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A Review of Engineering Research in Sustainable Manufacturing

Sustainable manufacturing requires simultaneous consideration of economic, environmental, and social implications associated with the production and delivery of goods. Fundamentally, sustainable manufacturing relies on descriptive metrics, advanced decision-making, and public policy for implementation, evaluation, and feedback. In this paper, recent research into concepts, methods, and tools for sustainable manufacturing is explored. At the manufacturing process level, engineering research has addressed issues related to planning, development, analysis, and improvement of processes. At a manufacturing systems level, engineering research has addressed challenges relating to facility operation, production planning and scheduling, and supply chain design. Though economically vital, manufacturing processes and systems have retained the negative image of being inefficient, polluting, and dangerous. Industrial and academic researchers are re-imagining manufacturing as a source of innovation to meet society's future needs by undertaking strategic activities focused on sustainable processes and systems. Despite recent developments in decision making and process- and systems-level research, many challenges and opportunities remain. Several of these challenges relevant to manufacturing process and system research, development, implementation, and education are highlighted. [DOI: 10.1115/1.4024040]

1 Manufacturing and Sustainability

The concept of sustainability emerged from a series of meetings and reports in the 1970s and 1980s, and was largely motivated by environmental incidents and disasters as well as fears about

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chemical contamination and resource depletion. As pointed out in the 1987 Brundtland Report, *Our Common Future* [1]:

> Major, unintended changes are occurring in the atmosphere, in soils, in waters, among plants and animals. Nature is bountiful but it is also fragile and finely balanced. There are thresholds that cannot be crossed without endangering the basic integrity of the system. Today we are close to many of those thresholds.

Thus, sustainability necessitates the need for a performance level that may be contrary to humanity's rational desire for continuous development and growth. This distinction 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 2005 United Nations World Summit [2] further posited that three *interdependent and mutually reinforcing pillars* exist to support sustainable development: economic development, social development, and environmental protection. These three interdependent pillars have been referred to as the triple bottom line (i.e., people, profit, and planet) and other related terms that evoke a holistic world view. The topics related to sustainability in manufacturing are discussed herein under this framework of sustainable development.

Manufacturing has had a significant influence on global development and growth, a trend that is likely to continue due to increased demand for consumer goods from a growing world population with improving quality of life. Thus, manufacturing plays a critical role within modern socio-economic systems, and will be a valuable contributor to wealth generation and job creation, especially in developing economies, for years to come. However, manufacturing activities also represent a significant burden on the environment. For example, in 2006, the U.S. manufacturing sector accounted for $\$1.65 \times 10^{12}$ (12.3%) of industry gross domestic product [3], but was responsible for 36% of carbon dioxide emissions within the U.S. industrial sector [4].

The phrase *sustainable manufacturing* is sometimes used carelessly to describe the actions related to characterizing and reducing the environmental impacts of manufacturing. Sustainability, however, implies a great deal more than the simple act of analyzing and modifying the environmental performance of manufacturing processes and systems. In spite of this caveat, this interpretation is likely to be maintained. A system might be thought of as unsustainable when society consumes resources and produces wastes at a rate that exceeds nature's ability to transform industry and society wastes into environmental nutrients and resources. Strictly speaking, sustainability can only be discussed in the context of a closed system, such as that displayed in Fig. 1. Manufacturing subsystems coexist alongside human, ecological, and natural subsystems. Therefore, sustainable manufacturing is a philosophy that cannot be considered independent of broader environmental and socioeconomic systems.

Faced with growing environmental concerns, mounting public pressure, and stricter regulations, manufacturers have been striving to set and achieve sustainability-oriented goals. As a result, significant advances in sustainable manufacturing have been made over the past decade. This paper reviews these developments along with ongoing research and recommendations for future research. In Sec. 2, a general overview of concepts related to sustainable manufacturing is presented. In Sec. 3, the discussion is focused on manufacturing research that has been undertaken at the process level, while Sec. 4 investigates sustainable manufacturing research at the systems level (e.g., facility design, and supply chains). Finally, Sec. 5 summarizes the discussion and provides several recommendations for future research in this area.

2 Sustainable Manufacturing Fundamentals

Manufacturing is a business function, and, as such, engineers are well-versed in establishing the economic value of engineering solutions for manufacturing. Measuring environmental and social performance presents a more challenging engineering and business task. Sustainability-related impacts result from operations and activities that manufacturing processes and systems employ to convert input materials and energy into marketable products. Material and energy are necessary inputs of manufacturing processes and systems; wastes and emissions, which are generally classified as outputs, are, in turn, inputs to other industrial and natural systems, where their impact is felt socially, environmentally, and economically (Fig. 1).

2.1 Defining Sustainable Manufacturing. Although widely accepted, the Brundtland Commission definition of sustainable development, presented above, is not an operational one for business and engineering decision makers in manufacturing. Mihelcic et al. [5] proposed a definition relevant to engineering contexts as 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."

Definitions have been proposed for sustainable manufacturing, but a broadly accepted definition is not available to date. The U.S. Department of Commerce (DOC) [6] defines sustainable manufacturing as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound." It may be noted that this definition conflicts with previous comments by the authors in that it neglects the concept of closing resource loops. The fact is that *sustainable manufacturing* has entered the lexicon, and the DOC has attempted to give meaning to this phrase. This does not change the fact that as researchers we should endeavor to

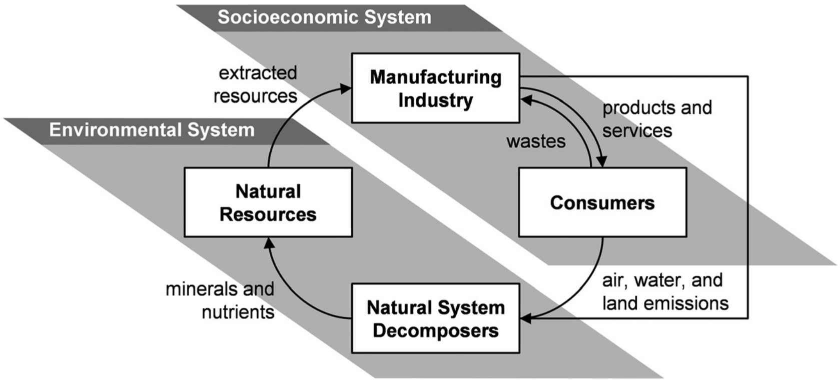

Fig. 1 The role of the manufacturing industry in a sustainable system

reduce the environmental footprint and enhance the social benefits of manufacturing. Moreover, we should work to advance the understanding of the broader manufacturing community about what sustainability is and is not.

2.2 Metrics. Qualitative and quantitative metrics are necessary for evaluating and improving the sustainability performance of manufacturing processes and systems. The ultimate goal of developing metrics for sustainable manufacturing is to improve decision-making criteria when optimizing process and system designs [7]. Pursuing sustainability-based decision making requires that the connections and interactions among the three pillars of sustainability be characterized and quantified.

A review of broad sustainability assessment methodologies is presented by Singh et al. [8]. Their work lists 41 sustainability indices that have been proposed globally. Singh et al. reiterates that only a few of the surveyed indices actually consider each pillar of sustainability, and most focus on a single pillar. Sala et al. [9] also provide a review regarding the progress of sustainability assessment, focusing on the ontology, epistemology, and methodology aspects. The review identified the major ontology challenge as characterizing the comprehensiveness of sustainability assessment in addressing capitals, values, goals, and tradeoffs. For epistemology, the major challenge was identified as inducing knowledge innovations through collaborative work and broader societal learning. Lastly, they concluded that the methodological challenge was that single methodologies are not capable of addressing, as they term, sustainability science questions. Guidelines have been introduced that assist decision makers in identifying and quantifying appropriate sustainability metrics [10,11]. Ideal metric traits identified by this prior work include comprehensiveness, controllability, cost-effectiveness, manageability, meaningfulness, robustness, and timeliness.

