Triebe *et al. Green Manuf Open* 2023;1:10
DOI: 10.20517/gmo.2022.11

Green Manufacturing Open

Perspective

Open Access

Perspectives on future research directions in green manufacturing for discrete products

Matthew J. Triebe[1], Sidi Deng[1,2], Jesús R. Pérez-Cardona[1,2], Byung Gun Joung[1], Haiyue Wu[1], Neha Shakelly[1], John P. Pieper[1], Xiaoyu Zhou[1,2], Thomas Maani[1], Fu Zhao[1,2,3], John W. Sutherland[1,2]

[1]Environmental and Ecological Engineering, Purdue University, West Lafayette, IN 47907, USA.
[2]Affiliate of the Critical Materials Institute (CMI),Ames National Laboratory, Ames, 50011, USA.
[3]Mechanical Engineering, Purdue University, West Lafayette, 47907, USA.

Correspondence to: Dr. Matthew J. Triebe, Environmental and Ecological Engineering, Purdue University, 500 Central Dr, West Lafayette, IN 47907, USA. E-mail: mtriebe@purdue.edu

How to cite this article: Triebe MJ, Deng S, Pérez-Cardona JR, Joung BG, Wu H, Shakelly N, Pieper JP, Zhou X, Maani T, Zhao F, Sutherland JW. Perspectives on future research directions in green manufacturing for discrete products. *Green Manuf Open* 2023;1:10. https://dx.doi.org/10.20517/gmo.2022.11

Received: 3 Nov 2022 **First Decision:** 28 Dec 2022 **Revised:** 24 Feb 2023 **Accepted:** 15 Mar 2023 **Published:** 31 Mar 2023

Academic Editors: Hongchao Zhang, Zhichao Liu **Copy Editor:** Yanbing Bai **Production Editor:** Yanbing Bai

Abstract

With the increasing concern due to climate change caused by a higher atmospheric concentration of CO_2 and other greenhouse gases, reducing environmental impact is becoming more important for every part of society. Manufacturing is responsible for a significant amount of energy/material consumption and environmental burden and, therefore, has a great opportunity to reduce its impact through green manufacturing. Green manufacturing presents opportunities across the manufacturing enterprise to increase the efficient usage of energy and material resources. These opportunities include designing products to consume fewer materials and energy during manufacturing and use, incorporating more efficient manufacturing processes, streamlining and optimizing manufacturing schedules and plans, and circularizing products. The goal of this paper will be to provide a perspective from the authors on the opportunities that exist within green manufacturing for discrete products through a review of pertinent topics and future directions. The paper will focus on processes, manufacturing equipment, manufacturing systems, recovering value at a product's end-of-life, and additional thoughts that include metrics and indicators, techno-economic assessment, and a discussion of efficiency and effectiveness. Key findings from this review include a need for social indicators and renewable energy considerations in scheduling and process planning, integrating Industry 4.0 into circular economy along with social and institutional dimensions, consistency in the ability to measure and conceptualize metrics and indicators, a detailed evaluation of the life cycle impacts and cost of Addit Manuf, and more human and environment-oriented considerations for smart manufacturing.

Keywords: Green manufacturing, sustainability, energy efficiency, circular economy

INTRODUCTION

The global population has increased from around 3 billion in 1960 to 7.8 billion in 2020, and UN forecasts predict that it will continue its increase towards 9.7 billion in 2050[1]. This population increase, in concert with the ever-increasing average affluence of the population, will lead to accelerated rates in the consumption of resources and the production of waste and associated environmental impact. From a climate change perspective, man-made activities have caused the global atmospheric concentration of CO_2 to increase from around 317 ppm (parts per million) in 1960 to 415 ppm in 2020[2].

The United States manufacturing sector plays a key role in the economy while at the same time being responsible for a large portion of energy/material consumption and environmental burdens. The industrial sector, which includes facilities and equipment used for manufacturing, agriculture, mining, and construction, represented 33% of total United States energy demand, of which manufacturing accounted for 77% of the energy consumption and was responsible for 24% of the greenhouse gas (GHG) emissions in 2020[3]. Manufacturing consumes both renewable and non-renewable materials as well as significant amounts of energy, resulting in substantial stress on the environment. Manufacturing also releases solid, liquid, and airborne streams that harm the environment. Moreover, manufacturing creates the products (vehicles, appliances, aircraft, tractors, HVAC systems, etc.), which during their use phase, account for much of the rest of the United States energy consumption and greenhouse gas emissions. As is evident, how we design products for use and how we manufacture them largely determines the energy/GHG impact on society.

The environmental challenges that we face in the near future are significant, and every part of society must proactively respond, including manufacturing. Opportunities exist across the manufacturing enterprise for more efficient usage of energy and material resources[4]. One encompassing mindset to incorporate these various opportunities is green, or sustainable, manufacturing. The Organization for Economic Co-operation and Development (OECD) defines sustainable manufacturing as “managing operations in an environmentally and socially responsible manner”[5]. Hauschild *et al.*[6] state that sustainable manufacturing, or green manufacturing, should consider the entire life cycle, not just the manufacturing stage. With this in mind, green manufacturing will have an impact on all stages of a life cycle: extraction and processing of materials, manufacturing, and assembly of the product, use, and end-of-life (EOL); and implementing a life cycle mindset can accomplish the goals of green manufacturing. Green manufacturing starts with the design phase, where a product is not only designed to have a lower use stage impact but also a lower impact during the manufacturing and EOL. Manufacturing processes are streamlined to reduce energy and waste. Manufacturing equipment is designed to require less energy and produce less waste. Manufacturing systems are optimized and designed with environmental goals in addition to cost and profit. Products are designed to be reused, recycled, or remanufactured, and processes are designed to better disassemble products for a circular life.

Since green manufacturing touches all stages of the life cycle, many topics can be included in its discussion. To limit the material, the topics of this paper will relate directly to the various authors’ research. These topics will include manufacturing processes, manufacturing planning, design of manufacturing equipment, recovery activities (e.g., disassembly), and recovery processes. This list of topics can be found in Figure 1. This paper will provide an overview of green manufacturing for discrete products from the authors’ perspectives through a review of the literature.

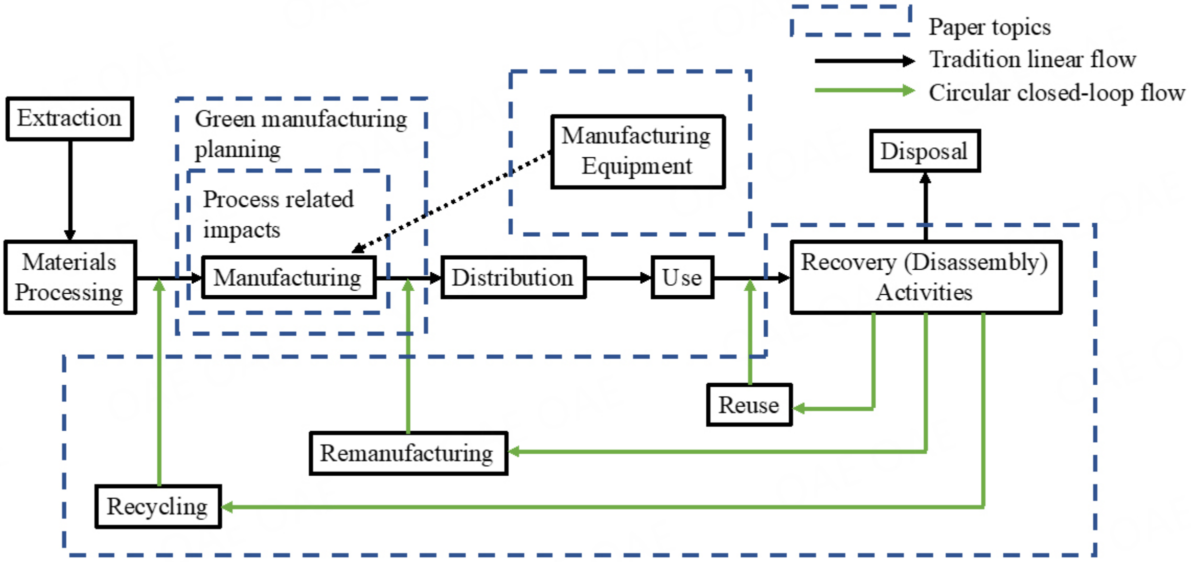

Figure 1. The topics covered in this paper from the life cycle of a product.

There have been many others that have provided a review of various aspects of green manufacturing over the years. Some of these papers, with their contributions and outcomes (from the last 10 years), can be found in Table 1. While there will be some overlap, this paper will provide the authors' perspectives on pertinent topics and future trends in green manufacturing for discrete products. These perspectives will be provided through a review of the literature from a life cycle viewpoint. Some aspects covered in this paper that are missing from other reviews of green manufacturing include the idea of a circular economy, the implementation of techno-economic assessment to assist design, the role of critical materials in green manufacturing, and a discussion of energy efficiency versus energy effectiveness.

To begin, this paper will first focus on manufacturing processes. The authors will provide an overview of the environmental impacts of various processes and methods for alleviating these impacts. Then, the paper will shift to manufacturing equipment with a focus on their energy consumption and methods for reducing consumption and improving efficiency. Following the discussion over manufacturing equipment, the paper will expand its focus to cover manufacturing systems. This section will include scheduling, process planning, and the enterprise level. Then the focus will shift to the EOL stage. Some additional thoughts will be provided regarding other important topics within green manufacturing, i.e., metrics and indicators, techno-economic assessment, and efficiency and effectiveness. Each section of the paper will provide future directions for the topics covered. Then, to close, the paper will summarize and provide conclusions.

PROCESSES

Manufacturing processes are the basic steps that convert raw materials into products. There have been many advances over the years, and new processes developed to increase the capability and performance of manufacturing. There are many types of processes, including cutting, forming, casting, and joining. This section will discuss the impacts of various manufacturing processes along with methods for reducing that impact and the emergence of smart manufacturing with its role in green manufacturing.

Table 1. Key contributions and outcomes of other reviews of green manufacturing

Papers	Key contributions/outcomes
Pimenov *et al.*[7]	● → Outlined methods within machining to decrease power consumption, carbon dioxide emissions, waste, and cost, while increasing productivity, air-water quality, and recycling and reuse ● → Reviewed optimization-based resource savings for the previous categories
Bhatt *et al.*[8]	● → Identified smart manufacturing paradigms and key elements of conceptual and methodological advances ● → Suggested an understanding of smart manufacturing can help practitioners achieve a sustainable competitive advantage while considering social, environmental, and economic objectives
Machado *et al.*[9]	● → Identified potential areas of implementation for Industry 4.0 in the development of sustainable business models, production systems, supply chains, and product designs ● → Identified well-researched areas that include energy efficiency, life cycle management, big data, and systems integration, and areas of opportunity including human factors, global impacts of Industry 4.0, and sustainable product and service development
Malek & Desai[10]	● → Found that integrated government legislations and environmental impacts must be included in economic optimizations ● → Concluded more research regarding sustainable manufacturing should be initiated within the steel, automobile, and food industries
Sartal *et al.*[11]	● → Highlighted the lack of agreement about the impact of Industry 4.0 in the social dimension ● → Identified the most used performance indicators by productive companies ● → Discussed opportunities provided by the digital transformation within Industry 4.0
Sharma *et al.*[12]	● →Demonstrated the advantages and disadvantages to end users and stakeholders in having access to data to make evidence-based decisions ● → Identified influential institutions and papers through a bibliometric analysis of sustainability in the field of Industry 4.0
Zarte *et al.*[13]	● → Analyzed current sustainability indicators and called for more consistent and less subjective indicators for decision-making tools
Akbar & Irohara[14]	● → Identified 43 sustainable indicators from 3 sustainable dimensions that are used in the manufacturing environment ● → Proposed a research framework for scheduling strategies to achieve sustainable manufacturing
Gbededo *et al.*[15]	● → Classified approaches for pursuing sustainable manufacturing into two categories: (1) approaches that support decision-making; and (2) approaches that support design or continuous improvement ● → Identified the research gap of how current approaches to sustainable manufacturing do not consider the interdependencies of the three dimensions of the triple bottom line
Moldavska & Welo[16]	● → Examined several definitions of sustainable manufacturing to determine the current understanding of the topic ● → Highlighted the agreements and differences across the research community in regard to the various interpretations of sustainable manufacturing
Hartini & Ciptomulyono[17]	● → Explored the relationship between lean manufacturing and sustainable production and how the two affect performance ● → Examined past research regarding the synergy of Lean and sustainable manufacturing and found more work is required to model the impact of the Lean philosophy on sustainability
Haapala *et al.*[18]	● → Identified the fundamentals of sustainable manufacturing, including its definition, metrics, methodologies for evaluating environmental performance, and important manufacturing areas ● → Provided key elements for a sustainable manufacturing system: energy auditing, planning and scheduling, and supply chains

Manufacturing processes

Environmental impact

Manufacturing processes consume energy, water, and materials while generating air and water emissions and solid waste. Taking machining as an example, removing material from the workpiece requires energy, and electricity is consumed to drive the spindle and the tool. For many heavy-duty machining operations, cutting fluids are needed, which have to be sent to the wastewater treatment at the EOL. Therefore, environmental impacts of manufacturing processes come from both process emissions and waste (direct impacts) and process inputs, e.g., electricity and cutting fluids (indirect impacts). Characterizing (and modeling) resource utilization and the emission profile is the first step toward greening manufacturing processes. Given the mounting concern over global warming, extensive work has been done on understanding the energy consumption of manufacturing processes. Sihag & Sangwan[19] recently reviewed the analysis and models done on machine tools and machining processes. Many studies model machine tool energy consumption according to operating states, i.e., standby, idling, air cutting, material removal, and tool change. Alternatively, there are also efforts to model energy consumption based on machine tool modules or sub-systems. Most of the models are for milling and turning operations. In either case, the goal is to fully understand the energy flows within a machine tool. This topic of energy consumption within a machine tool will be explored further in section 3.

