Increasing our fundamental knowledge of process science and equipment characteristics is necessary to assist this endeavor. Optimal use of energy and other assets should be the aim, taking into account the effects on employees and society as a whole.

Process hybridization, equipment sizing for efficiency, using novel process mechanisms, and using safer materials and chemicals to support processes—like metalworking fluids—are some of the strategies that could be used.

Manufacturing Systems

Focus areas must remain on the utilization of resources, waste creation, and reducing adverse ecological effects through continuous enhancement approaches, both at the industrial system level and beyond. There are undoubtedly many chances to include environmental considerations in a variety of system, facility, company, and supply chain decision-making processes (such as manufacturing planning, choosing suppliers, and facility placement).

There is a lot of opportunity for the advancement of logistics plans and technological advancements to support product recovery and material reutilization, which includes the refurbishing of more complicated elements and the advancement of procedures and systems for the reusing of plastics. Reprocessing and recycling techniques aim to manage end-of-life products. Thus, manufacturers and forward/reverse supply chains, among other manufacturing processes, stand to be greatly impacted by the advancement of techniques and technology.

Changes in Life Cycle Paradigms

Regarding product life cycles, advancements and novel perspectives are maybe some of the interesting possible future advancements. The sustainable design approach and sustainable manufacturing must be coordinated. Put another way, "over the wall" design in terms of part shape, material type, etc., might result in the requirement for more expensive and environmentally harmful production methods and systems. To prevent any environmental problems, it is extremely desired to integrate life cycle assessment (LCA) or comparable approaches into new manufacturing process and system evaluation. It is necessary to have prognostic LCA models that can quantify environmental effects by increasing the scale of the testing procedures. Stakeholder support for next generation LCI databases must be substantial. Many businesses are intrigued, but in order to get the momentum needed, further rules and incentives to ease concerns about data security and sharing probably need to be implemented.

Education

Manufacturing-related courses must also include sustainability and resource considerations, as the industry is becoming increasingly dependent on these factors. It seems that collaborative strategies to course offerings and curriculum development may be helpful in equipping aspiring engineers with a comprehensive understanding of the design of products and processes, resources handling and manufacturing, and their effects across various phases of the life cycle, given the dearth of faculty with expertise in this area. Furthermore, these methods can help communicate workable strategies for integrating societal, regulations, and economic concerns into the design and production process.

The research discussed here is an example of some of the most interesting work done in the area of sustainable manufacturing, which includes both the basics of sustainable manufacturing systems and processes. The social, environmental, and financial consequences of manufacturing operations are taken into consideration. A vital component of global societal sustainability is manufacturing because of a growing need for products and solutions in both developed and developing nations. It will be the goal of future manufacturing systems to smoothly combine industrial, sociocultural, ecological, and biological systems to build an all-encompassing, closed-loop network that generates and oversees resources, goods, and services in an environmentally friendly way.

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