The United Nations Division for Sustainable Development (UNDSD) has created a framework for sustainability that categorizes metrics first by the sustainability aspect (environment, society, and economy), then by theme, e.g., education, and then by sub-theme, e.g., literacy [12]. Over the past few decades, environmental issues have received more attention, and a variety of environmental measures have been set forth, e.g., toxic chemical releases, energy consumption, and ecological footprint. Measuring the social performance of engineering solutions presents a greater challenge than environmental performance measurement, and social metric development is in the very early stages [13]. The United Nations Environment Programme (UNEP) has compiled national level social sustainability indicators for many countries [14]. These data are useful in evaluating the relative performance of various nations in terms of social sustainability, but has limited applicability to manufacturers interested in characterizing and reducing their social impacts. Parris and Kates [15] reported on the results from 12 initiatives to develop social sustainability metrics, which developed hundreds of indicators ranging in scale from global to local. Brent and Labuschagne [16] examined a large number of societal/business standards and structures related to Corporate Social Responsibility (CSR) and impact assessment, and they established their own framework. Recently, Hutchins et al. [17] developed a social sustainability framework for manufacturers based on a hierarchy of social needs and social groupings; the Delphi data collection method was then employed to find metrics for each of 30 need/group categories.

Efforts to develop methods that simultaneously take into consideration all three pillars of sustainability for manufacturing processes and systems have been undertaken. Based on the early work by Wanigarathne et al. [18], Jawahir and Dillon [19] proposed six major elements that affect the sustainability of manufacturing processes. Three of these, i.e., manufacturing cost, energy consumption, and waste management are easily measured, while the other three, i.e., environmental impact, personnel health, and operator safety are not easily quantified. According to General Motors, sustainability metrics should address the needs of all stakeholders, facilitate innovation and growth, harmonize business units of different geographical locations, be compatible with value-adding business systems, and be compatible with related measurement needs [20]. Eastlick et al. [21] described recent work that developed a sustainable manufacturing assessment tool to quantify a broad set of metrics using unit process-based modeling.

Lu et al. [22] presented a framework for developing sustainable manufacturing metrics and discussed the interrelationships and potential interactions among metrics. Based on this work, several potential metrics are listed in Table 1 for sustainable manufacturing processes (the metrics were developed by focusing on sustainable machining). Metrics cover economic, environmental, and social aspects and measure the inputs and outputs of a manufacturing process at a workstation or line level [11,23]. Workstation level measurements focus on a single machine performing one or more operations, or a piece of auxiliary equipment providing a specific function. The line or operational level focuses on single process operations, such as a single machine doing a specific job with certain tools and materials under particular operating conditions.

Sustainable manufacturing spans across more than individual, unit manufacturing processes, or even process flows at the line level. Metrics used in lower (process) levels aggregate up to higher (system) levels, where new metrics are added based on specific production systems [24]. Graedel and Allenby [25] present an example describing the interactions of sustainable manufacturing metrics in a production system bridging the process/workstation level with the supply chain level. In their example, Chapparal Steel decided to provide waste slag and gypsum to cement manufacturers, which would reduce energy use in cement production. Process-level metrics considered residue reuse and energy reduction and management-level metrics considered the costs of raw materials and energy. At the same time, supply chain partners were concerned with the amounts and types of materials traded [25]. In this case, it can be seen that different system entities emphasize different sustainable manufacturing aspects. Each metric that was applied contributed to evaluating sustainability, but

Table 1 Potential sustainable manufacturing process metrics (focus on machining; adapted from Ref. [22])

Process metric type	Example
Environmental impact	—GHG emissions (kg CO_2 eq./unit) —Ratio of renewable energy used (%) —Total water consumption (kg/unit)
Energy consumption	—In-line energy use (kWh/unit) —Energy use for maintaining working environment (kWh/unit) —Energy consumption for material handling (kWh/unit)
Economic cost	—Labor cost (\$/unit) —Energy cost (\$/unit) —Maintenance cost (\$/unit)
Worker safety	—Exposure to corrosive/toxic chemicals (incidents/person) —Injury rate (injuries/unit) —Near misses (near misses/unit)
Worker health	—Chemical contamination of working environment (mg/m^3) —Mist/dust level (mg/m^3) —Physical load index (dimensionless)
Waste management	—Mass of disposed consumables (kg/unit) —Consumables reuse ratio (%) —Ratio of recycled chips and scrap (%)

the importance of each metric varied across the manufacturing process and manufacturing system hierarchy.

2.3 Manufacturing Environmental Performance Evaluation. The approach most commonly used by manufacturers to improve their environmental performance is an Environmental Management System (EMS). An EMS is a framework that allows an organization to consistently control its significant impacts on the environment, reduce the risk of pollution incidents, ensure compliance with relevant environmental legislation, and continually improve its processes and operations. The ISO 14001/14004 is an internationally accepted standard that defines the requirements for establishing, implementing, and operating an Environmental Management System [26,27]. The ISO 14001 is simply a reporting system that does not imply compliance with the environmental policy or environmental laws; it neither sets nor endorses any environmental performance standards. It does, however, enable a focus on environmental performance and offers a framework for continuous improvement.

Life cycle assessment (LCA) has emerged as the most common method for environmental impact evaluation of manufactured goods. As defined in ISO 14040, LCA addresses the environmental aspects and potential environmental impacts, e.g., resource use and environmental consequences of releases, over a product's life cycle from raw material acquisition through production (cradle to gate), use, end-of-life recovery, and disposal (cradle to grave) [28,29]. Trade-offs among a variety of environmental impacts further complicate analyses of manufacturing processes and systems.

Ideally, any decision to improve the environmental performance of a manufacturing process or system should be supported by LCA, as demonstrated by recent work for a number of processes, including steelmaking, die casting, sand casting, machining, grinding, selective laser sintering, and injection molding [30–38]. According to the ISO 14040 standard, a formal LCA consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation [29]. It is during inventory analysis that inputs (e.g., energy, water, and materials) and outputs (e.g., air emissions, solid waste, and wastewater) are identified and quantified. Collection of such data is time and resource intensive, which has led to the development of life cycle inventory databases for common materials and processes. The most comprehensive inventory database available is *ecoinvent 2.2*, which mainly consists of European scenarios and data [39]. United States databases are under development, but their scope is limited, with less than 30 unit processes related to manufacturing, and most are for primary metal production [40]. More importantly, unit processes are treated as black boxes, with no correlation between inputs, outputs, and process conditions. Aggregated data is used, while size and operating conditions of machines and equipment are not taken into consideration. In addition, the unit process model in many manufacturing processes is based on the weight of the part being manufactured, which is not well-correlated with the actual process. As a result, manufacturing processes are usually the weakest aspect of life cycle databases and exploration of "what-if" scenarios, e.g., process changes or technology updates, remains difficult. These limitations are being addressed by recent efforts of the U.S. UPLCI (Unit Process Life Cycle Inventories) and the European CO2PE! (Cooperative Effort on Process Emissions in Manufacturing) programs [41,42]. A comprehensive review of work conducted (over 200 publications) in the international research community in energy efficient manufacturing has been reported by Duflou et al. [43]. They offer a number of conclusions regarding the potential for significant energy efficiency gains from the machine through the supply chain level.

There are many process-based LCA and environmental assessment software tools available. Some are for specific applications, e.g., alternative fuels and vehicles (GREET) and building materials (BEES). Commonly used tools for general applications include SIMAPRO, GABI, QUANTIS, ECOBILAN, UMBERTO, and EIME. Economic Input–Output Life Cycle Assessment (EIO–LCA) is an alternative to process-based LCA that avoids the difficulty of inventory data collection by using a combination of publically available economic and environmental data [44]. Every five years, the U.S. Bureau of Economic Analysis (BEA) releases transaction information for all economic sectors (428 as of 2002). At the same time, the U.S. Environmental Protection Agency (EPA) collects and publishes emissions information for all the major industrial facilities and the various industrial sectors. EIO–LCA combines the two data sources to determine the effects of changing the output of a single sector [45]. As with process-based LCA, the shortcomings of EIO–LCA are primarily related to using aggregated data to make decisions at a finer level, as it may not be practical to track the purchases of every type of material from all suppliers for a given product. Furthermore, there are a limited number of basic classifications in the EIO tables, which makes the method more suitable for high-level overview studies. In addition, EIO–LCA does not work well for new technologies because data tables are usually several years old.

Recently, an approach that aims at developing the next generation life cycle inventory databases for environmental impact assessment of manufacturing processes has been proposed by researchers in the E.U. and the U.S [41,42,46]. It is argued that life cycle inventory data must be obtained in a relatively rapid fashion and have some important characteristics, such as transparency, engineering quality, and the ability to reflect changes when new information is secured. The new database is expected to allow a user, with only the most basic information of how a product might utilize specific unit processes, to produce a life cycle inventory of that component. For example, when developing a unit process for drilling, inputs such as workpiece material properties, feed rate, cutting speed, drill diameter, drilling time, coolant properties, and setup time should be considered. Correlations derived from either first principles or empirical equations have to be specified. For process taxonomy, the standard *DIN 8580: Manufacturing processes—Terms and definitions, division* has been adopted. Initial development largely has been focused on machining processes.