Compared with efforts on energy, much less work has been done in understanding water consumption in manufacturing processes. To date, most of the work has focused on assessing water use in manufacturing processes, with very few attempts to model water usage. For machining operations, Zhao *et al.*[20] are one of the first to quantify the water withdrawal and consumption (both direct and indirect due to energy consumption) of three representative machining processes. It was found that water withdrawal and consumption due to electricity (indirect or scope 2 water footprint) are higher than those due to cutting fluid usage (direct or scope 1 water footprint). An extensive review of water consumption in metal cutting is done by Pervaiz *et al.*[21].

To fully quantify the environmental impacts (direct and indirect) of manufacturing processes, the widely used LCA method is often used. Unfortunately, traditional LCA databases have limited coverage of manufacturing processes, especially machining operations. The available datasets are largely rough estimates of material and energy consumption per kg of material removed. To address this issue, researchers have been trying to integrate energy models and material consumption assessment data, as discussed above, into LCA. One representative effort is the CO2PE! Initiative (Cooperative Effort on Process Emissions in Manufacturing)[22,23] and its counterpart in the U.S. named unit process life cycle inventory (UPLCI) project[24]. The datasets are organized according to manufacturing process taxonomies, such as DIN 8580. To date, these efforts have covered many traditional and new manufacturing processes (e.g., turning, milling, grinding, hot forming, welding, FDM, binder jet, and stereolithography).

Process impact reduction

Understanding resource utilization and pollution/waste generation makes it possible to develop new approaches to improve the energy efficiency and environmental sustainability of manufacturing processes. Although there exist general guidelines such as those based on industrial energy assessment[25], one may expect that the most effective approaches should be sector/application specific. For machining processes, energy consumption can be reduced via optimization of process parameters and tool path selection[26,27], which only incurs minimal operation interruption and capital cost. As modern machine tools become more digitalized and smarter, more data and information are available for decision-making and planning that can further improve energy efficiency[28].

Another important development in reducing the environmental footprint of manufacturing processes is the minimization or elimination of cutting fluids. Traditionally cutting fluids were applied in either flood or jet form, which leads to a significant amount of waste fluids that need treatment. There are also reports on occupational health risks associated with cutting fluid exposure. Close examination of cutting fluid functions and how these functions are achieved reveal that flood or jet form application is not necessary. As a result, the concept of MQL and dry machining were proposed[29]. Combined with the development of tool materials, MQL has been extended to hard machining conditions including grinding. Vegetable oils are the preferred lubricants in MQL due to both performance and environmental considerations. To improve performance, nanoparticles such as copper, carbon, and aluminum oxide can be added. Since MQL relies on high-speed delivery of cutting fluid to the cutting zone, excessive aerosol could be generated, and proper control equipment is needed. Dry machining eliminates the use of cutting fluid completely. For hard-to-machine materials and difficult operations, cooled air or liquid nitrogen can be used to enhance heat removal. Some hybrid systems, such as MQL with vegetable oil dissolved in supercritical carbon dioxide (instead of water), have also been developed. It should be noted that LCA is needed to compare the alternative strategies with traditional cutting fluid applications. A comparison of life cycle energy and water use on several cutting fluids systems can be found in Supekar *et al.*[30].

Since its introduction back in the 1980s and especially in the past decade, Addit Manuf (AM) has achieved rapid development and market penetration. AM has the potential to significantly improve resource utilization due to its high material efficiency. It also generates much less waste, and no cutting fluid is needed. However, AM carries its own environmental profile at both the process level and throughout the life cycle[31]. Many studies have been reported to compare the environmental impacts of emerging manufacturing technologies such as AM. Faludi *et al.*[32] compared the environmental impacts of AM with traditional machining processes. Le *et al.*[33] studied environmental trade-offs and advantages of the combination of additive and subtractive manufacturing techniques for producing a particular part. In general, AM's environmental superiority has to be confirmed by LCA studies[34,35].

Smart manufacturing

Digitization of manufacturing processes has been obtaining increasing attention with the emergence of Industry 4.0, which offers opportunities for the reduction of carbon emissions[36]. For example, highly connected Industrial Internet of Things (IIoT) and AI-based production increase the efficiency and flexibility of production, reduce waste, and improve production capacity and logistics. Digitization of manufacturing systems provides the capability of monitoring manufacturing equipment which allows users to minimize inefficient utilization of equipment. Some researchers reported that the consequences of using electric motors with poor efficiency can be significant from the perspective of maintenance and the environment as they consume much more power over time when compared to motors running under more efficient conditions. Proper selection of maintenance strategies can improve the environmental impact of products and manufacturing processes as it lengthens the lifespan of manufacturing equipment and, therefore, minimizes waste while preserving resource and energy efficiency[37]. Their findings demonstrate that a predictive maintenance strategy can be used to minimize the environmental impact of manufacturing plants while optimizing production performance.

Extending the lifetime of manufacturing equipment and products is a significant strategy to reduce environmental impact in many circumstances [outlined in Figure 2]. Lengthening a production equipment life cycle is often associated with the concept of prognostics and health management (PHM) or predictive maintenance in smart manufacturing[38]. PHM aims to provide users with an integrated view of the health state of a single piece of equipment or an overall system, in which diagnostic and prognostic analyses are conducted to detect an incipient failure and predict the remaining useful life (RUL). Based on analytical results, timely and appropriate maintenance actions (such as fastening, lubricating, and replacing components) can be taken to prevent a failure that could lead to the equipment's eventual breakdown. Lee *et al.*[39] developed a speed-invariant deep learning model to identify targeted faults of rotary machinery under different operating conditions. The proposed model achieved high accuracy in detecting the target fault while quantifying the model's uncertainties of varying speeds. Wu *et al.*[40] established a new data-driven model based on the Long Short-Term Memory Recurrent Neural Networks algorithm to identify a manufacturing system's deterioration and forecast its future health state. The method provides significant insights into the RUL of a bearing system to avoid environmental consequences. The mentioned literature provides methods and tools for decision-making for equipment lifetime extension.

The other literature investigated in this review put more focus on lengthening the product life by monitoring products with sensors and analyzing the data to predict failure. Bakker *et al.*[41] map the environmental impacts of refrigerators and laptops against their increasing energy efficiency over time and finds that product life extension is the preferred strategy in both cases. They hypothesized that these

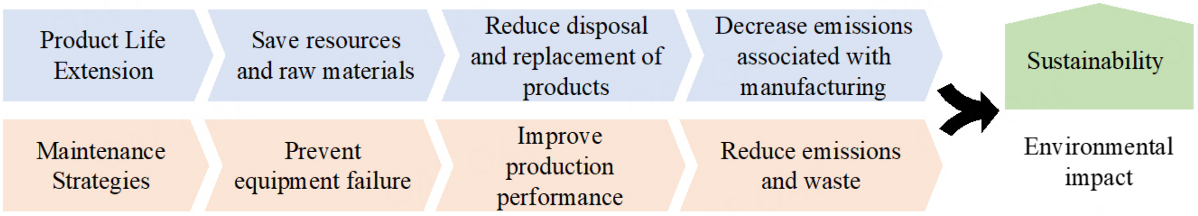

Figure 2. An outline of how extending product life through maintenance strategies contributes to green manufacturing.

findings may apply to other electrical and electronic products. Morioka *et al.*[42] designed and evaluated advanced loop-closing systems for the recycling of EOL vehicles and electric household appliances and found that a strategy to lengthen the product life with parts reuse improves the eco-efficiency in terms of CO_2 emissions by 4% when compared with the conventional practice of replacing of the appliance. Another trend is to address product life extension through design/redesign. Guo and Leu[43] found that some designs of novel geometries in AM can have the benefits including increased strength and stiffness, corrosion resistance, and improved operational efficiency and functionality.

There is also great potential to reduce the environmental impact and improve production efficiency through the implementation of smart manufacturing techniques. Several studies have been reported to attempt to reduce the environmental impact of manufacturing through a smart and sustainable production system. Zhang *et al.*[44] presented a data-driven analytical framework to reduce energy consumption and CO_2 emissions for energy-intensive industries. The experimental results of the proposed methodology on ball milling processes showed a 3%-4% reduction in total energy consumption. Kellens *et al.*[45] demonstrated a power measurement for a metal-cutting process to reduce standby energy and optimize the process parameters. Bermeo-Ayerbe *et al.*[46] presented adaptive predictive control for equipment management to enhance energy efficiency. Song *et al.*[47] proposed a similar approach for an HVAC system on a factory level. Their experimental work achieved 8.6% of the total energy consumption without compromising production efficiency.

Future directions in process improvement and smart manufacturing

With regard to manufacturing processes, more research is required to understand machine tool energy consumption. Sihag and Sangwan[19] state that research is needed to benchmark energy consumption for standard machining processes to allow for energy management and process planning. In regards to cutting fluids, continued advances are required in dry cutting, MQL, cryogenic cooling, and other alternate green cooling/lubrication strategies[21], which will assist in the reduction of environmental impacts, including water footprint.

The adoption of smart energy management within the industry, plus decarbonization through electrification and the adoption of renewable energy, will significantly reduce the industry's carbon footprint. Electrification can be accomplished through upgrades with electric boilers and arc furnaces, and industrial process heat pumps[25]. One method, as pointed out by Patterson *et al.*[25], is the installation of a smart energy management system (EMS). An EMS can save facility costs and energy through a low investment cost and a short payback period. This EMS should also be integrated into Industry 4.0. In addition, machines should be scheduled during non-peak hours, a shutdown management program to turn off machines when not in use should be installed, and machine power should be monitored[28]. For AM, more work is required to produce a standard methodology to characterize the energy consumption of AM processes[31]. A better understanding of the embedded energy of AM feedstocks is also needed. Best practices for energy-efficient AM printing need to be investigated and shared with AM communities. More research is required to provide a detailed evaluation of life cycle impacts and to integrate sustainability and cost for AM[35].

As smart manufacturing has enabled ever-increasing productivity, new technologies, and theories can be deployed and integrated in a more holistic way for green manufacturing development. Big data and AI analytics, digital twins, cloud, Addit Manuf, and the IIoT will be used more frequently to (1) reduce direct or indirect costs, waste, and emissions at the process level, such as increasing material use efficiency and optimizing energy consumption; and (2) improve product quality and durability, as well as EOL management. It requires a strategic approach to determine how and what outcomes will be obtained by actually implementing those technologies. Future research will have to address the application strategies for smart manufacturing in each of the life cycle steps, including planning, design, manufacture, operation, and maintenance. Reference literature and guidelines will be needed on how to connect to the existing heterogeneous legacy systems in current manufacturing sites. Furthermore, smart manufacturing is mostly addressed from the perspective of effectiveness. Developing it into an effective yet sustainable growth engine still requires more human and environment-oriented consideration.

MANUFACTURING EQUIPMENT

There are many types of manufacturing: chemical, pharmaceutical, electronics, food, metalworking, and so on, with many types of manufacturing equipment. Each type of equipment has its own environmental impact through energy and material consumption. This section will focus mostly on metal cutting machine tools.

To perform the required shaping and forming by a machine tool, large amounts of energy are required. Therefore, when the machine is operating, it consumes a significant amount of energy. Since electrical energy consumption is associated with fossil fuel consumption and emissions, and the machine tool can run for 10 or more years, this energy consumption can have a significant impact. This substantial amount of energy has been shown by Diaz *et al.*[48] to have the largest contribution to the machine tool's environmental impact. Therefore, to reduce the impact of machine tools, it is important to focus on energy consumption. However, focusing on other aspects of the machine can have important impacts as well, e.g., reducing cutting fluid, as mentioned in section 2.