2.4 Major Manufacturing Impact Areas. Manufacturing processes and systems affect the economic and environmental pillars via resource efficiency and emissions to air, water, and land. The social dimension is impacted in a number of ways, including physiological and psychological effects on employees, public perception, community engagement, and customer loyalty. Several sustainability aspects related to manufacturing are briefly reviewed below.

2.4.1 Energy Consumption. In 2006, the U.S. Energy Information Administration's (EIA) survey of energy use in manufacturing detailed energy consumption in terms of electricity, heating fuels, and other process energy inputs, such as coal and coke, over a five year period [47]. Ultimately, the U.S. industrial sector consumes about one-third of delivered energy on average (21.8 quadrillion BTU in 2009) [48]. In addition, "…the top five energy-intensive manufacturing industries—bulk chemicals, refining, paper, steel, and food accounted for 61% of industrial energy consumption and 25% of total value of shipments in 2009" [48]. It is important to keep in perspective, however, that the bulk of energy consumption often is not due to processing metals into finished products, or in the manufacture of plastics or semiconductors used in products, but rather during the use of a product. This indicates that opportunities to reduce energy consumption should be balanced against the other environmental and social impacts of manufacturing. For instance, replacing solvent-based paints with powder coating often increases total electricity consumption, but reduces air and water pollution and improves the work environment. Often, such tradeoffs are avoided when energy conservation options are synergistic with other sustainability dimensions; for example, machine and motor efficiency, operator training, HVAC efficiency, process heating and cooling efficiencies, as well as with recycling and remanufacturing practices [49,50].

2.4.2 Airborne Emissions. Sutherland et al. [51] reviewed the sources and impacts of manufacturing process airborne emissions, specifically focusing on the effects of particulate matter in the workplace. Health effects described included asthma, emphysema, silicosis, and cancer in the lungs, larynx, and urinary tract. Regulations in the U.S. that set permissible exposure limits to airborne pollutants in manufacturing have been previously described [52].

Airborne emissions have an impact on the environment in addition to worker health. Greenhouse gas emissions are associated with energy use, coke combustion, semiconductor etching, and acquisition of input materials, among other sources. Airborne emissions also come from the fugitive release of ozone-depleting chemicals, e.g., refrigerants, propellants, and foam insulators; photochemical ozone creating chemicals, e.g., paint fumes, cleaning solvents, and products of combustion; smog forming chemicals, e.g., nitrogen oxides and volatile organic compounds (VOCs); and toxics, e.g., metals from casting and coal combustion, etchant gases, and fumes from fuels and solvents.

Sources of airborne emissions in manufacturing are varied and ubiquitous. Notable processes include welding (fumes and nanoparticles), machining/grinding (mists of chemicals, microbial byproducts and metal particulates), casting (microparticles and organic chemicals), electronics production (toxic and greenhouse gases), and polymer production (fugitive particulates and toxic organic exposure). Some of these emissions are revisited in Sec. 3.

2.4.3 Water Consumption and Wastewater. Many manufacturing processes in the U.S. are highly water intensive, with those that involve agricultural feedstocks being much higher. For instance, production of a single newspaper requires 950 L (250 gal) of water, while production of a car requires 380,000 L (100,000 gal) of water [52], a disproportionate amount on a per mass basis. Water consumption in manufacturing processes associated with cooling, quenching, cleaning, and delivery of process chemistry leaves ample room for improvements in efficiency. As a starting point, attempts have been made to quantify direct and indirect water consumption of manufacturing processes [53] and manufactured products [54,55]. While not the largest consumers of water, manufacturing processes are among the highest polluters of water systems. The most toxic substances in water supplies, e.g., VOCs and heavy metals, often originate from manufacturing processes such as cleaning, lubricating, and coating. These manufacturing processes create other water quality concerns such as biochemical oxygen demand, fats, oils, grease, and nutrients.

In response to water pollution concerns in the metals industry, the U.S. EPA proposed the Metal Products and Machinery Rule that requires oil and grease disposals to be below 17 mg/L [56]. Since liquid effluents from manufacturing may easily have oil and grease levels above 2000 mg/L, achieving this standard would significantly increase on-site treatment and disposal costs [57]. In addition to concerns about worker health and financial costs associated with maintaining manufacturing fluids and chemicals, disposal concerns have resulted in a strong move among manufacturers in the U.S., E.U., and Japan to reduce the use of fluids in manufacturing. Dry or near dry processes under intense development include dry machining, minimum quantity lubrication, powder coating, and other finishing operations [58–62].

2.4.4 Solid Waste and Resource Recovery. Solid wastes are inevitable byproducts of most manufacturing operations and range from machining chips to excess packaging materials and pallets. More restrictive landfilling policies and increasing commodities prices have led to significant advancements in zero-waste manufacturing. Honda, GM, Xerox, and Proctor & Gamble, to name a few, are currently operating or striving for zero-waste or landfill-free manufacturing facilities. Generally, zero-waste facilities use the benefits of lean manufacturing principles to improve environmental performance through reduced waste generation and resource consumption [63,64]. Most companies first attempt to reduce wastes as much as possible, and then look for opportunities to recycle unavoidable wastes. If waste cannot be eliminated or recycled, it is converted to energy. Packaging material has been a solid waste stream of particular concern because it does not add value to a product, but is necessary for shipping and protection. GM has recycled cardboard shipping materials into automobile sound absorbers, while the E.U. has had policies in affect since 1994 to reduce the amount of packaging material entering the waste stream [65]. Ideally, only *clean* emissions and the final product leave zero-waste manufacturing facilities. Products, while not considered waste upon shipment, can be a source of waste during use and at their end-of-life (EoL). Environmentally conscious use-life design decisions and resource recovery operations are required if a zero-waste product life cycle is to be achieved.

Product Stewardship and Extended Producer Responsibility (EPR) policies strive to create zero-waste product life cycles. Product Stewardship places a portion of the EoL responsibility on consumers, since they own and retain benefits from product use. Penalties, fines, or refunds often incentivize consumers to participate in EoL programs. Retailers and remanufacturing companies offer take-back programs that rely on consumer returned products. In some instances, a store credit or refund is offered in exchange for the used product. EPR, on the other hand, places all responsibility of product EoL on manufacturers, including ensuring EoL product collection from consumers. These philosophies have been drivers of policies, such as the E.U. directives on EoL Vehicles (ELVs) and Waste from Electrical and Electronic Equipment (WEEE) [66,67]. Consequently, these policies have spread to other countries including the U.S., Japan, and Korea [68–71]. Such public policy initiatives can accelerate the implementation of reverse supply chains and EoL product collection for complete resource recovery.

2.5 Design and Decision Making.

Sustainable manufacturing is critical to the pursuit of sustainable production/development, but it must be noted that product specific environmental impacts are largely determined during the design stage. This is similar to product costs where decisions made during design lock in 70–80% of the total cost [72]. Therefore, it is highly desirable to make design decisions that facilitate sustainable manufacturing. Minimizing cost and maximizing productivity have been traditional driving forces for developing new manufacturing processes and systems. Accounting for sustainable manufacturing at the design stage requires the inclusion of metrics and assessment methods discussed above in addition to common economic performance metrics, e.g., net present value, total life cycle cost, internal rate of return, payback period, and benefit to cost ratio.

Designers wishing to promote sustainable manufacturing must weigh factors such as time, quality, resources, and costs along with environmental performance [73]. Conflicts between environmental, economic, and social (if able to be measured) factors are highly probably and require the application and development of Multi Criteria Decision Making (MCDM) tools [74]. MCDM tools span a range of methods such as Gray Relational Analysis (GRA) and fuzzy logic, among others, and are often accompanied with a preference evaluation method such as Analytic Hierarchy Process (AHP) or Quality Function Deployment (QFD) to characterize the relative importance of assessment metrics [75,76]. Recently, the TRIZ (an acronym meaning *the theory of inventive problem solving*) method has been proposed as a systematic tool to resolve potential conflicts in order to facilitate process and system improvement [75,77].

The aforementioned tools have previously been applied to Design for X (DfX) methods, e.g., Design for the Environment (eco-design), Design for Disassembly, Design for Recycling, and Material Selection. Ilgin and Gupta [75] reviewed DfX methods related to environmentally conscious design, as well as typical

MCDM evaluation methods. Krill and Thurston [78] specifically targeted Design for Remanufacturing, for a cylinder liner case. A Design for Sustainable Manufacturing (DfSM) framework was developed by Garbie [79], which aggregated international issues, contemporary issues, innovative products, reconfigurable manufacturing systems, manufacturing strategies, performance measurements, and flexible organizational management into a single index using a weighted sum approach. Harun and Chang [80] presented a DfSM approach for manufacturing systems to evaluate an automobile paint shop. Their method integrated modeling, simulation, and LCA to analyze the performance and potential environmental impact of the paint shop given multiple system setups.

Ramani et al. [76] reviewed design issues as related to sustainable product realization, and highlighted critical gaps preventing the integration of eco-design for sustainable manufacturing. It was found that few efforts accounted for sustainability considerations within Design for Manufacturing and Assembly (DFMA) due to the lack of analytical methods with the ability to accurately integrate eco-design principles into DFMA tools. Ramani et al. [76] suggested that current research efforts into information model/ontology-based methods represent a promising approach that may be able to integrate next generation life cycle inventory databases currently under development. Further information and discussion regarding these principles and other MCDM tools can be found in Ilgin and Gupta [75] and Ramani et al. [76]. A comprehensive review of integrated product and process life cycle planning has been reported by Umeda et al. [81], wherein the lack of a systematic and strategic life cycle planning method is identified as a key barrier to sustainable manufacturing.

3 Manufacturing Processes

Two key sustainable manufacturing process issues to consider are where manufacturing processes are performed and which manufacturing processes are performed. The *where* question is important in terms of the economic dimension of sustainability as nations have a strategic interest in manufacturing activities as a way to raise standards of living and sustain quality of life. This question is also important from the environmental dimension as countries have different values, workplace practices, regulations, and energy production technologies. Following up on Ref. [82], this section will focus primarily on the *which* question, considering different processes that can be selected for materials forming, shaping, joining, and finishing. Chemicals and lubricants oftentimes used in these different processes are also discussed, and semiconductor manufacturing is discussed independently due to its importance to current technology.

3.1 Metals Manufacturing. Selecting the type(s) of metal manufacturing processes based on a product design can, as discussed previously, have a significant impact on sustainability. For instance, optimizing material properties for a specific application by developing a wide range of highly tailored, and largely incompatible, alloys can negatively affect machinability, which can increase energy and coolant/lubricant requirements. In another case, certain metals are more difficult to cast to net shape than others, thereby impacting the environmental profile of casting processes. Several common manufacturing processes are discussed below within the context of sustainable manufacturing, including casting, forming, machining and grinding, consolidation processes, and cleaning and finishing.

3.1.1 Casting. The environmental impacts of sand casting are major, ranging from hazardous air pollutants caused by off-gassing sands and molds to metal oxide fumes, which are combustion products and organics emanating from the interactions of molten metal with fuel and mold materials. There are also significant water emissions from metal cooling processes and solid wastes due to sand handling. Casting emissions can be reduced via on-line process control and integrated sensing technology, which are used for minimizing casting distortions and preventing recasting. As described by Sutherland et al. [31,83], opportunities to improve the environmental quality of casting processes exist in the development of sand mold and permanent mold coatings, binders, and lost foam materials, as well as improved thermal management and process-based models to support environmental assessment.

Increased utilization of heat reclamation technologies can reduce energy and greenhouse gas footprints of casting. Improved casting methods leading towards net-shape casting could permit a reduction or even elimination of machining or finishing steps downstream in production [84,85]. This would involve improved prediction of mold distortion via modeling and simulation, which is necessary for accurate dimensioning and integration of risers and gating into the part itself.

3.1.2 Forming. Major opportunities for improvement of forming operations exist in the domains of machine efficiency, forming tool production, and forming system lubrication [86]. One such technology is single point incremental forming (SPIF). While only applicable to small scale prototyping, SPIF allows for reductions in material and energy requirements normally invested in forming tooling [83,87]. The remanufacture of tooling, through combinations of additive and subtractive manufacturing processes, can lead to the prevention of conventional forming tool manufacture. In one automotive example it was shown to save $250,000, 30 weeks of lead time, and more than a ton of CO_2 emissions [38].

Net-shape forging and forming can reduce impacts downstream and can be achieved via tool-less forming, e.g., laser processing, increased use of tailor welded sections, and improved design of preforming operations [88]. Reconfigurable dies can also reduce the environmental impact associated with die manufacturing, reduce cycle time during tooling switchover, and reduce costs. The development of integrated die coatings would also extend the life of dies, as well as reduce the need for external coolants and lubricants.

3.1.3 Machining and Grinding. Machining and grinding are subtractive (material removal) processes that require energy and process chemistries to create finished shapes. Scrap machining chips and grinding swarf are almost always recycled (in some cases these are highly valuable), but from a financial and environmental perspective it is best to minimize subtractive operations to the extent possible through part design and process planning. Machining process chemicals and lubricants called metalworking fluids (MWFs) are a major health and environmental concern, and are being addressed by research groups around the world. The major approaches include dry machining [89–93], minimum quantity lubrication (MQL) [94–98], and alternative fluids such as liquid nitrogen [99,100]. Each option must be considered within a total life cycle context. Dry machining, for example, requires alternative means for corrosion control, chip evacuation, metallic dust control, decreased tool wear, and thermal management in the absence of MWFs.

The MQL strategies are generally challenged in the area of cooling performance, while liquid nitrogen is generally challenged in the area of lubrication performance [101]. Hybrid MQL/MQC (Minimum Quantity Cooling) approaches are also under development [102–104]. Other improvements to machining and grinding can be achieved using process planning to minimize engineered scrap and energy consumption, design of reconfigurable machine tools to limit scrapping of production lines at their EoL, development of technologies for improved recovery and recycling of scrap metals generated during metalworking, and creation of aluminum alloys that would facilitate machining [83].

3.1.4 Consolidation Processes. Whereas subtractive manufacturing processes remove material from input stock, consolidation processes are additive and assemble materials or components to create a final or net-shape part, e.g., additive manufacturing, powder metallurgy, and joining. Solid Freeform Fabrication (SFF) technologies have made it possible to eliminate environmentally polluting supply chain activities in the tooling industry, and to repair and remanufacture tools and dies [38]. Ideally, such processes would eliminate casting, forming, machining, and finishing processes. In reality, powder metal production often includes casting, although it need not, and requires finish machining and surface operations.

Additive manufacturing of metal components suffers from low production rates and high energy intensity due to the use of lasers to melt and focus streams of metal powder into a sintered product. Technology improvements, such as direct metal deposition, have addressed concerns of poor material properties, and have yielded parts that have similar strength and other properties to cast and forged material [105–110], while environmental concerns are just beginning to be explored. It has been shown that the environmental merits of additive manufacturing relative to conventional routes depend significantly on electricity sources, machine efficiency, sources of powder metal, and, critically, the ratio of deposited material to cavity volume [38].

As for material removal processes, the environmental impacts of joining can be minimized by net-shape processes implemented upstream. The environmental impacts of welding can be minimized through less welding, the use of friction stir welding, as well as reducing flux use and using lower-fume coatings [111]. Furthermore, joining approaches are critical for disassembly. This has led to research in the area of reversible fasteners [112,113].

3.1.5 Cleaning and Finishing. Finishing operations that impart the engineered surface properties of metallic parts are among the most polluting activities in manufacturing [114,115]. Life cycle-based process designs could minimize the pollution originating from finishing operations such as metallic heat treatment, cleaning, plating, and rinsing operations. For instance, a better understanding of surfaces would reduce the use of lubricants upstream of finishing operations and lead to the development of multifunctional coatings for both manufacturing processing and in-use function without the need for separate finishing operations.

The environmental performance improvement of finishing depends, in part, on the development of novel, low-energy processes to eliminate bulk heat treatment, including thermo-mechanical approaches such as sonication, laser processing, microwave treatment, and ion irradiation. Selective localized surface treatments such as thermal spray coatings can also replace specific bulk plating operations, and avoid their characteristic use of toxic chemicals, e.g., cadmium and chromium, and their high volumes of hazardous aqueous waste. Additional research has considered reducing the use of solvents in traditional operations, improving recycling rates for aqueous cleaners, increased metals and chemical recovery from rinse water, and targeting the development of entirely closed-loop finishing processes [116].

3.2 Process Chemicals and Lubricants. In addition to the impact of metals manufacturing, solvents, etchants, and other fluids are often used. These chemicals affect the performance of manufacturing from a sustainability perspective.