Energy mapping

With much of the environmental footprint of a machine tool being attributed to its energy consumption[48], it has been important to understand how the energy is consumed. From previous studies, it has been found that a significant portion of the energy is not attributed to cutting but to other systems[49]. Dahmus and Gutowski[49] and Kordonowy[50] have shown that with the implementation of automation and the progression of technology, the power demand for machine tools has become more complex, and the cutting power portion has become a smaller percentage of the total. Zhou *et al.*[51] (along with many others) created a power profile of a milling machine by recording power throughout the use of the machine, including starting up, preparing the machine to cut, cutting, and powering off the machine. An example, a power profile for both a milling machine and a turning machine can be found in Figure 3. What was found was that basic power and spindle power are responsible for a significant portion of energy consumption. Behrendt *et al.*[52] monitored the power consumption of various milling machines and divided the power-consuming systems into two categories: constant and variable. The constant category consists of items such as the main switch, hydraulics, servos, doors, and lighting. The authors found that these systems can

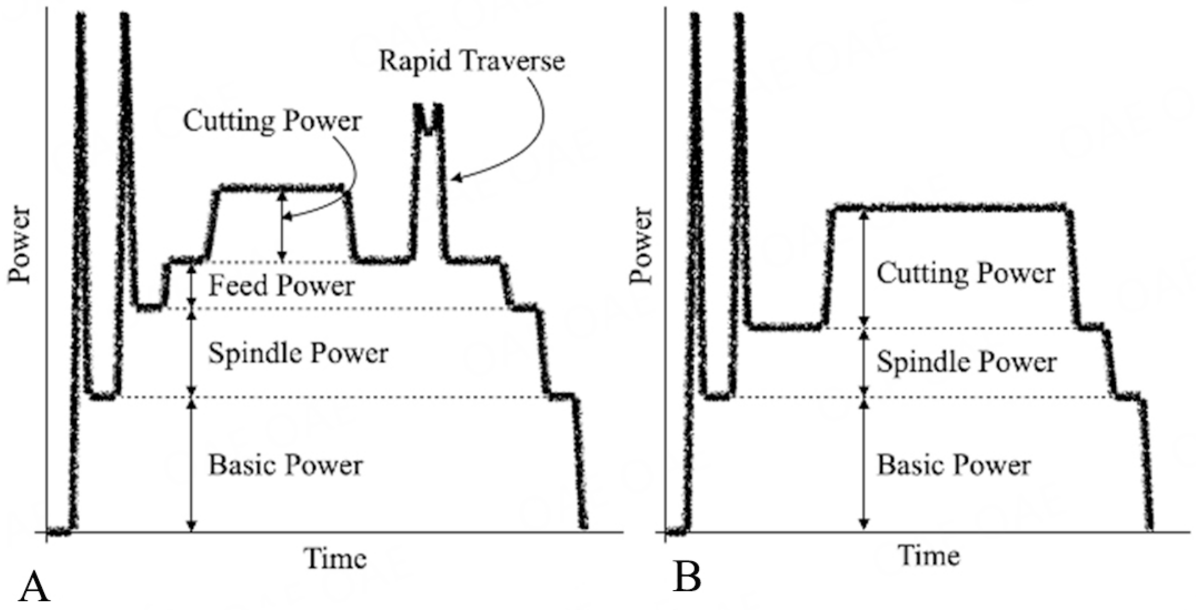

Figure 3. (A) Power profile of a milling machine; (B) power profile of a turning machine. Figure adapted from Triebe *et al.*[54] with permission from Elsevier.

consume the majority of the energy. Li *et al.*[53] investigated the fixed energy consumption of turning machines and found that the major contributors to the fixed energy included the cooling lubricant system, hydraulic system, auxiliary system, and servo drives.

The variable power is accounted for by the cutting power and rapid traverse power (associated with rapid traverse) shown in Figure 3. The cutting power depends on various conditions, including the material of the workpiece, cutting depth and width, cutting speed, the use of cutting fluids, tool wear, and so on. One method of calculating the cutting energy (cutting power × time) is using the specific cutting energy (SCE). SCE can be defined as the amount of energy required to remove a unit of material (J/mm^3). Li and Kara[55] and Kara and Li[56] investigated the relationship between SCE, various cutting parameters, and different materials. They found there is a strong relationship between SCE and the material removal rate (MRR). MRR is defined as the amount of material removed per time (mm^3/s). The authors found that as the MRR increases, the SCE decreases [see Equation. (1)]. Over the years, the modeling of SCE has been investigated more, and more complex models have been proposed. Sihag and Sangwan[19] outline the various models in their review of machine tool energy consumption.

$$SEC = C_0 + \frac{C_1}{MRR} \tag{1}$$

Energy reduction

There has been much investigation into reducing the environmental impact of machine tools, which includes the scheduling of the machines, modifying process parameters, optimizing process plans, and reducing cutting fluid. However, these methods are discussed in the other sections (processes and manufacturing systems). This short section will focus on reducing energy consumption through the design of machine tools.

To reduce the environmental impact of machine tools, there has been a number of design strategies. Albertelli[57] explored the use of a direct drive spindle system to reduce the energy consumption of the spindle. Traditionally, a gearbox-based spindle system has been used; however, Albertelli found energy savings when a chiller, oil pump, and gearbox are not required. Diaz *et al.*[58] explored the energy-saving potential of a kinetic energy recovery system (KERS). This system recovers energy from the deceleration of motors. The authors found that when the KERS was implemented on the spindle of a machine tool, power savings of up to 25% was obtained. Huang *et al.*[59] provided a method to reduce the energy consumption of hydraulic presses by selecting the optimal motors to drive pumps. This method ensures that the load rate of all motors is within the specified range to provide high efficiency. The authors were able to save 26.97% of the energy in a working cycle.

Lightweighting has also been explored as a method of reducing energy consumption. Kroll *et al.*[60] found that a load reduction of 30% can be obtained through the lightweighting of structural components and can lead to a decrease in the electrical power losses of servo drives by up to 50%. Similarly, Triebe *et al.*[54] examined the energy savings by lightweighting the slide table of a milling machine. The authors found savings of up to 38% of the table drive energy. Lv *et al.*[61] explored reducing the inertia of the spindle on a computer numeric control (CNC) lathe. The material of the chuck on the spindle was changed to a lightweight aluminum which reduced the inertia of the spindle from 0.3354 to 0.2380 kg-m^2. This resulted in energy savings of 20.6% and a reduction in peak power by 21.2%. However, with lightweighting, there are concerns about increased vibration and decreased stiffness. To address these concerns, Dietmair *et al.*[62] presented a lightweighting method that encompassed mechanical and electrical systems along with control processes. This method explored the reduction of mass for moving structural components in order to reduce inertia and friction and optimize transmission efficiency. The authors also applied high stiffness-to-mass ratio materials to ensure structural components did not have plastic deformation, wear, or break. Aggogeri *et al.*[63] also explored methods for reducing vibration in lightweighting through various lightweight structures. Some of these structures included aluminum foam and corrugated sandwiches. Suh and Lee*et al.*[64] examined the use of composites for slides in machine tool structures to allow for rapid acceleration and deceleration. The authors were able to decrease the mass of the horizontal and vertical slides while increasing damping and not sacrificing the stiffness.

Future directions for manufacturing equipment

To reduce the environmental impact of manufacturing equipment, the energy performance of the machine should be a higher priority during the design phase. To assist companies in this, a benchmark for energy efficiency assessment and an energy consumption index should be developed[19,51]. The index can be included in the machine tool specification data to allow for better comparison between machines. It will help in the selection of the machine that is best suited for the application. Value stream mapping can also be used to visualize energy consumption and carbon emissions for the different systems of the machine tool[19]. This will allow for a better understanding of how energy is consumed in the machine and assist in the design of more efficient machine tools. More investigation into key factors and their correlation to energy consumption is necessary for more accurate energy models[51]. More experiments for different machine tools are required as well.

Other research topics pertaining to manufacturing equipment include the implementation of energy-efficient components. This includes replacing pneumatic and hydraulic components with electromechanical actuators[65]. Another strategy includes implementing intelligent standby modes to turn off systems that are not needed. There also should be an investigation into how to retrofit existing machines with more efficient components and systems. Another design to consider for improved energy efficiency would be the implementation of hybrid manufacturing processes[66]. There are also opportunities to improve efficiency through lightweight designs, which can include structural optimization that reduces overall mass and improves structural stability. While structural optimization may not directly lead to greater energy efficiency, it improves structural stability, which can indirectly increase energy efficiency. Other research opportunities include reducing transmission losses in drives and motors and implementing the use of energy recovery systems[66]. In addition, currently, there is a gap in the understanding of customer requirements. Bridging this gap will allow for less over-designed machines that will reduce energy loss from inefficient loading of motors and waste energy during idling[19].

MANUFACTURING SYSTEMS

Manufacturing systems are built up of machines and processes and have the goal of producing products. Manufacturing systems can be thought of as a step above processes, where processes are the individual steps to producing products while systems are built up of these steps. Similar to how processes can be improved and designed to become more efficient and less wasteful, systems can similarly be optimized and streamlined. This can include scheduling machines to have less downtime or planning processes to be less wasteful. This section will explore the ways green manufacturing can reduce the environmental burden within manufacturing systems. This will include first the topic of scheduling machines and constructing process plans. Then the focus will shift to strategies for green manufacturing at the enterprise level. Finally, future directions within manufacturing systems will be reviewed.

Scheduling and process planning

Manufacturing scheduling aims to sequence a series of operations and allocate resources (e.g., machines and operators) for each operation in order to deliver products within a specified time frame. Traditionally manufacturing scheduling has been focused on productivity or throughput (for example, makespan has been used as a common performance indicator). Since the selection of machines and the order of operations have effects on energy consumption and resource utilization, manufacturing scheduling can be used as a strategy to improve energy efficiency and environmental performance. Fang *et al.*[67] are one of the first to explore the possibility of including energy and carbon emissions in manufacturing scheduling. Using a hypothetical two-machine flow shop as an example, this study develops a time-indexed multi-objective mixed integer programming to demonstrate the potential trade-off among peak load, makespan, and carbon footprint. Since then, energy-efficient scheduling has attracted increasing interest. Different types of shop floors, electricity rate structures, energy sources, and storage have all been explored[68]. Efforts have also been explored toward developing programming models and solution methods. In addition to energy-related objectives, material efficiency, water intensity, and noise level have also been considered in several studies[14].

Manufacturing process planning chooses the sequence of manufacturing steps to build a product. It differs from scheduling in that process planning plans the processes while scheduling is focused on the machines themselves. Process planning plays a critical role in the cost and environmental footprint of manufacturing. Making proper decisions while planning can greatly affect the overall cost and footprint of a product. To assist, Munoz and Sheng[69] constructed a model for calculating the environmental impact of machining processes. This model examined process mechanics, lubricant, and wear and calculated energy consumption, mass flow, and process rate. Zhao *et al.*[70] proposed an environmentally conscious planning method that identifies impactful process steps and the associated design features within an existing process plan. Then alternative plans that can achieve the same features are generated and then compared and evaluated in terms of environmental and economic performance. These alternative plans are compared using a Pareto front to create a set of non-dominated plans. Guo *et al.*[71] developed a life cycle energy analysis integrated process planning (LCEA-PP) method that considers the energy footprint of a product throughout its life cycle in order to produce energy-efficient process plans. The authors applied this method to the production of steel and aluminum component and were able to identify methods for producing these components that will reduce energy consumption during manufacturing when compared to the traditional manufacturing method. Reiff *et al.*[72] proposed a method to abstract and generalize resources and part descriptions and then match the manufacturing resources to the part descriptions. The resources are ranked based on their cost, required time, and environmental impacts. Multi-criteria decision analysis is then used to evaluate all the possible combinations based on cost, required time, and environmental impact. Jiang *et al.*[73] provided an approach that evaluates the environmental impact of process plans by first producing an inventory for every operation of the plan, then scoring each step, and finally, a normalized score is given for the overall process.

Enterprise

The goal of sustainable supply chains is to transform inputs into outputs with increased financial value while not affecting environmental or social factors[74]. These supply chains take the form of forward supply chains with reduced manufacturing emissions[75] and reverse supply chains (closed loop) that incorporate recycling and remanufacturing to reduce the overall carbon emissions of manufacturing[76-78]. As government entities and consumer preferences lean towards sustainable practices, carbon emission reduction strategies are becoming more prevalent within supply chains. These governmental carbon emission reduction strategies affect how sustainable the supply chains look. Carbon pricing is a cost that producers incur for the number of emissions. Higher carbon pricing incentivizes supply chains to turn to a more closed-loop scenario due to a lower profit with high emissions. The volatility of carbon pricing affects the probability of a company adopting a closed-loop supply chain due to the resulting high volatility for profit[79]. Cap and trade practices reduce emissions by setting limits on emissions for producers that can be traded within industries but never exceeded[78]. This reduction strategy suggests that manufacturers will converge towards carbon emission reduction strategies, and retailers will switch to low-carbon products as carbon credits can be sold on the market[78].

Even with carbon emission reduction strategies in place, supply chains are subject to uncertainties in demand and supply which are increased with the concept of the reverse supply chain. As the use of rare earth elements (REEs) increases as renewable energy practices and electric vehicle use increases, recycling these materials is crucial as some REE supplies are critical[77]. Demand and supply of these recycled materials are subject to volatile variables such as the price of material, recycling extraction rate, feedstock flow rate, etc.[76]. Different approaches have been made to model the demand and supply of these materials for closed-loop supply chains, such as assigning random variables or assigning the variables to behave similarly to mechanical oscillations[76,77]. In addition, a case study in hard disk drive (HDD) recycling highlights the importance of recycling based on the demand for different components within the product. Weights are assigned to components based on the economic value that determines how much demand to fulfill depending on supply[76].

As the public becomes more environmentally conscious due to growing connectiveness with the internet, consumer preference is shifted towards sustainable products in terms of carbon emission reductions[80]. This phenomenon even shifts consumers to pay more for a product that has significant emission reductions. With consumer preference in mind, manufacturers and retailers have another pressure to implement emission reductions to their practices and choose lower emission products respectively[78]. Higher profits for manufacturers selling directly to consumers with lower emissions cause competition between traditional manufacturer-to-retailer supply chains and newer direct online supply chains[80]. This effect can be modeled with the Stackelberg game and suggests higher profits and lower overall emissions for decentralized competition.

Green supply chain optimization can be complex due to both quantitative and qualitative variables as well as having multiple objective functions, as seen in Figure 4[81-83]. Various methods are needed to incorporate economic, environmental, and social aspects to make informed decisions. One approach is to incorporate LCAs within supply chains to include hotspots regarding emissions, land use, and water footprint along the production pathway[83]. In addition, Geographic Information Systems (GIS) assisted data allows for spatial aspects of supply chains to be compared and quantified. In relation to green supply chains, comparing plant locations and sizes to feedstock production locations is crucial for ensuring optimal cost and environmental performance[81,83]. GIS and LCAs implementation within supply chain management allows for complex data such as environmental performance and spatial location to be streamlined and quantitatively compared, and these studies have had success within the biofuel supply chain and plastic recycling studies[75,81-84]. Results for green supply chain optimization problems can follow a singular optimal solution or a Pareto front, depending on the nature of the optimization problem. This adds further complexity to green supply chain problems due to potential indefinite solutions. Should both economic and environmental factors be optimized, or should environmental factors be a constraint within an economic optimization problem? Studies suggest a multi-objective approach, but this comes at the disadvantage of expert analysis of results to suggest an optimal solution[82,85].

Future directions within manufacturing systems

To improve manufacturing scheduling, Fang *et al.*[67] suggest first constructing a simplified model of the shop floor and then designing algorithms that are specialized for this simplified model. The use of a simplified model will provide acceptable schedules with a reasonable computation effort. Akbar and Irohara[14] find through their review that future work is required to include additional sustainability indicators in the objectives of the scheduling models. These can include wastewater discharge, water reuse, harmful gas releases, and packaging material discarded. Social indicators should also be used. Schedules can also consider the various types of renewable energy and the constraints that go along with them. The authors also find that more work is required to expand current scheduling models to encompass a larger manufacturing scale.

Within the area of process planning, more comprehensive approaches should be explored[70]. These should consider all major issues, such as tooling, operating parameters, quality assessment, and fixture design. In addition, currently, a manufacturing expert is required to model the various manufacturing processes for a part, and this can be very time-consuming[72]. One potential opportunity is to reduce this time-consuming step to implement a feature extraction algorithm that suggests possible manufacturing processes and includes required constraints. This would allow for feedback as to the parts' manufacturability, costs, required time, and CO_2 emissions during the design stage. Further, energy and other resource consumption should be monitored through the connection of machine control and sensor systems to automate the quantification of CO_2[72]. This will assist in the development of more LCA databases, and validation of these databases should be scaled up to provide more applicability to real industrial settings. With the introduction of AM, there has been a new set of challenges in process planning. These challenges include choosing the right parameters, such as wire-feed rate and travel speed, as well as deposition paths and generation of layers. These choices affect the quality of the parts, such as the porosity or cracking[86].

The future trends within enterprise focus on the idea of a circular economy (CE) and the future of carbon pricing. Carbon pricing can be viewed as the driving force behind companies adopting carbon-reducing technologies and practices[78]. Cap and trade models adopt the mechanisms of supply and demand within a capitalistic economy and allow for carbon reductions to be made even with an uncertain, fluctuating carbon price[78]. This price can fluctuate, but it incurs different consumer and producer behaviors at different prices[78,80]. At higher prices, companies often choose to invest in carbon-reducing technologies or practices

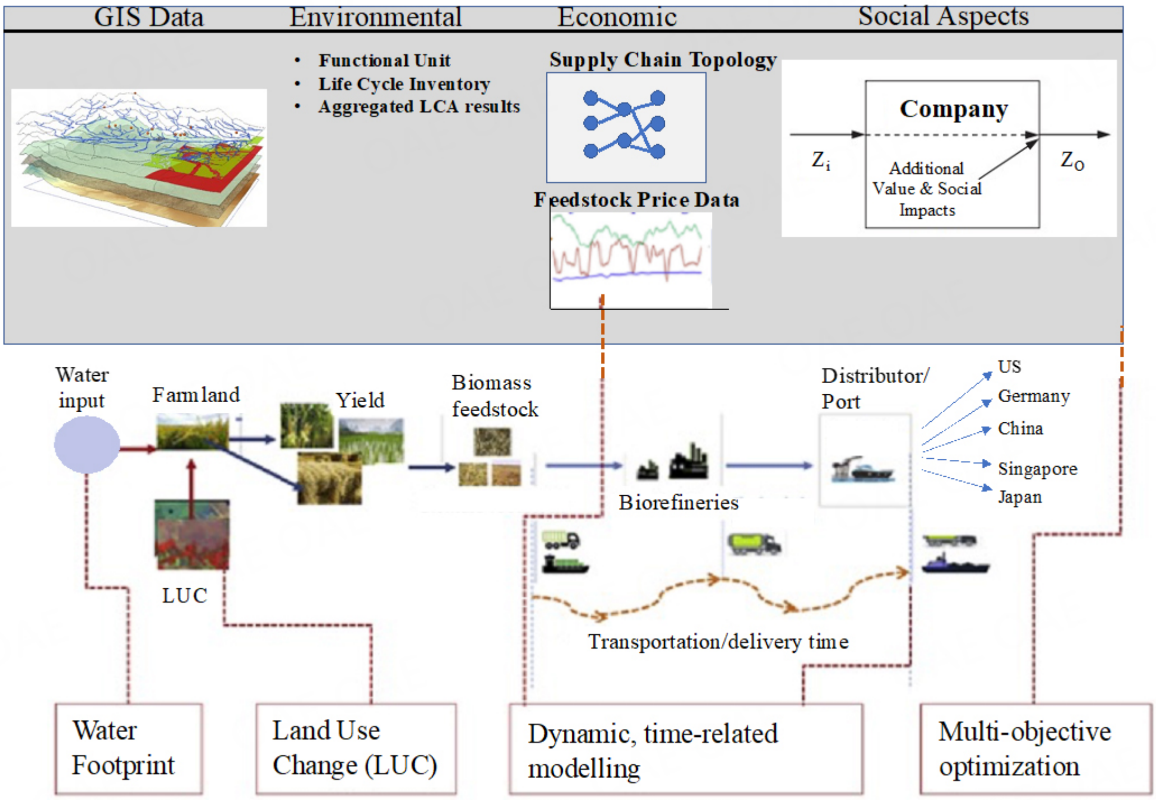

Figure 4. Complex interactions of supply chain multi-objective optimization are shown here. System parameters within supply networks are characterized by topological, economic, environmental, and social features that are dynamic and usually incomparable. Figure adapted from Khoo *et al.*[83] with permission from Elsevier.

such as CE due to the large cost incurred by business-as-usual emissions[78]. At lower prices, companies will be seen buying and selling carbon credits instead of immediately investing in these technologies and practices. Consumers' demand for reduced carbon products is related to the idea of centralized versus decentralized supply chains, and demand rises as carbon pricing increases only within centralized scenarios[80]. These trends impact the future trends of supply chain research due to the increase in carbon pricing strategies within laws and policies. In particular, the practice of a CE is featured in many journal articles and is found to be an immediate solution in lieu of high carbon prices[76-78]. Future trends are dealing with uncertainty within demand and supplies of recovered materials. With recovery technologies still under development, the variance in material recovery for a single product is high, and the influent feedstock of materials also faces uncertainty[76]. For example, REEs within electronics vary in amount and type, in addition to their fluctuating market value and demand which creates uncertainty for return on investment for the practice of a CE.

PROCESSES FOR RECOVERING VALUE AT THE END-OF-LIFE

Eventually, all products come to the point that they can no longer be used, i.e., the end-of-life (EOL). At this point, decisions need to be made as to what to do with the product. Unfortunately, it is very common to dispose of used products as opposed to preserving EOL values through recovery processes such as recycling, remanufacturing, or reusing. However, none of these value recovery routes will be initialized if an EOL infrastructure does not exist in the first place, and the valuable materials or functional content in EOL products could be irretrievably lost. Ideally, such an EOL infrastructure should encompass and coordinate elements, including product collection, upstream disassembly, midstream sorting and processing, and downstream assembly.

To illustrate the role and criticality of the EOL infrastructure, a representative example would be electric vehicles (EVs). The rapid development of EVs calls for the use of batteries and electric motors, which are reliant on such critical materials as REEs (notably neodymium and dysprosium), lithium, and cobalt[87,88]. The increasing demand for lithium-ion batteries (LiBs) and rare earth permanent magnet (REPM) motors leads to supply chain stress for critical materials, which are often geographically concentrated in one or two regions[89]. One seemingly obvious way to reduce the demand for critical materials is to recover and recycle them from EOL vehicles, which is not being practiced at an industrial scale in the US. At present, EOL vehicles end up at dismantlers. The present vehicle EOL infrastructure is not capable of separating and recovering critical materials from vehicles; these valuable resources are irretrievably lost as a waste stream[90]. Given the rapid growth in EVs, there is a risk that the clean energy technologies embedded within EVs will be yet another EOL waste that needs to be managed (like e-waste and single-use plastics)[91]. Moreover, the failure to recover critical materials for EOL vehicles would only add more pressure to the increasing demand for virgin critical materials[92].

Cases like EVs prompt the need for an EOL infrastructure to recover (thus reuse or repurpose) valuable materials from used products. Value recovery of key components will dramatically lessen the need for unsustainable mining, energy-intensive processing, importation of reliant materials, and solid waste disposal. Moreover, it will generate economic value and create jobs. This idea of closing material loops by reclaiming value from EOL products aligns with the concept of CE.

As an alternative to the traditional linear economy (take-make-use-dispose), the CE aims to close material loops by employing sustainable approaches such as maintenance, reuse, refurbishment, remanufacturing, recycling, etc. A CE seeks to increase the share of renewable or recyclable resources while reducing the consumption of raw materials and energy[93]. By closing material loops, CE can extend the useful life of materials that have already been extracted from the ecosphere, as well as minimize emissions and energy leakages[94].

Kirchherr *et al.*[95] concluded that CE is most commonly associated with reuse, remanufacturing, and recycling activities. The specific CE methods to take (e.g., whether to reuse, remanufacture, or recycle) would depend on the categories of products and the specific EOL conditions. An overview of the life cycle of a general product is illustrated in Figure 5, where the conventional linear economy flow is presented by the black arrows, and the CE routes are depicted in green dash arrows.

The ever-growing environmental awareness calls for escalating attention to decarbonization. However, designing circular systems that are truly sustainable would also require an evaluation of the other environmental impact categories, such as acidification, toxicity, eutrophication, and biodiversity loss[96]. In view of this, LCA has been widely applied to identify the environmental hotspots of CE activities[97]. Other methods that can be integrated with LCA approaches include life cycle impact assessment (LCIA), material flow analysis (MFA), and system dynamics[98]. Once the system boundary (“cradle to grave” in linear models, “cradle to cradle” in typical CE models) is specified, the environmental impacts attributed to CE approaches can be quantified by standard/self-defined performance metrics[99].

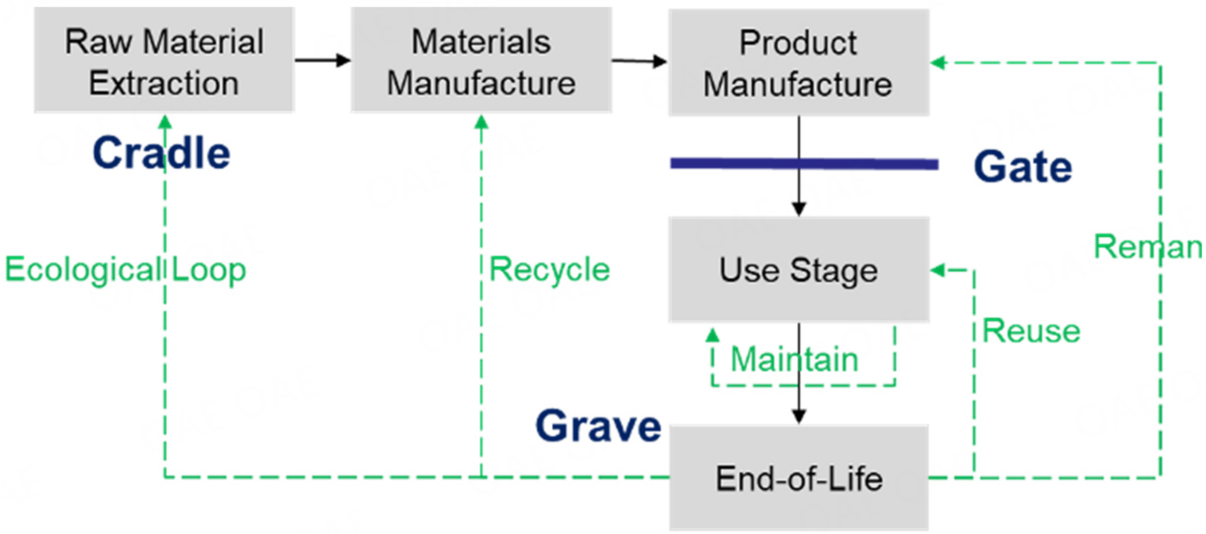

Figure 5. The life cycle of general products.