3.2.1 Solvents. Solvents are used in industrial facilities to perform everything from chemical synthesis to component processing and cleaning to separations [117]. Many of the most contaminated industrial sites in the country have legacy problems with solvents that were improperly disposed. Environmentally benign alternatives to traditional organic or chlorinated solvents have received a great deal of attention in recent decades because they are used in such large quantities, their health implications for workers are high, and the cost of these fluids is high when considering their entire life cycle from purchase to disposal.

Supercritical fluids, particularly supercritical CO_2 ($scCO_2$), have been the subject of intensive research [118]. Supercritical CO_2 is attractive because it has a relatively low critical point and is nontoxic, nonflammable, and inexpensive [119]. It also greatly simplifies separation processes, which can typically be enabled by controlling the pressure, and $scCO_2$ is miscible with a large number of compounds [120]. In spite of their potential, supercritical fluids have only been adopted in limited applications, such as high value pharmaceutical separations. The cost and challenge associated with retrofitting industrial operations to handle extremely high pressures is not often worth the environmental benefits that supercritical fluids can provide. As an alternative, several research groups have recently demonstrated the technical advantages of gas-expanded liquids (GXLs), which are a hybrid of conventional organic solvents and a supercritical fluid [121]. A GXL is typically a binary mixture of a solvent and an industrial gas, most often CO_2. The media is a liquid, but unlike a supercritical fluid, it is only maintained at 1–2 bars rather than 10–20 bars [122].

Ionic liquids are another type of alternative solvent that have received significant attention from academic and industrial research groups [123]. Ionic liquids are molten salts under standard atmospheric pressure and temperature conditions [123]. A characteristic of these liquids is that they have no vapor pressure, and as such, fugitive emissions to the atmosphere can be effectively eliminated. A wide variety of chemical compositions have been developed and recent work suggests that the toxicology of some of these compounds may be undesirable [124]. From an environmental life cycle standpoint, the degree to which a specific ionic liquid represents an improvement over conventional solvents depends on the chemical composition and on the solvent it is replacing [125]. As with many "green" alternatives, ionic liquids represent an improvement only under certain circumstances. In many applications, they are cost prohibitive, which limits their wide-scale adoption.

3.2.2 Lubricants. Conventional lubricants are based on petroleum feedstocks. Approximately 1.3% of each barrel of crude oil is refined and/or modified for lubricants [126]. Worldwide, this amounts to nearly 1×10^6 barrels of petroleum-based lubricants produced each day [127] with only a small fraction (<5%) of the world's consumption coming from renewable bio-based sources [128]. Recent record-high crude oil prices have driven a boom in bio-fuel production and research [129]. Although less work has been done on bio-based lubricants and tunable alternatives when compared with work on biofuel over the past decade [130,131], significant efforts have been undertaken [132]. Vegetable oils, animal fats, and esters derived from them have attracted particular interest for a variety of machining processes [133–138]. It has been reported that mineral oil is unable to provide the efficiencies necessary for engines designed for biofuels or for lubrication of advanced machining processes [139]. Bio-based lubricants have emerged as promising alternatives in these applications.

Meanwhile, the increase in U.S. biofuel production has been linked to the worldwide spike in food prices. As demand for edible oils and other agricultural products rises, their availability for lubricant applications will inevitably decrease, suggesting that current reliance on canola, soy, and other oils for lubricant formulations may not be viable [140]. The current trends in petroleum and bio-based oil availability suggest that alternative chemistries must be identified to ensure the sustainability of key industrial processes. As such, glycerol and biopolymer based formulation have been evaluated in metalworking applications [141–143].

In an effort to enable bio-based alternative lubricants, a great deal of research has focused on the delivery of these compounds since their chemistries are fundamentally different than petroleum-derived compounds. Emulsion theory for oil-in-water mixtures; for example, is well characterized for heterogeneous mixtures, i.e., crude oils, but it is poorly understood for biologically derived oils such as soy and canola oils [144]. This lack of fundamental understanding is an obstacle for the design of stable microemulsions of bio-based oils in water over a range of conditions relevant for metalworking applications [145]. Similarly, the delivery of these oils in minimum quantities could represent an effective means by which to reduce the impact of lubricated systems in certain contexts such as metalworking [146,147].

Several researchers have been working to develop a novel method to deliver lubricants dissolved in $scCO_2$ to obtain the cooling potential of water-based coolants with the lower economic and environmental costs of MQL sprays [103]. Life cycle analyses of alternative lubricants suggest that the environmental burdens of sprays delivered in CO_2 are lower than those of sprays delivered in water or air [148]. It also suggests that bio-based lubricants, on their own, do not necessarily have lower environmental impacts than petroleum blends, because conventional industrial agriculture is so energy and fertilizer intensive.

3.2.3 Hydraulic Fluids. Hydraulic fluids are used in a wide range of manufacturing operations and, in the context of environmental burdens, are most often implicated for their use in injection molding machines [149]. These machines are highly inefficient and represent one of the largest energy sinks in many manufacturing facilities producing plastics. The energy needed to run the hydraulic motors is fixed and represents the second largest draw on power in an injection molding machine second only to clamping, which can vary depending on the operation. In the production of most plastics, the energy draw on the hydraulic injection molding machines is orders of magnitude higher than other steps in the life cycle [32].

3.2.4 Etchants. Etching is the common practice of removing unwanted material from a manufactured part by dissolving it in an etchant. The process is widespread in metals processing industries and the electronics industry, as discussed below [150]. The solutions that are needed to remove the materials involved have significant environmental consequences. For both metals and semiconductors, strong acids or bases are typically used. From a life cycle standpoint, these fluids represent a critical burden for electronics producers [151]. Research efforts in recent years have focused on more effective means by which to regenerate the etchants so that they can be recycled longer, greatly reducing the environmental burden per part [150].

3.3 Semiconductor Manufacturing. Modern semiconductor devices require hundreds of manufacturing processes and use high purity materials in energy-intensive clean rooms. Each wafer is processed to form layers of patterns using a repetition of three basic processes. First, thin films of conductive, insulating, or semiconductor materials are deposited on the wafer by physical or chemical means. This is followed by a lithography step, in which a pattern is transferred from a mask to a sacrificial photosensitive material. Finally, the thin films are etched (Sec. 3.2.4) through the pattern in the photosensitive material resulting in its transfer to the deposited film. Other processes are related to growing insulating layers (oxidation), introduction and control of dopants to moderate transistor active regions (ion implant), chemical mechanical planarization (CMP) of films, and wafer cleaning. It is not possible to cover these complex manufacturing processes in great detail, and the reader is referred to a number of standard references, e.g., the work of Dornfeld and Lee [152]. More detailed discussions of environmental aspects of semiconductor manufacturing and green semiconductor manufacturing methods have been reported [153,154].

In general, life cycle energy use and greenhouse gas emissions have been increasing per wafer and per die, but are decreasing when normalized by computational power as technology has progressed. The primary driver of increases in per-wafer and per-die life cycle impacts has been the escalation of use-phase chip (integrated circuit) power [154]. The growth in per-wafer impacts is also due to the lengthening of the manufacturing process flow and accompanying expansion in manufacturing infrastructure and equipment. The complexity of semiconductor device designs has increased, which has led to a growth in the number of process steps required to produce a finished wafer.

The increase in manufacturing and materials-related impacts in semiconductor manufacturing has been offset somewhat by shrinking die sizes, which allow more dies to fit on each wafer. Thus, use-phase power is the lone reason for increases in impacts per die. Global Warming Potential (GWP) of transportation has been found to be almost insignificant due to the small mass of the product, despite the long distances that semiconductor wafers and chips are typically shipped during production and prior to use [154]. Even though reduced feature sizes have made maintaining wafer yield difficult, reports from industry indicate that wafer yields for full scale production have not fallen with decreasing device dimensions. Mature wafer yield is assumed to be 75% for all technology nodes, based on ITRS reports [154–158].

Semiconductor process development occurs as a joint effort between commercial and academic institutions. Promising design and processes are refined by semiconductor manufacturing companies. This stage, known as commercial development, is the ideal time to determine whether the process emissions may be hazardous or toxic, and if the process can be conducted safely. Arduous process development is wasted if the environmental impact of the process flow is unable to meet the requirements of environmental regulations. The general techniques used for emission analysis include mass and energy flow modeling based on measurement estimation methods used by governments for GWP impacts and using published LCA data as a means to estimate impacts related to a specific device type [154,159].