EOL product management should consider multiple factors (e.g., economic, technical, sociological, and environmental), and the overarching principle in selecting the EOL methods is that products, components, and materials should be kept at the highest utility and value at all times. A hierarchy chart for selecting EOL treatments is presented in Figure 6.

According to Mathur *et al.*[91], direct reuse (of the entire product, subassemblies, or individual components) is always preferable compared to other remanufacturing and recycling. For example, an investigation carried out by Richa *et al.*[100] revealed that around the EOL phase of an EV as a whole, the lithium-ion battery can still preserve 70%-80% of its original capacity and, therefore, may still be usable for another EV or other power storage applications. Nevertheless, it should be noted that reuse is only possible for certain products and requires the least amount of energy and materials.

Although CE may encompass every phase throughout product lifecycles, this review paper will concentrate on EOL-oriented CE approaches, as EOL products tend to generate significant waste and constitute tremendous value loss. The remainder of this section will first examine some representative EOL processes, including disassembly, remanufacturing, and recycling. A dedicated discussion will then follow on the role of CE in addressing the supply risks of critical materials (which are essential to advanced manufacturing). Toward the end of this section, an overview of future trends in EOL management will be provided.

Disassembly and demanufacturing

Demanufacturing refers to the disassembly of a product to its individual components/parts, which will further be reused, remanufactured, or recycled[101]. The level of disassembly is dependent on the selected downstream CE approaches. Take the recycling for Lithium batteries as an example: pyrometallurgical recycling can begin at the module level, whereas hydrometallurgical recycling requires disassembling to the cell level[102].

According to the research done by Cong *et al.*[103,104], a demanufacturing process can be characterized by a transition matrix and a succession matrix. The transition matrix presents all the possible routes a product can be disassembled through, both non-destructive disassembly and destructive disassembly. The

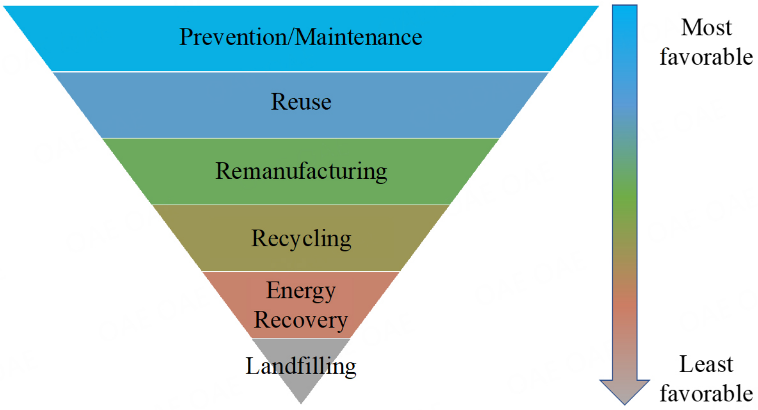

Figure 6. Waste treatment hierarchy.

succession matrix, on the other hand, describes possible transitions between operations. Based on the transition and succession matrices, a mathematical model can be established to optimize the demanufacturing process, where the environmental impacts can be accounted for by defining pertinent optimization criteria.

One common challenge in designing disassembly systems is the uncertain quality or state of EOL products, which heightens the need for flexible process planning[105]. With respect to the applications in the EV industry, disassembly can be optimized through disassembly sequence planning (DSP)[106], lean principles (line balancing)[107], as well as other analytical tools. Deng *et al.*[108] implemented a stochastic activity network (SAN) to model a remanufacturing workflow that can directly rebuild used EVs into "new" EVs, where the initial disassembly process was discovered to be a major bottleneck that hinders the operational performance at a system level.

In pursuit of an optimal disassembly sequence, environmental impact is another critical factor to consider. Alfaro-Algaba and Ramirez[109] proposed a multi-objective optimization model that balances the trade-off between economic profit and environmental impact in disassembly processes and the recovery procedures for the disassembled components. In this study, the environmental impact of each individual step is quantified by means of the Eco-indicator 99 methodology. The environmental sub-objective function is defined as the difference between the environmental impact avoided due to CE approaches (reuse, remanufacturing, or recycled) and the environmental impact caused by the disassembly processes. The model was able to generate the optimal level for the disassembly process achieving the maximum profit while minimizing the environmental impact.

Remanufacturing

If a product reaches an EOL condition such that it cannot be directly reused, the next option is to pursue remanufacturing approaches. According to Ortegon *et al.*[110], remanufacturing refers to the process of returning a used product (nonfunctional, discarded, or traded in) to at least the original design performance/specification. A remanufactured product is assembled using a combination of reused, repaired, and replaced parts[111]. Motivations for a company to remanufacture include profit, high demand for parts, brand protection, and long lead times to manufacture new parts[112]. In addition, remanufacturing can also reduce the environmental impact of the product.

The environmental benefits derived from remanufacturing are quantified by the energy savings, and CO_2 avoided when extending the useful life of a product[113]. These benefits are a result of preserving both material and functional values from core components[114]. Adler *et al.*[115] found that the energy required to remanufacture metal parts for a Caterpillar diesel engine ranged from 51% to 55% of the energy required for original manufacturing. Other studies[116-118] have reported energy savings for other industries – including automotive (68%-83%), tires (66%-68%), and appliances (14%-44%)-as well as CO_2 savings for automotive (73%-87%) and photocopiers (23%).

For clean energy technologies such as wind turbines, remanufacturing is envisioned as an opportunity to concomitantly reduce virgin material consumption, preserve embodied energy, and reduce the carbon footprint relative to new installations. In an investigation undertaken by Ortegon *et al.*[113], the energy saving from remanufacturing wind turbines is expected to be 5 million MJ per unit, which is equivalent to 70% of the total energy consumption from new production. On the carbon footprint front, it was shown that remanufacturing would avoid 862,656 kg of CO_2 per wind turbine.

Recycling

Under certain circumstances, it could be too difficult or expensive to remanufacture certain EOL products compared with producing new products from raw materials. Under such circumstances, we can resort to recycling. Recycling refers to the processes that convert products back into materials that can be used for a new product, and it is by far the most practiced CE strategy[1]. Recycling activities provide means to separate and recover individual materials from integrated EOL products, thus generating a secondary supply source of raw materials. While remanufacturing can preserve a high degree of the functional value of a product, recycling only retains the material value. Therefore, in terms of the waste management hierarchy, recycling is a less attractive option compared to reuse and to remanufacture.

Nevertheless, recycling still has a key role to play in EOL management, as it promotes economic and environmental sustainability by reducing raw material input and redirecting EOL output back into material loops[119]. Compared to waste disposal (e.g., incineration and landfilling), recycling can not only save potentially useful and precious materials (i.e., critical materials) but also help reduce energy use and pollution (especially when primary/virgin production is energy-intensive)[94]. A case in point would be electronics. The material recovered from secondary feedstocks, such as waste printed circuit boards (PCBs), generally entails significant reductions in embodied energy and CO_2 emissions relative to virgin materials production, which alleviate the environmental burden caused by improper e-waste management[120].

It should be noted that the primary resources and recycled materials are only different stages in the material flow of the product life cycle, which are intercorrelated. To reduce environmental impacts, decision-makers must strike a balance between the utilization of primary and recycled resources, and the optimal distribution varies by product[99].

Applying CE to mitigate the supply risks of critical materials

In particular, with respect to critical materials, the implementation of CE strategies is expected to present a systematic solution to alleviate potential sociopolitical supply risks, as well as the associated environmental burdens. Sutherland *et al.*[121] proposed that CE strategies have a wide range of applications in clean energy industries, including recycling neodymium and dysprosium from used wind turbines and EVs, recovering tellurium, gallium, and indium from EOL PV solar panels, and reusing worn batteries to reduce the consumption of lithium, cobalt, and nickel. Gaustad *et al.*[122] have conducted a comprehensive literature review combined with case studies (e.g., Volkswagen and General Electric) to provide specific business examples for integrating circularity principles.

To address the imbalance in supply and demand of critical materials, instead of only focusing on virgin material production using new sources of materials (whether they are critical materials or substitutes), another perspective to consider is to use available materials more efficiently by reducing the waste in manufacturing processes and to increase the adoption of recovery activities[123]. Prevalent recycling and reuse of critical materials could provide additional supply resources and significantly lower the global demand for raw materials. In addition, the enormous environmental concerns associated with the extraction and processing of ores containing these materials (especially rare earths) also encourage nontraditional feedstocks such as waste streams[124]. For example, Arshi *et al.*[125] concluded that the recycling of magnets had a significantly lower environmental impact compared to virgin production as it drastically reduces the amount of wasted neodymium.

As summarized by Akcil*et al.*[126], to date, only a very small proportion of the total critical materials in used and obsolete components are being recycled (i.e., 1% for REEs). Accordingly, there is a need and growing trend for researchers to investigate new technologies to recover materials from used electrical products, EOL energy storage systems, and other secondary resources through recycling. Since the acquisition of the feedstock for these approaches can serve as the waste management for other more conventional processes, successful industrial implementations of these recovery techniques can also enable or strengthen the co-production among different manufacturing sectors[127].

The studies on REE recovery are exemplary in this direction of research endeavors. In a comprehensive review of the state of the art of rare earth recovery, Binnemans *et al.*[128] stated that conventional REE recovery methods largely depend on hydro-metallurgical or pyro-metallurgical approaches. As Priya and Hait[129] remarked, a major drawback of these conventional approaches is the generation of secondary hazardous waste streams, e.g., large amounts of acid wastewater. This kind of waste stream is not compatible with the environment and raises undesirable ecological concerns, which contradicts the original motivation behind these interventions. In response to this, recent studies have started to transition to bio-metallurgical techniques. As Brierley *et al.*[130] highlighted in an investigation, microbiology approaches tend to be eco-friendly and energy efficient and are unlikely to generate secondary hazardous waste streams. As a representative study in biosorption, Brewer *et al.*[131] developed a novel biosorption-based flow-through process for selective REE recovery from electronic wastes. With regard to bioleaching, Reed *et al.*[132] and Thompson *et al.*[133] have studied the opportunities to recover REEs from waste phosphors and cracking catalysts using biolixiviant produced from Gluconobacter-oxydans-strain.

Aside from inventing foundational processing technologies that enable material recovery, other efforts are devoted to systematically renovating the life cycle structure of products that rely on critical materials. The waste of critical materials can be alleviated by addressing any phase of a product's life cycle, whether it be the design stage, raw material extraction, production, use, or EOL[134]. Such efforts could involve improving product design. Cong *et al.*[135] put forward a market-driven design approach to overcome the difficulties in recyclability, reduce disassembly times, ensure the quality of recovered components, and reduce the cost incurred during manufacturing and assembly. In addition, the challenge involved in the collecting, transporting, and disassembly of EOL products (which are prerequisites for downstream material recycling) also galvanizes investigations. For example, Cong *et al.*[103] also inquired into the dismantling operations of used HDDs for rare earth permanent magnet (REPM) recovery.

In a more macro sense, researchers have attempted to establish integrated/comprehensive EOL infrastructures that are focused on closing the material loops within the life cycle of a certain type of product. Mathur *et al.*[136] used a multi-objective optimization model to estimate the industrial symbiotic network results of EoL photovoltaic modules. In an investigation to advance EOL vehicle recovery, Kumar and Sutherland[137] presented a model that integrates the requirements of recovery efficiency and related economic constraints to understand the complex interaction among the business entities within the automotive recovery eco-system, based on which improvement strategies are proposed to achieve better overall economic performance. In terms of the EOL management for EVs, Deng *et al.*[108] put forward a holistic CE system for rebuilding/renewing used EVs and extracting maximum value from EOL components and materials. For a pioneer study in the PV industry, Choi and Fthenakis[138] proposed a holistic framework to provide decision-making guidelines to establish an economically feasible and environmentally viable PV recycling infrastructure at a system level.

End-of-life future trends

The traditional "take-make-dispose" linear economy has been successful in generating material wealth and improving social welfare since the first industrial revolution[139]. However, this model has been found to be hardly sustainable in the new millennium considering the ever-growing world population and the depletion of natural resources. Alternatively, CE has been proposed to fill the gap between the exhaustion of and the growing demand for materials[140]. In this part, we will discuss the future trends of CE.

The extensive literature review done by Kara *et al.*[1] led to the conclusion that CE might be helpful in addressing the material challenge, but research and innovation efforts are advised to pursue the following directions: (i) core technologies and methodologies; (ii) product development; (iii) business models; and (iv) socio-institutional change[1]. Nevertheless, the authors indicated that mere material recycling could also be problematic due to high energy intensity and contaminated materials. In fact, the 3Rs initiatives, i.e., reduce, reuse, recycle, were introduced by Japan at the G8 Summit in 2004[141]. Recently, these research strings have been extended into a framework with 9Rs, which are refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle, and recover[142].