3.3.1 Process Emissions. The semiconductor manufacturing process employs a large variety of chemistries. Wafer processing involves a number of different acidic (hydrofluoric and sulfuric acids), basic (ammonia), and oxidizing (peroxide) chemicals as wafer cleaners, and other highly reactive (fluorine used in etching) and extremely toxic (arsine and phosphine used in implant) chemistries. The equipment used to administer these reactions must be designed to protect manufacturing personnel by following safety rules outlined by government agencies, such as the Occupational Safety and Health Administration (OSHA), and standards developed by industry groups, such as the Semiconductor Equipment and Materials International SEMI S2 standard.

As all mainstream semiconductor manufacturing equipment currently sold and used follows these regulations, the direct human health impacts and risks within the fab have been nearly eliminated in normal operation, though hazards still exist in cases of catastrophic breakdown, fire, or earthquake. Once chemicals leave the equipment, they must be further handled and neutralized by the Point-of-Use (POU) and facility abatement systems, in a safe and efficient way.

3.3.2 Emission Abatement. The abatement and neutralization of emissions is not as predictably efficient or controlled as the reaction of chemicals within the process equipment, in part because the processes used to neutralize emissions to the extent necessary to make them safe for release into the environment do not need to be as precise as those used within the process chamber. Additionally, within the facility abatement systems (the house gaseous waste, fluorine abatement, and acid waste neutralization systems), the chemistry of the combined emissions of the many processes running on site can be unpredictable. Facility abatement systems are designed to continuously measure the incoming waste stream and adjust the neutralization chemistry accordingly. Nevertheless, neutralization of an unpredictable waste stream cannot be as efficient or controlled as that of a known waste stream.

When a facility abatement system is not operating ideally, or is not designed or built to adequately handle the current waste streams, a variety of environmental impacts can result. For example, the "house scrubber" (facility gaseous abatement system) may be accepting significant concentrations of gaseous fluorine

(F_2), either because no POU abatement is set up on plasma etching equipment, or because POU systems are not sufficiently scrubbing the F_2 gas. This gaseous fluorine will react with water to a small extent to form OF_2, a reactive and highly toxic gas [160]. Another product of the reaction of fluorine with water is HF. When fluorinated compounds are effectively abated from processes at the POU, the resulting liquid HF is sent to a fluorine waste treatment system separate from the house acid waste neutralization system. Any HF captured in the house scrubber system cannot be effectively treated before being released into the environment, as it would already be mixed in with the larger volume of nonhazardous waste. Ineffective abatement of fluorine, and the consequent release of reactive fluorine species into the environment, could result in human and ecological impacts.

While the potential environmental and health impacts from semiconductor manufacturing are understood and, in most cases, successful efforts are made to eliminate or mitigate them, the GWP impacts associated with certain per-flouro-compounds (PFCs) were not recognized or controlled until many years after the introduction of their use. PFCs are an important group of emissions from semiconductor manufacturing due to their high infrared absorption, long lifetimes, and consequential global impact. These compounds are used in wafer etching and include CF_4, C_2F_6, NF_3, and SF_6. For this reason, global warming impacts are an important impact category to consider in the production of integrated circuits (ICs).

The abatement of some PFC emissions is regulated by the Kyoto Protocol (in Annex I and II nations) and, in 1999, the World Semiconductor Council (WSC), which includes the semiconductor industry associations of Japan, the E.U., Korea, Taiwan, and the U.S., issued a position paper which committed members to PFC emissions reduction by 10% of 1995 or 1999 baseline levels by the end of 2010 [161,162]. The WSC reported in 2011 that participating countries, in fact, had surpassed the original 10% reduction goal, achieving a 32% reduction in PFC emissions [163]. The WSC also established three new ten-year goals which include a 30% reduction in Normalized Emission Rates (NER) via implementing best practices, adding “Rest of the World” emissions reporting for regions not in the WSC, and developing an NER-based measurement in kilograms of carbon equivalent per area of silicon wafers processed to be used as a single WSC goal, globally [163]. Although these two agreements have resulted in tremendous progress in the reduction of semiconductor PFC emissions, more than half of semiconductor production occurs outside of Kyoto Protocol Annex I and II nations, and, in 2008, almost 20% of semiconductor production capacity was held in China, Singapore and Malaysia, where the industrial consortia have not committed to the WSC PFC goals. Semiconductor capacity has continued to grow in those countries where PFC emissions control is not required by any public agreement or national policy.

4 Manufacturing Systems

Environmentally sustainable manufacturing systems have traditionally focused on two main areas: (1) the design of environmentally conscious production systems, and (2) the design of closed loop supply chains that consider the life cycle of a product from cradle to gate. The three key elements to developing a sustainable manufacturing system discussed in this section are energy auditing, sustainable planning and scheduling, and sustainable supply chains. Figure 2 illustrates the interaction between sustainable manufacturing systems and manufacturing processes. Manufacturing processes, reprocessing operations, and inspection/disassembly are considered plant level processes that interact with system level aspects, such as process planning, production scheduling, the forward supply chain, and the reverse supply chain. Energy auditing is not explicitly included in Fig. 2; however, it is a system level element that interacts with each other system and process level element.

4.1 Energy Auditing. Engineers face many demands in life cycle facility design (spanning construction, operation, and decommissioning), and face the additional difficulty of accounting for sustainability objectives within constrained budgets [164]. Leadership in Energy and Environmental Design (LEED) certification has contributed to evaluating a facility’s overall sustainable manufacturing level, where impacts are generally measured with LCA and energy audits [165]. Energy auditing is a facility-level practice long used by manufacturing companies to reduce energy consumption and its associated costs [166,167]. Energy audits have been increasingly used to reduce the environmental impacts of manufacturing [167]. An energy audit consists of characterizing the energy use in the facility, performing economic and environmental analysis of potential changes of operations, and recommending energy saving measures [167,168]. Manufacturers have found energy reduction to be the most attractive way to reduce their environmental impact due to the resultant financial benefits [169]. The range of potential savings for industry facilities is usually 5–10% for low-cost measures, and up to 50% for high-cost, engineering-intensive measures [167]. Recently, the ISO has introduced a new standard on organizational energy management [170], which details how to follow a systematic approach in achieving continuous improvement of energy performance and specifies requirements on measurement, documentation, design of equipment/processes/systems, and personnel involved in the practices. The recent trend in research is toward advanced energy monitoring systems, controls, and computer simulation to achieve lasting energy savings [171,172].

Energy auditing is also prevalent for many manufacturing processes. Commonly, the total energy requirement for the active deformation and removal of material can be quite small compared to the background functions needed for manufacturing equipment

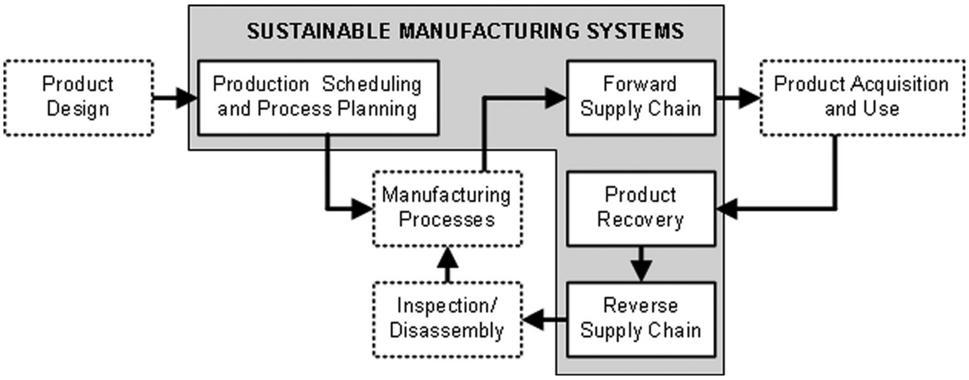

Fig. 2 Key elements of a sustainable manufacturing system include process planning, production scheduling, and forward and reverse supply chains

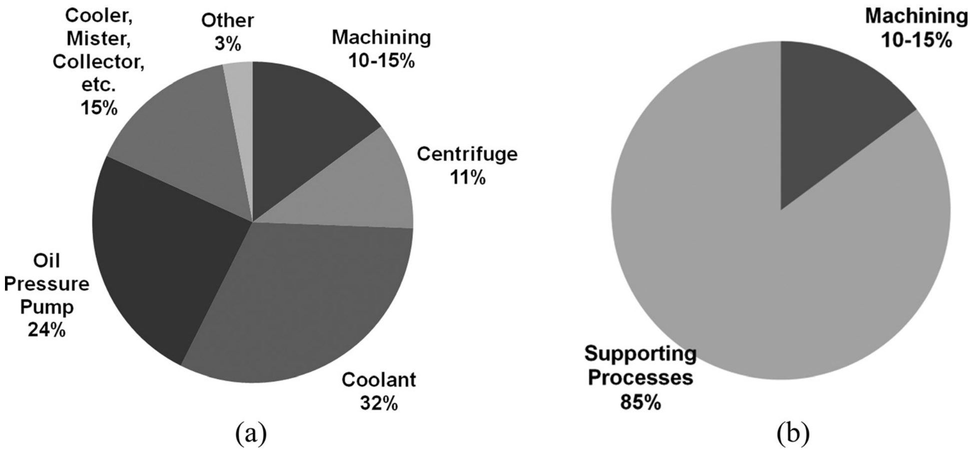

Fig. 3 Energy use breakdown for machining (the chart on the right combines the categories other than machining shown in the chart on the left; adapted from Ref. [176])

operation [30,173]. Drake et al. [174] showed that when a machine is idle, a significant amount of energy is consumed. As shown in Fig. 3, 85% of the energy utilized in a production environment can be attributed to functions that are not directly related to the actual production of parts [175,176]. In the example presented in Ref. [158], this percentage remains constant regardless of production numbers; however, the energy required for machining increases with production. This suggests that energy saving efforts that focus solely on updating individual machines or processes are not sufficient, and that system-level approaches could lead to more significant benefits.

4.2 Planning and Scheduling. Planning and scheduling operations in manufacturing systems control which, how often, when, and in what order manufacturing processes take place. Manufacturing systems can improve their sustainability level when process plans and production schedules take into account sustainability metrics. Research regarding sustainability in process planning and production scheduling in manufacturing systems is discussed below, and a discussion of planning, scheduling, and inventory management for remanufacturing operations can be found in Ref. [75].

4.2.1 Process Planning. A process modeling approach linked with LCA was employed to assist in production planning based on product and process design modifications in [177,178]. Work by Srinivasan and Sheng [179,180] described how robust process planning that integrates environmental factors could be achieved through multiobjective analysis in micro planning and macro planning. Micro planning considers the parameters, tooling, and related variables that are necessary to produce individual features, while macro planning investigates the interaction among features to determine a globally optimal process plan, taking into account job scheduling, line balancing, facility planning, and related issues. Their approach was demonstrated for incremental design changes to a machined part.

4.2.2 Production Scheduling. Traditionally, the scheduling of tasks within a job shop has focused exclusively on throughput time, productivity, tardiness, and related metrics [181–187]. In contrast, research on scheduling considering environmentally-oriented objectives is relatively scarce. At the equipment level, Mouzon et al. [188,189] investigated the problem of scheduling for a single machine to minimize total energy consumption. In particular, they looked at the scheduling of a CNC machine in a machine shop for a supplier of small aircraft parts. At the shop floor level, Subai et al. [190] incorporated energy and waste considerations into hoist scheduling problems associated with surface treatment processes. In terms of social aspects, Liu et al. [191] investigated machine-workpiece pairing for noise reduction.

Research in energy-aware scheduling is growing [192,193]. In particular, Wang et al. [194,195] proposed an optimal scheduling procedure for vehicle sequencing in order to reduce energy consumption in an automotive paint shop. By selecting appropriate batch and sequence policies, they found that the paint quality could be improved and repaints could be reduced. Mani et al. [196] proposed an approach for manufacturing planning and scheduling based on energy monitoring of a set of equipment within a facility to complement cost, quality, and time metrics. Herrmann and Thiede [197] reported that up to 30% energy efficiency improvement could be achieved through process chain simulation in a shop with two identical production lines that manufacture bearing inner races. Fang et al. [198] proposed a new scheduling philosophy that considers production time and environmental performance measures, e.g., energy consumption, carbon footprint, and peak power load. The authors presented a general multiobjective model for the problem, and analyzed a simple case study that considers the scheduling of 36 jobs on two machines. A Pareto frontier was established that showed the tradeoff between throughput time and peak power.

4.3 Supply Chains. Supply chain sustainability focuses on two aspects: the design of sustainable enterprises and closing the production loop (reverse supply chain). Badurdeen et al. [199] provided a definition for sustainable supply chain management that includes "the planning and management of sourcing, procurement, conversion and logistics activities involved during premanufacturing, manufacturing, use, and post-use stages in the life cycle," as well as closing the production loop "through multiple life cycles with seamless information sharing about all product life cycle stages between companies by explicitly considering the social and environmental implications to achieve a shared vision." Sustainable supply chain management has evolved from the traditional green supply chain management which, in general, focuses on environmental aspects. Figure 4 provides a detailed depiction of a sustainable supply chain. Raw material and components are supplied by initial suppliers and are delivered to focal or peripheral manufacturing companies. Finished products reach consumers through multiple channels (depicted as Tier 1 and Tier 2 customer suppliers). The conventional view of supply chain management is limited to three life cycle stages (premanufacturing, manufacturing, and use). Sustainable supply chains, by definition, account for the post-use stage. EoL products are collected via recovery enterprises and redistributed to the supply chain at multiple stages, e.g., recycled material to premanufacturing, remanufactured products to the

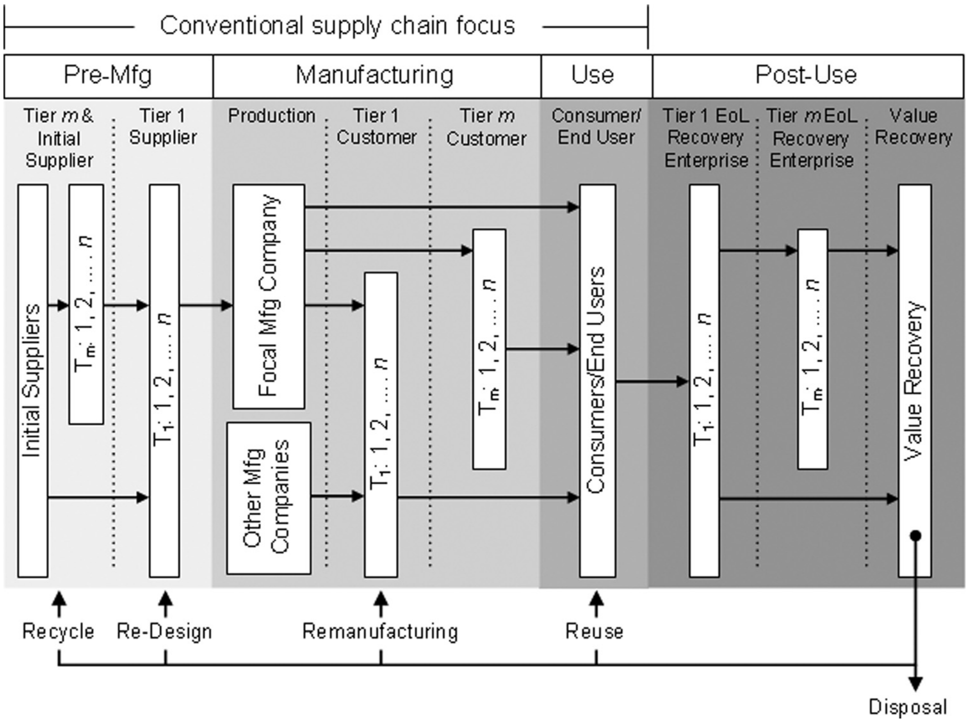

Fig. 4 Integrated approach to sustainable supply chains (adapted from Ref. [200])

manufacturing stage (or the use-phase), and reused products to the use-phase.

It is critical that a sustainable supply chain be integrated with sustainable manufacturing processes, design, and systems in order to fulfill the sustainable manufacturing philosophy. Consider the manufacturing and recovery of automobiles (the most recycled of all products). The vehicle recycling infrastructure in the U.S. recovers 95% of all vehicles and approximately 80% of the material content. Yet, vehicle design changes (more aluminum and composites) being pursued by automotive manufacturers to lighten vehicles and reduce the environmental impacts of the use phase may result in deleterious effects on sustainability, jeopardize the financial success of dismantlers, and increase the level of ASR (automotive shredder residue). Kumar and Sutherland [201] discussed the challenges facing the automotive infrastructure and presented a model for material flows and economic exchanges (MFEE) across the entire automotive value chain. In a follow-on paper [202], it was reported that material recovery rates can only be increased through new technologies, e.g., plastic recycling and vehicle dismantling technologies, and that the economic burden for supporting such technological changes might need to be shared among all stakeholders and supported via regulatory strategies.