One of the most discussed topics in correlation with CE is Industry 4.0. Industry 4.0 integrates manufacturing operation systems and information and communication technologies (ICT) and is a salient route to gaining a sustainable development advantage[142,143]. Rosa *et al.*[144] argued that the combination of CE and Industry 4.0 represents two industrial paradigms that have the potential to enable new natural resource strategies. Bag *et al.*[145] developed a theoretical model linking key resources for Industry 4.0 to motivate manufacturers to focus on smart manufacturing and CE in developing countries. Wu *et al.*[146] decomposed the black box of deep neural networks and proposed a method with layer-wise relevance propagation (LRP) technique which can be used for predictive maintenance using vibration data.

While tackling environmental concerns, social sustainability cannot be overlooked[94]. Padilla-Rivera *et al.*[147] found that social aspects are relevant in CE since they can provide an overview of how the economic model can impact and benefit society but also how this concept is perceived. The selection of social CE indicators was proposed using the fuzzy Delphi method[148]. The biophysical and social perspective of CE was examined by Moreau *et al.*[149], revealing the lack of social and institutional dimensions in the current CE framework. Multiple strategies toward CE, such as shifting the bulk of taxes from labor to resource consumption, are reviewed. Moreover, political processes are suggested to help build a more equitable CE.

ADDITIONAL THOUGHTS

In addition to processes, systems, and EOL, there are other important topics within green manufacturing. These include metrics and indicators, techno-economic analysis, and efficiency and effectiveness. These three topics will be discussed here, and their importance to green manufacturing.

Metrics and indicators

According to Reich-Weiser *et al.*[150], sustainable manufacturing is composed of 3 main components: (i) selection and application of appropriate metrics; (ii) completion of comprehensive and repeatable LCAs; and (iii) adjustment/optimization of the system to minimize environmental impacts and cost based on the chosen metrics and the LCAs. However, there is a lack of measurement science and a baseline to measure and effectively compare the environmental performances of manufacturing processes and resources with respect to sustainability[151]. Evaluating and improving the sustainability performance of manufacturing processes and systems requires qualitative and quantitative metrics. These metrics help to improve decision-making criteria when optimizing process and system designs[152]. One major obstacle in developing absolute measures for sustainability is the absence of a well-defined approach to characterize sustainability for manufacturing. There are a number of indicators for sustainability, which include indicators based on environmental management, economic growth, social well-being, and technological advancement. A summary of these can be seen in Table 2.

Several tools and metrics have been developed to measure the environmental impact of a product from the life cycle perspective of the whole production chain. Carbon footprint is a metric that has gained prominence[160]. Laurent *et al.*[161] investigated the validity of carbon footprint as a performance indicator for product manufacturing. Their goal was to see if there was any correlation between the carbon footprint and other types of environmental impacts like human toxicity impacts. Singh *et al.*[162], in their review of broad sustainability assessment methodologies, list 41 sustainability indicators that have been proposed globally and find that only a few of the surveyed indices actually consider each pillar of sustainability, and most focus on a single pillar. They group environmental indices into (i) eco-system indices such as living planet index (LPI) and ecological footprint (EF); (ii) environmental indices for policies, nations, and regions such as environmental quality index and environmental sustainability index; and (iii) environmental indices for industries such as eco-points and eco-indicator 99.

Sarkar *et al.*[163] found that numerous indicator sets have been devised to analyze and score sustainable manufacturing. However, they note that this has created difficulty in selecting the appropriate set. In their paper, they present a sustainability indicator repository, called Sustainable Manufacturing Indicator Repository (SMIR), that is based on 5 dimensions of sustainability: environmental stewardship, economic growth, social well-being, technological advancement, and performance management. The motivation for the repository is to provide an organized set of centralized, web-based, open, and neutral indicators that can be accessible by small and medium size manufacturing enterprises. Reich-Weiser *et al.*[150] developed a methodology to evaluate key metrics for energy use, CO_2 emissions, and resource consumption. Their goal was to provide manufacturing engineers and scientists with a set of tools with which they can better design and characterize sustainable manufacturing systems.

Haapala *et al.*[18] provide a literature review evaluation of manufacturing environmental performance metrics. They note that the most commonly used approach by manufacturers is an Environmental Management System (EMS). The authors define an EMS as 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. They further mention that LCA is the most common method for the environmental impact evaluation of manufactured products.

Techno-economic assessment

Manufacturing processes need to be optimized towards minimal environmental impact and maximum economic value. As we have already discussed the metrics associated with environmental impacts, our

Table 2. Summary of publicly available sets of sustainability indicators

Sustainability indicators	Purpose	Reference
Dow Jones sustainability index (DJSI)	Used to assess the financial and sustainability performance of the top 10% of the companies in the Dow Jones Global Total Stock Market Index	[153]
OECD core set of environmental indicators (OECD Env)	Includes about 50 indicators, which cover a broad range of environmental issues and economic data to track pressures on the environment and responses by governments, industry, and households	[154]
Ford product sustainability index (FORD's PSI)	Has 8 indicators that consider environmental, economic, and societal aspects	[155]
General motors metrics for sustainable manufacturing (GM M4SM)	Includes 30 metrics considering environmental impact, energy consumption, personal health, occupational safety, waste management, and manufacturing costs aspects	[156]
Environmental pressure indicators for the European Union (EPI-EU)	Contains 60 indicators giving an overview of the pressure of human activities on our environment in 10 policy fields covering air pollution, climate change, biodiversity, and dispersion of toxic substances	[157]
United Nations commission on sustainable development indicators (UN-CSD)	Set of 50 indicators under 14 different themes that provide guidance on applying and adapting to sustainable development	[158]
Walmart sustainability product index questions (Walmart Qs)	Designed to help customers to make purchase decisions and to encourage suppliers to meet sustainability requirements	[159]

attention now shifts to the economic side of sustainable manufacturing. During the early stages of technology development, there is more flexibility in adapting the technology. Therefore, a techno-economic assessment (TEA) is required. Techno-economic analysis, or techno-economic assessment, oftentimes abbreviated as TEA, is a method to analyze the economic performance of processes in industries[164]. The prospective assessment differs at the different stages of technology development defined by the Technology Readiness Levels (TRL), ranging from 1 to 9[165].

Although the number of published TEAs has increased steadily over the years, methodological discussions are still rare. In general, the methodology is based on cost engineering estimate practices and cost-benefit analyses. Van Dael *et al.*[166] provided a general methodology for TEA based on current procedures. They describe 4 major steps of a TEA: (i) market study to determine prices and market volumes; (ii) process flow diagram and mass and energy balance calculations; (iii) economic analysis, e.g., net present value (NPV), or the internal rate of return (IRR); and (iv) risk analysis to assess the influence of uncertainty on the indicators.

Other methods, such as LCC have been used as well to assess the economic potential of product manufacturing. A major downside of LCC is that it excludes important costs such as labor and equipment costs, greatly affecting the overall results. Moreover, LCC focuses more on the total cost distribution of the product over its total life cycle, while TEA analyses the economic profitability from an investor's perspective.

Several studies apply TEA to investigate the economic feasibility of manufacturing processes. Thompson *et al.*[133] used TEA to assess the potential of applying bioleaching to the practical recovery of critical metals from industrial and post-consumer wastes. Huang *et al.*[167] used TEA to evaluate the economic performance of a novel technology to extract lithium from geothermal brine using lithium-aluminum-layered double hydroxide chloride (LDH) sorbent and forward osmosis. Deng *et al.*[77] acknowledged that several TEAs have been conducted to evaluate innovative approaches to recover REEs from waste streams. They note, however, that most of these studies do not consider the price volatility of REEs, which raises concern over the reliability of the analysis in an unpredictable dynamic market. They thus propose a dynamic price model to simulate a dynamic market behavior and investigate its effect on TEA.

From efficiency to effectiveness

Throughout this paper, there have been a number of examples of reducing environmental impact and energy consumption through increased efficiency; however, there is a need for a discussion regarding effectiveness and its role in green manufacturing. Much focus within green manufacturing is on efficiency, as is evident throughout this paper. However, effectiveness can be of equal importance.

Efficiency focuses on achieving the outcome with the least amount of energy, time, and effort and the lowest amount of waste, while effectiveness focuses on identifying the outcome with the best use of resources[168]. Efficiency may focus on a specific manufacturing process, but effectiveness will have a broader focus that can include the entire system. For example, efficiency will focus on Scope 1 or Scope 2 energy (consumed onsite in a manufacturing process), while effectiveness will have a broader focus that may include Scope 3 energy (embodied energy). Below is a description of the three scopes of energy:

- → Scope 1: Energy that is generated onsite at a facility and used in a process, e.g., using methane as a fuel to heat a furnace.

- → Scope 2: Energy transported to a facility in the form of electricity or steam that is consumed in a process.

- → Scope 3: Embodied energy of all materials, chemicals, and equipment used in support of a manufacturing operation and is at least partially consumed due to the manufacturing operation.

Understanding the different scopes of energy for a product and making design and manufacturing changes based on that understanding can more effectively reduce energy consumption than when focusing on a specific process. For example, a machine tool uses electricity as the energy source, and the electricity may come from a coal power plant many miles away. To produce and transmit the power, there are a number of losses. Even to turn that electricity into useful power within the machine tool, there are a number of losses. Below is an example of a fictitious efficiency chain adapted from Shade and Sutherland[168].

$$100\ units\ fuel\ (coal) \rightarrow \underset{30\%}{e_{power\ plant}} \rightarrow \underset{91\%}{e_{transmission}} \rightarrow \underset{90\%}{e_{motor}} \rightarrow \underset{98\%}{e_{drivetrain}} \\ \rightarrow \underset{25\%}{e_{pump}} \rightarrow \underset{67\%}{e_{throttle}} \rightarrow \underset{20\%}{e_{pipe}} \rightarrow 9.7\ units\ useful\ work$$

In this example, fuel, in the form of coal, is provided to a coal power plant with an efficiency of 30%. The electricity generated is transmitted to the manufacturing plant, and a number of losses occur due to chained efficiencies. In the end, 9.7% of the energy is useful. Similar losses are illustrated by the Advanced Manufacturing Office[169], in which about 61% of all energy in manufacturing is lost. This includes sources of offsite fuel, offsite steam generation, onsite renewable energy, and offsite electricity generation. In the case of manufacturing a product with a machine tool, reducing energy consumption by improved efficiency could happen through improving the manufacturing process, while reducing energy consumption through effectiveness could occur by changing the manufacturing process or changing the design of the product.

Future directions

From earlier discussions, it is apparent that developing metrics for green manufacturing is critical to enable manufacturing companies to quantitatively measure their sustainability performance. It is evident that some of the metrics proposed for green manufacturing are quantitative and easily measured, while others are difficult to conceptualize. There is a lack of consistency in combination with several competing methods to measure even relatively simple concepts such as energy efficiency[170]. Cohen *et al.*[171] propose the compilation of all metrics in use for green manufacturing. Thereafter, develop a process to analyze and select among the variety of environmental sustainability indicators tentatively proposed by governments, corporations, and other organizations with the objective of arriving at a specific, valid, robust, and parsimonious set of measures. This would eliminate redundancy and facilitate decision-making.

The increasing competition among businesses has led to a growth in the use of TEA. One major challenge with TEA is the lack of accessibility to data required for input parameters or the lack of advanced computational tools for concise estimation. Chai *et al.*[164] propose the integration of data-driven technologies, i.e., genetic algorithm (GA), blockchain, machine learning (ML), artificial neural network (ANN), Internet of Things (IoT), cyber-physical system (CPS), digital twin (DT), metaverse, cloud computing, and big data analytics to optimize both process and economic parameters concurrently.

SUMMARY AND CONCLUSIONS

With the increased environmental harm from society and its role in climate change, it is important for every part of society to respond, including manufacturing. Manufacturing has a great opportunity due to its significant environmental burden to limit climate change. There exists an encompassing opportunity across the entire manufacturing enterprise, including efficient usage of energy and material resources; this encompassing opportunity is known as green manufacturing. The implementation of green manufacturing will impact all stages of the life cycle, not only the manufacturing stage.

With green manufacturing becoming an extremely popular topic, the authors felt it was important to provide their perspective as to some of the key areas within green manufacturing and their future trends. To do this, the authors provided a review and discussion of the critical topics and future directions. The paper first looked at methods for reducing manufacturing process energy consumption and waste with a focus on the emerging field of smart manufacturing. The environmental impacts of manufacturing processes were examined, and methods to reduce the impact were reviewed, including cutting fluid technologies, AM, and EMS. Further investigation into these technologies and strategies is required to understand their impacts throughout the life cycle, e.g., confirming the life cycle environmental benefits of AM. The potential role of smart manufacturing within green manufacturing was also examined. For the full potential of smart manufacturing to be realized, smart technologies should be employed throughout each life cycle step.

Following the discussion over smart manufacturing, the environmental impact of manufacturing equipment, specifically machine tools, was examined along with work to reduce that impact. Due to the significant energy consumption of machine tools, methods to reduce that energy consumption were surveyed, including the implementation of energy recovery components, lightweight designs, and energy-efficient systems. Then, the focus of the paper was expanded to manufacturing systems, including strategies for scheduling and process planning with their future directions of incorporating social indicators when constructing schedules and plans. Within manufacturing systems, the enterprise level was examined, and it was found that CE and carbon pricing are needed to drive carbon-reducing technologies and practices.

The paper further expanded its focus to include a deep dive into EOL and the benefits of CE. Future work includes expanding beyond the traditional 3 Rs (reduce, reuse, and recycle) and including social sustainability. Finally, additional thoughts on related topics, including metrics, TEA, and energy and effectiveness, were provided. Currently, there is a lack of consistency in metrics. With TEA, a major challenge includes the accessibility of data. Incorporating green manufacturing through these topics will provide a significant reduction in the environmental burden of manufacturing.

Key findings from this paper for future directions in green manufacturing research for discrete products include the following:

- → Continued advances in coolant reduction during cutting;
- → Detailed evaluation of the life cycle impacts and cost of Addit Manuf;
- → More human and environment-oriented consideration for smart manufacturing;
- → Energy mapping in manufacturing equipment;
- → Considerations of social indicators and renewable energy in scheduling and process planning;
- → Carbon pricing to drive carbon-reducing technologies and practices;
- → Integration of Industry 4.0 and circular economy;
- → Incorporation of social and institutional dimensions in the circular economy;
- → And consistency in the ability to measure and conceptualize metrics and indicators.

DECLARATIONS

Authors' contributions

Made substantial contributions to the conception and design of the paper and wrote portions of the paper: Triebe MJ
Wrote portions of the paper: Deng S, Pérez-Cardona JR, Joung BG, Wu H, Shakelly N, Pieper JP, Zhou X, Maani T
Wrote portions of the paper and provided feedback: Zhao F
Provided feed and funding: Sutherland JW

Availability of data and materials

Not applicable.

Financial support and sponsorship

The authors gratefully acknowledge the support of the Army Research Laboratory accomplished under Cooperative Agreement Number W911NF-20-2-0189; the Critical Materials Institute (CMI) accomplished under Contract No. DE-AC02-07CH11358; the Ford Motor Company; Wabash Heartland Innovation Network (WHIN) grant at Purdue University; and The United States Department of Energy (DOE) Bioenergy Technologies Office (BETO). The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Army Research Laboratory or The United States Government. The United States Government is authorized to reproduce and distribute reprints for Government purposes, notwithstanding any copyright notation herein.

Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Copyright

REFERENCES

1. Kara S, Hauschild M, Sutherland J, Mcaloone T. Closed-loop systems to circular economy: a pathway to environmental sustainability? *CIRP Annals* 2022;71:505-28. DOI
2. Pye K, Blott SJ, Forbes N, Maskell LC. Geomorphological and ecological change in a coastal foreland dune system, Sandscale haws, Cumbria, UK: the management challenges posed by climate change. *J Coast Conserv* 2020:24. DOI
3. Use of energy in explained - U.S. energy information administration (EIA). Available from: https://www.eia.gov/energyexplained/use-of-energy/ [Last accessed on 28 Mar 2023].
4. Duflou JR, Sutherland JW, Dornfeld D, et al. Towards energy and resource efficient manufacturing: a processes and systems approach. *CIRP Annals* 2012;61:587-609. DOI
5. OECD. About sustainable manufacturing and the toolkit. Available from: https://www.oecd.org/innovation/green/toolkit/aboutsustainablemanufacturingandthetoolkit.htm [Last accessed on 28 Mar 2023].
6. Hauschild M, Dornfeld D, Hutchins M, Kara S, Jovane F. Sustainable manufacturing. In: Laperrière L, Reinhart G, editors. CIRP encyclopedia of production engineering. Berlin: Springer Berlin Heidelberg; 2014. pp. 1208-14. DOI
7. Pimenov DY, Mia M, Gupta MK, et al. Resource saving by optimization and machining environments for sustainable manufacturing: a review and future prospects. *Renew Sust Energ Rev* 2022;166:112660. DOI
8. Bhatt Y, Ghuman K, Dhir A. Sustainable manufacturing. Bibliometrics and content analysis. *J Clean Prod* 2020;260:120988. DOI
9. Machado CG, Winroth MP, Ribeiro da Silva EHD. Sustainable manufacturing in industry 4.0: an emerging research agenda. *Int J Prod Res* 2020;58:1462-84. DOI
10. Malek J, Desai TN. A systematic literature review to map literature focus of sustainable manufacturing. *J Clean Prod* 2020;256:120345. DOI
11. Sartal A, Bellas R, Mejías AM, García-collado A. The sustainable manufacturing concept, evolution and opportunities within industry 4.0: A literature review. *Adv Mech Eng* 2020;12:168781402092523. DOI
12. Sharma R, Jabbour CJC, Lopes de Sousa Jabbour AB. Sustainable manufacturing and industry 4.0: what we know and what we don't. *JEIM* 2021;34:230-66. DOI
13. Zarte M, Pechmann A, Nunes IL. Decision support systems for sustainable manufacturing surrounding the product and production life cycle – a literature review. *J Clean Prod* 2019;219:336-49. DOI
14. Akbar M, Irohara T. Scheduling for sustainable manufacturing: a review. *J Clean Prod* 2018;205:866-83. DOI
15. Gbededo MA, Liyanage K, Garza-reyes JA. Towards a life cycle sustainability analysis: a systematic review of approaches to sustainable manufacturing. *J Clean Prod* 2018;184:1002-15. DOI
16. Moldavska A, Welo T. The concept of sustainable manufacturing and its definitions: a content-analysis based literature review. *J Clean Prod* 2017;166:744-55. DOI
17. Hartini S, Ciptomulyono U. The relationship between lean and sustainable manufacturing on performance: literature review. *Procedia Manuf* 2015;4:38-45. DOI
18. Haapala KR, Zhao F, Camelio J, et al. A review of engineering research in sustainable manufacturing. *J Manuf Sci Eng* 2013;135:041013. DOI
19. Sihag N, Sangwan KS. A systematic literature review on machine tool energy consumption. *J Clean Prod* 2020;275:123125. DOI
20. Zhao F, Ogaldez J, Sutherland JW. Quantifying the water inventory of machining processes. *CIRP Annals* 2012;61:67-70. DOI
21. Pervaiz S, Kannan S, Kishawy HA. An extensive review of the water consumption and cutting fluid based sustainability concerns in the metal cutting sector. *J Clean Prod* 2018;197:134-53. DOI
22. Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR. Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! *Int J Life Cycle Assess* 2012;17:242-51. DOI
23. Kellens K, Dewulf W, Overcash M, Hauschild MZ, Duflou JR. Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)-CO2PE! *Int J Life Cycle Assess* 2012;17:69-78. DOI
24. Overcash M, Twomey J, Kalla D. Unit process life cycle inventory for product manufacturing operations. In: ASME 2009

International Manufacturing Science and Engineering Conference; 2009 49-55. DOI

25. Patterson M, Singh P, Cho H. The current state of the industrial energy assessment and its impacts on the manufacturing industry. *Energy Rep* 2022;8:7297-311. DOI
26. Diaz N, Redelsheimer E, Dornfeld D. Energy consumption characterization and reduction strategies for milling machine tool use. In: Hesselbach J, Herrmann C, editors. Glocalized Solutions for Sustainability in Manufacturing. Berlin: Springer Berlin Heidelberg; 2011. pp. 263-7. DOI
27. Mori M, Fujishima M, Inamasu Y, Oda Y. A study on energy efficiency improvement for machine tools. *CIRP Annals* 2011;60:145-8. DOI
28. Matsunaga F, Zytkowski V, Valle P, Deschamps F. Optimization of energy efficiency in smart manufacturing through the application of cyber-physical systems and industry 4.0 technologies. *J Energy Resour Technol* 2022;144:102104. DOI
29. Adler DP, Hii WW, Michalek DJ, Sutherland JW. Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns. *Mach Sci and Technol* 2006;10:23-58. DOI
30. Supekar SD, Graziano DJ, Skerlos SJ, Cresko J. Comparing energy and water use of aqueous and gas‐based metalworking fluids. *J Ind Ecol* 2020;24:1158-70. DOI
31. Rejeski D, Zhao F, Huang Y. Research needs and recommendations on environmental implications of additive manufacturing. *Addit Manuf* 2018;19:21-8. DOI
32. Faludi J, Bayley C, Bhogal S, Iribarne M. Comparing environmental impacts of additive manufacturing vs. traditional machining via life-cycle assessment. *Rapid Prototyp J* 2015;21:14-33. PubMed
33. Le VT, Paris H, Mandil G. Environmental impact assessment of an innovative strategy based on an additive and subtractive manufacturing combination. *J Clean Prod* 2017;164:508-23. DOI
34. Gao C, Wolff S, Wang S. Eco-friendly additive manufacturing of metals: energy efficiency and life cycle analysis. *J Manuf Syst* 2021;60:459-72. DOI
35. Khalid M, Peng Q. Sustainability and environmental impact of additive manufacturing: a literature review. *Comput Aided Des Appl* 2021;18:1210-32. DOI
36. Ghobakhloo M. Industry 4.0, digitization, and opportunities for sustainability. *J Clean Prod* 2020;252:119869. DOI
37. Lee WJ, Joung BG, Sutherland JW. Environmental and economic performance of different maintenance strategies for a product subject to efficiency erosion. *J Clean Prod* 2023;389:135340. DOI
38. Lee J, Wu F, Zhao W, Ghaffari M, Liao L, Siegel D. Prognostics and health management design for rotary machinery systems-reviews, methodology and applications. *Mech Syst Signal Process* 2014;42:314-34. DOI
39. Lee WJ, Xia K, Denton NL, Ribeiro B, Sutherland JW. Development of a speed invariant deep learning model with application to condition monitoring of rotating machinery. *J Intell Manuf* 2021;32:393-406. DOI
40. Wu H, Huang A, Sutherland JW. Avoiding environmental consequences of equipment failure via an lstm-based model for predictive maintenance. *Procedia Manuf* 2020;43:666-73. DOI
41. Bakker C, Wang F, Huisman J, den Hollander M. Products that go round: exploring product life extension through design. *J Clean Prod* 2014;69:10-6. DOI
42. Morioka T, Tsunemi K, Yamamoto Y, Yabar H, Yoshida N. Eco-efficiency of advanced loop-closing systems for vehicles and household appliances in hyogo eco-town. *J Ind Ecol* 2005;9:205-21. DOI
43. Ford S, Despeisse M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *J Clean Prod* 2016;137:1573-1587. DOI
44. Zhang Y, Ma S, Yang H, Lv J, Liu Y. A big data driven analytical framework for energy-intensive manufacturing industries. *J Clean Prod* 2018;197:57-72. DOI
45. Kellens K, Dewulf W, Lauwers B, Kruth J, Duflou J. Environmental impact reduction in discrete manufacturing: examples for non-conventional processes. *Procedia CIRP* 2013;6:27-34. DOI
46. Bermeo-ayerbe MA, Ocampo-martínez C, Diaz-rozo J. Adaptive predictive control for peripheral equipment management to enhance energy efficiency in smart manufacturing systems. *J Clean Prod* 2021;291:125556. DOI
47. Song B, Ao Y, Xiang L, Lionel K. Data-driven approach for discovery of energy saving potentials in manufacturing factory. *Procedia CIRP* 2018;69:330-5. DOI
48. Diaz N, Helu M, Jayanathan S, Chen Y, Horvath A, Dornfeld D. Environmental analysis of milling machine tool use in various manufacturing environments. Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology; 2010. DOI
49. Dahmus JB, Gutowski TG. An environmental analysis of machining. In: manufacturing engineering and materials handling engineering. ASMEDC; 2004:643-652. DOI
50. Kordonowy DN. A power assessment of machining tools. Available from: https://dspace.mit.edu/handle/1721.1/31108 [Last accessed on 28 Mar 2023].
51. Zhou L, Li J, Li F, Meng Q, Li J, Xu X. Energy consumption model and energy efficiency of machine tools: a comprehensive literature review. *J Clean Prod* 2016;112:3721-34. DOI
52. Behrendt T, Zein A, Min S. Development of an energy consumption monitoring procedure for machine tools. *CIRP Annals* 2012;61:43-6. DOI
53. Li W, Zein A, Kara S, Herrmann C. An investigation into fixed energy consumption of machine tools. In: Hesselbach J, Herrmann C,

editors. Glocalized Solutions for Sustainability in Manufacturing. Berlin: Springer Berlin Heidelberg; 2011. pp. 268-73. DOI