4.3.1 Forward Supply Chain. Jayal et al. [200] presented an overview of current trends in sustainable manufacturing and highlighted the importance of a holistic approach to understanding the entire supply chain, as well as the need for new product and process performance and predictive models capable of capturing environmental impacts. Metta and Badurdeen [203] discussed the importance of coordinating manufacturing processes and product design with sustainable supply chain design. They presented hierarchical, multistage decision support models that consider economic, environmental, and societal performance of supply chains to evaluate alternative sustainable product designs. In the past, case-based research has indicated that supply chain environmental performance improvements can result from communicating with suppliers to make their processes more sustainable, evaluating their overall sustainability, and improving inbound logistics processes, such as packaging material and waste; in addition to material selection and product design at each supplier [204]. These factors can be included in supplier selection strategies and supply chain decision making. Hutchins and Sutherland [205] proposed a general approach for integrating sustainability considerations into supply chain decision making. Their approach utilized a value based method for combining sustainability-related impacts of multiple suppliers. They illustrated how the method can be utilized to select suppliers with lower sustainability impacts. Additional discussion of supply chain research in support of sustainability has been published, e.g., Refs. [75,76,199,206,207].

4.3.2 Reverse Supply Chain. Reverse supply chains are a system of operations that work together to collect products from consumers and route them to a desired destination, generally a remanufacturing or recycling facility. Achieving sustainable manufacturing relies, in part, on the implementation of reverse logistics and the creation of a reverse supply chain, regardless if recovery is performed by original equipment manufacturers or third parties. In the last decade, significant work has been done in regards to reverse supply chains and reverse logistics [75,199]. In general, the primary research areas within reverse supply chains are network design (routing and facility location), integrating network design with product design, and EoL product acquisition management. Network design has been an area that has made significant strides in terms of model development, and includes routing and facility location models surveyed in Refs. [75,199]. Clarke et al. [209] presented a location modeling strategy for shoe manufacturing/remanufacturing. Product acquisition management research has developed methods to model the process by which EoL products enter the reverse supply chain, in order to manage EoL product quality, return quantity, and return timing uncertainty. Offering an incentive, government subsidies, or a deposit/refund approach can impact the acquisition of EoL products and may eventually lead to a level of control over EoL product returns [75,210].

As part of the design of the reverse supply chain, the design of new post-use enterprises must be studied. Sutherland et al. [211] investigated the challenge of selecting a size for a remanufacturing facility. They developed a cost model for establishing a facility for diesel engine remanufacturing. The model addressed such factors as production, transportation, and inventory-related costs and it described economies of scale effects. The optimal unit cost and facility size were studied as a function of remanufacturing efficiency, product yield, and transportation cost rate. Capacity planning in regards to remanufacturing facilities has been reviewed in Ref. [75].

5 Challenges, Future Trends, and Recommendations

Despite the many recent advances made in engineering research, challenges and opportunities remain to be addressed in pursuing sustainable manufacturing goals. These research needs generally fall into one of four categories: (1) manufacturing processes and equipment, (2) manufacturing systems, (3) changes in life cycle paradigms, and (4) education.

5.1 Manufacturing Processes and Equipment. With respect to manufacturing processes and equipment, opportunities exist in terms of both technology and improved knowledge. On the technology front, research must continue to develop new manufacturing processes and equipment that reduce ecological footprints, with selection decisions guided by environmental LCA evaluations. This work must be supported by improving fundamental understanding of process physics and equipment attributes. The goal should be to utilize energy and other resources more efficiently, while being cognizant of impacts to the workers and local and global communities. Strategies pursued might include process hybridization, right-sizing of equipment, utilization of new process mechanisms, and more benign process-assisting materials/chemicals, e.g., metalworking fluids.

Sustainable manufacturing processes can lead to virtuous cycles. For instance, removal of oil from metal cutting processes can reduce cost, improve working environments, and eliminate wastewater disposal costs while further eliminating or simplifying downstream cleaning operations which have their own environmental and financial burdens. Identifying the most sustainable manufacturing process is rarely a case of "one size fits all," therefore requiring life cycle engineering to select the most appropriate process for specific conditions. A manufacturing process that might be consistent with the goals of sustainability in one case (e.g., additive manufacturing of parts with low material requirements and complex geometries) may not be consistent with the goals of sustainability in other cases (e.g., additive manufacturing of parts with a high solid to cavity ratio with simple geometry).

In terms of improved knowledge to support better process and equipment design and decision-making, perhaps the most promising trend is that of research collaboration. Examples of this include the CO2PE! worldwide research consortium and U.S. UPLCI collaborative research effort [41,42]. These initiatives are working to establish improved data on the environmental impact of manufacturing processes. Many incremental changes are being pursued for process improvement. Collectively, these changes represent a giant step forward.

5.2 Manufacturing Systems. At the manufacturing system level and beyond, attention to resource consumption, waste production, and reduction of environmental impacts through continuous improvement methods must continue to be areas of emphasis. Certainly, significant opportunities exist to infuse environmental objectives into a range of decision-making activities (e.g., production scheduling, supplier selection, and facility location) that exist at the system, facility, enterprise, and supply chain levels.

At the facility level, opportunities of 5–10% in energy savings exist for low-cost changes, with 50% or more energy savings potential through more profound changes in operations and practices. In one case, it was reported that 85% of equipment energy use was during idle time [176]. Tremendous opportunities exist for developing plans and schedules based on sustainability metrics. Although examples are limited, Herrmann and co-authors [197,212] reported up to 30% improvement in energy efficiency through simulation-assisted process planning.

While remanufacturing and recycling systems seek to manage end of life products, there is a great deal of potential for development of logistics strategies and technology development in support of product recovery and material reutilization, which includes recovery processes and systems for plastics and the remanufacturing of more complex components. Thus, the development of methods and technology stands to significantly affect the impacts of manufacturing systems, including production lines and forward/reverse supply chains.

5.3 Changes in Life Cycle Paradigms. Perhaps the most exciting potential future developments surround innovations and new paradigms with respect to product life cycles. Sustainable manufacturing must be identified in concert with the sustainable design process. In other words, "over the wall" design with respect to part geometry, material type, etc., can lead to the need for manufacturing processes and systems that are more environmentally and financially costly.

New approaches to and increased levels of recycling and remanufacturing will drive process development, changes in product design, greater use of reverse logistics, and even re-envisioning of the entire product life cycle (for a review on reverse supply chain and remanufacturing, see Ref. [75]); of course, these changes require significant rethinking of business models across the life cycle, including capturing social impacts [17]. Efforts to evaluate the societal aspects in manufacturing engineering have recently arisen, and there are debates on metrics and measurements among stakeholder groups that must be resolved.

It is highly desirable to incorporate life cycle assessment (LCA) or similar methods into new manufacturing process and system evaluation to avoid potential environmental pitfalls. Predictive LCA models that can estimate environmental impacts by scaling up experimental processes are needed. Next generation LCI databases require significant industry buy-in. Many companies are interested, but to achieve needed momentum, incentives and other policies are likely required to assuage issues related to data sharing and data security.

Economic activity has historically been linked to material consumption, and as we consider a future where the global GDP per capita doubles or triples, we must adopt new principles that decouple economic growth from materials. In this regard, the development of product-service systems and concomitant business models and decision support methods will be a high priority. Within each of these categories, focus needs to be placed on methods to quantitatively capture the social impacts of manufacturing and to juxtapose those metrics with better understood economic and environmental performance measures, which also continue to be under development.

5.4 Education. Of course, since environmental considerations are a growing imperative for manufacturing, manufacturing-related curricula must also address environmental and resource considerations [213]. Given the small number of faculty with expertise in this area, it appears that team-based approaches to course offerings and courseware development may be effective in educating future engineers with a broad-based understanding of product and process design, materials processing and manufacturing, and their influences across other stages of the life cycle. In addition, such approaches can facilitate communication of practical approaches to incorporating economic, societal, and policy issues into the design and manufacturing process.

The research described herein represents a selection of compelling work in the field of sustainable manufacturing encompassing the fundamentals of sustainable manufacturing processes and sustainability in manufacturing systems. Issues considered include economic, environmental, and social implications of manufacturing activities. Manufacturing is a critical aspect of societal sustainability, globally, due to the increased demand for products and services in developed and developing economies. Future manufacturing systems will strive to seamlessly integrate industrial, societal, and natural processes and systems to create a holistic, closed-loop network that produces and manages materials, products, and services in a sustainable manner.

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