54. Triebe MJ, Zhao F, Sutherland JW. Modelling the effect of slide table mass on machine tool energy consumption: the role of lightweighting. *J Manuf Syst* 2022;62:668-80. DOI
55. Li W, Kara S. An empirical model for predicting energy consumption of manufacturing processes: a case of turning process. *Proc Inst Mech Eng B J Eng Manuf* 2011;225:1636-46. DOI
56. Kara S, Li W. Unit process energy consumption models for material removal processes. *CIRP Annals* 2011;60:37-40. DOI
57. Albertelli P. Energy saving opportunities in direct drive machine tool spindles. *J Clean Prod* 2017;165:855-73. DOI
58. Diaz N, Choi S, Helu M, et al. Machine tool design and operation strategies for green manufacturing. Proceedings of 4th CIRP International Conference on High Performance Cutting; 2010 October 271-276.
59. Huang H, Zou X, Li L, Li X, Liu Z. Energy-saving design method for hydraulic press drive system with multi motor-pumps. *Int J Pr Eng Man-Gt* 2019;6:223-34. DOI
60. Kroll L, Blau P, Wabner M, Frieß U, Eulitz J, Klärner M. Lightweight components for energy-efficient machine tools. *IRP J Manuf Sci Technol* 2011;4:148-60. DOI
61. Lv J, Tang R, Tang W, Liu Y, Zhang Y, Jia S. An investigation into reducing the spindle acceleration energy consumption of machine tools. *J Clean Prod* 2017;143:794-803. DOI
62. Dietmair A, Zulaika J, Sulitka M, Bustillo A, Verl A. Lifecycle impact reduction and energy savings through light weight eco-design of machine tools. In: Proceedings of the 17th CIRP Conference on Life Cycle Engineering. 2010:105-110.
63. Aggogeri F, Borboni A, Merlo A, Pellegrini N, Ricatto R. Vibration damping analysis of lightweight structures in machine tools. *Materials* 2017;10:297. DOI PubMed PMC
64. Suh J, Lee D, Kegg R. Composite machine tool structures for high speed milling machines. *CIRP Annals* 2002;51:285-8. DOI
65. Denkena B, Abele E, Brecher C, Dittrich M, Kara S, Mori M. Energy efficient machine tools. *CIRP Annals* 2020;69:646-67. DOI
66. Yoon H, Lee J, Kim M, Ahn S. Empirical power-consumption model for material removal in three-axis milling. *J Clean Prod* 2014;78:54-62. DOI
67. Fang K, Uhan N, Zhao F, Sutherland JW. A new approach to scheduling in manufacturing for power consumption and carbon footprint reduction. *J Manuf Syst* 2011;30:234-40. DOI
68. Gahm C, Denz F, Dirr M, Tuma A. Energy-efficient scheduling in manufacturing companies: a review and research framework. *Eur J Oper Res* 2016;248:744-57. DOI
69. Munoz A, Sheng P. An analytical approach for determining the environmental impact of machining processes. *J Mater Process Technol* 1995;53:736-58. DOI
70. Zhao F, Murray VR, Ramani K, Sutherland JW. Toward the development of process plans with reduced environmental impacts. *Front Mech Eng* 2012;7:231-46. DOI
71. Guo Y, Duflou JR, Deng Y, Lauwers B. A life cycle energy analysis integrated process planning approach to foster the sustainability of discrete part manufacturing. *Energy* 2018;153:604-17. DOI
72. Reiff C, Buser M, Betten T, et al. A process-planning framework for sustainable manufacturing. *Energies* 2021;14:5811. DOI
73. Jiang Z, Zhang H, Sutherland JW. Development of an environmental performance assessment method for manufacturing process plans. *Int J Adv Manuf Technol* 2012;58:783-90. DOI
74. Hutchins MJ, Sutherland JW. An exploration of measures of social sustainability and their application to supply chain decisions. *J Clean Prod* 2008;16:1688-98. DOI
75. Xu L, Wang C. Sustainable manufacturing in a closed-loop supply chain considering emission reduction and remanufacturing. *Resour Conserv Recycl* 2018;131:297-304. DOI
76. Jin H, Yih Y, Sutherland JW. Modeling operation and inventory for rare earth permanent magnet recovery under supply and demand uncertainties. *J Manuf Syst* 2018;46:59-66. DOI
77. Deng S, Prodius D, Nlebedim IC, Huang A, Yih Y, Sutherland JW. A dynamic price model based on supply and demand with application to techno-economic assessments of rare earth element recovery technologies. *Sustain Prod Consum* 2021;27:1718-27. DOI
78. Tong W, Mu D, Zhao F, Mendis GP, Sutherland JW. The impact of cap-and-trade mechanism and consumers' environmental preferences on a retailer-led supply Chain. *Resour Conserv Recycl* 2019;142:88-100. DOI
79. Ren H, Zhou W, Guo Y, et al. A GIS-based green supply chain model for assessing the effects of carbon price uncertainty on plastic recycling. *Int J Prod Res* 2020;58:1705-23. DOI
80. Xu L, Wang C, Zhao J. Decision and coordination in the dual-channel supply chain considering cap-and-trade regulation. *J Clean Prod* 2018;197:551-61. DOI
81. Zhang F, Wang J, Liu S, Zhang S, Sutherland JW. Integrating GIS with optimization method for a biofuel feedstock supply chain. *Biomass Bioenergy* 2017;98:194-205. DOI
82. Zhang X, Zhao G, Qi Y, Li B. A robust fuzzy optimization model for closed-loop supply chain networks considering sustainability. *Sustainability* 2019;11:5726. DOI
83. Khoo HH, Eufrasio-espinosa RM, Koh LS, Sharratt PN, Isoni V. Sustainability assessment of biorefinery production chains: a combined LCA-supply chain approach. *J Clean Prod* 2019;235:1116-37. DOI
84. Munasinghe M, Jayasinghe P, Deraniyagala Y, et al. Value–supply chain analysis (VSCA) of crude palm oil production in Brazil, focusing on economic, environmental and social sustainability. *Sustain Prod Consum* 2019;17:161-75. DOI

85. Ghadimi P, Wang C, Azadnia AH, Lim MK, Sutherland JW. Life cycle-based environmental performance indicator for the coal-to-energy supply chain: a Chinese case application. *Resour Conserv Recycl* 2019;147:28-38. DOI
86. Singh S, Sharma SK, Rathod DW. A review on process planning strategies and challenges of WAAM. *Materials Today: Proceedings* 2021;47:6564-75. DOI
87. Sato FEK, Nakata T. Recoverability analysis of critical materials from electric vehicle lithium-ion batteries through a dynamic fleet-based approach for Japan. *Sustainability* 2020;12:147. DOI
88. Jin H, Reed DW, Thompson VS, et al. Sustainable bioleaching of rare earth elements from industrial waste materials using agricultural wastes. *ACS Sustainable Chem Eng* 2019;7:15311-9. DOI
89. Nelson GJ, Ausderau LJ, Shin S, et al. Transport-geometry interactions in li-ion cathode materials imaged using X-ray nanotomography. *J Electrochem Soc* 2017;164:A1412-24. DOI
90. D'adamo I, Rosa P. A structured literature review on obsolete electric vehicles management practices. *Sustainability* 2019;11:6876. DOI
91. Mathur N, Deng S, Singh S, Yih Y, Sutherland JW. Evaluating the environmental benefits of implementing industrial symbiosis to used electric vehicle batteries. *Procedia CIRP* 2019;80:661-6. DOI
92. Lee WJ, Mendis GP, Triebe MJ, Sutherland JW. Monitoring of a machining process using kernel principal component analysis and kernel density estimation. *J Intell Manuf* 2020;31:1175-89. DOI
93. European Environment Agency. Circular economy in Europe - developing the knowledge base. available from: https://ec.europa.eu/environment/ecoap/policies-and-practices-eco-innovation-uptake-and-circular-economy-transition_en [Last accessed on 28 Mar 2023].
94. Geissdoerfer M, Savaget P, Bocken NM, Hultink EJ. The circular economy – a new sustainability paradigm? *J Clean Prod* 2017;143:757-68. DOI
95. Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: an analysis of 114 definitions. *Resour Conserv Recycl* 2017;127:221-32. DOI
96. Ghosh T, Hanes R, Key A, Walzberg J, Eberle A. The circular economy life cycle assessment and visualization framework: a multistate case study of wind blade circularity in United States. *Resour Conserv Recycl* 2022;185:106531. DOI
97. Sassanelli C, Rosa P, Rocca R, Terzi S. Circular economy performance assessment methods: a systematic literature review. *J Clean Prod* 2019;229:440-53. DOI
98. Hanes R, Ghosh T, Key A, Eberle A. The circular economy lifecycle assessment and visualization framework: a case study of wind blade circularity in texas. *Front Sustain* 2021;2:671979. DOI
99. Tian X, Xie J, Xu M, Wang Y, Liu Y. An infinite life cycle assessment model to re-evaluate resource efficiency and environmental impacts of circular economy systems. *Waste Manag* 2022;145:72-82. DOI PubMed
100. Richa K, Babbitt CW, Gaustad G, Wang X. A future perspective on lithium-ion battery waste flows from electric vehicles. *Resour Conserv Recycl* 2014;83:63-76. DOI
101. Sutherland J, Gunter K, Weinmann K. A model for improving economic performance of a demanufacturing system for reduced product end-of-life environmental impact. *CIRP Annals* 2002;51:45-8. DOI
102. Dunn J, Kendall A, Slattery M. Electric vehicle lithium-ion battery recycled content standards for the US – targets, costs, and environmental impacts. *Resour Conserv Recycl* 2022;185:106488. DOI
103. Cong L, Zhao F, Sutherland JW. Integration of dismantling operations into a value recovery plan for circular economy. *J Clean Prod* 2017;149:378-86. DOI
104. Cong L, Zhao F, Sutherland JW. A design method to improve end-of-use product value recovery for circular economy. *J Mech Design* 2019;141:044502. DOI
105. Colledani M, Battaïa O. A decision support system to manage the quality of end-of-life products in disassembly systems. *CIRP Annals* 2016;65:41-4. DOI
106. Bentaha M, Voisin A, Marangé P. A decision tool for disassembly process planning under end-of-life product quality. *Int J Prod Econ* 2020;219:386-401. DOI
107. Kara Y, Gökçen H, Atasagun Y. Balancing parallel assembly lines with precise and fuzzy goals. *Int J Prod Res* 2010;48:1685-703. DOI
108. Deng S, Kpodzro E, Maani T, et al. Planning a circular economy system for electric vehicles using network simulation. *J Manuf Syst* 2022;63:95-106. DOI
109. Alfaro-algaba M, Ramirez FJ. Techno-economic and environmental disassembly planning of lithium-ion electric vehicle battery packs for remanufacturing. *Resour Conserv Recycl* 2020;154:104461. DOI
110. Ortegon K, Nies L, Sutherland JW. Remanufacturing. In: Chatti S, Laperrière L, Reinhart G, Tolio T, editors. CIRP Encyclopedia of Production Engineering. Berlin: Springer Berlin Heidelberg; 2019. pp. 1428-30.
111. Johnson MR, Mccarthy IP. Product recovery decisions within the context of extended producer responsibility. *J Eng Technol Manage* 2014;34:9-28. DOI
112. Seitz MA. A critical assessment of motives for product recovery: the case of engine remanufacturing. *J Clean Prod* 2007;15:1147-57. DOI
113. Ortegon K, Nies LF, Sutherland JW. Remanufacturing: an alternative for end of use of wind turbines. In: Dornfeld DA, Linke BS, editors. Leveraging Technology for a Sustainable World. Berlin: Springer Berlin Heidelberg; 2012. pp. 155-60. DOI

114. Ortegon K, Nies LF, Sutherland JW. The impact of maintenance and technology change on remanufacturing as a recovery alternative for used wind turbines. *Procedia CIRP* 2014;15:182-8. DOI
115. Adler DP, Kumar V, Ludewig PA, Sutherland JW. Comparing energy and other measures of environmental performance in the original manufacturing and remanufacturing of engine components. In: Proceedings of the ASME International Manufacturing Science and Engineering Conference 2007; 2007. DOI
116. Boustani A, Sahni S, Graves SC, Gutowski TG. Appliance remanufacturing and life cycle energy and economic savings. In: Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology; 2010. DOI
117. Kerr W, Ryan C. Eco-efficiency gains from remanufacturing. *J Clean Prod* 2001;9:75-81. DOI
118. Boustani A, Sahni S, Gutowski T, Graves S. Tire remanufacturing and energy savings. Available from: http://web.mit.edu/ebm/www/Publications/MITEI-1-h-2010.pdf [Last accessed on 28 Mar 2023].
119. Allwood JM. Squaring the circular economy. Handbook of Recycling. Elsevier; 2014. pp. 445-77. DOI
120. Baxter J, Lyng KA, Askham C, Hanssen OJ. High-quality collection and disposal of WEEE: environmental impacts and resultant issues. *Waste Manag* 2016;57:17-26. DOI PubMed
121. Sutherland JW, Skerlos SJ, Haapala KR, Cooper D, Zhao F, Huang A. Industrial sustainability: reviewing the past and envisioning the future. *J Manuf Sci Eng* 2020;142:110806. DOI
122. Gaustad G, Krystofik M, Bustamante M, Badami K. Circular economy strategies for mitigating critical material supply issues. *Resour Conserv Recycl* 2018;135:24-33. DOI
123. Charles RG, Douglas P, Dowling M, Liversage G, Davies ML. Towards increased recovery of critical raw materials from WEEE–evaluation of CRMs at a component level and pre-processing methods for interface optimisation with recovery processes. *Resour Conserv Recycl* 2020;161:104923. DOI
124. Jin H, Park DM, Gupta M, et al. Techno-economic assessment for integrating biosorption into rare earth recovery process. *ACS Sustainable Chem Eng* 2017;5:10148-55. DOI
125. Arshi PS, Vahidi E, Zhao F. Behind the scenes of clean energy: the environmental footprint of rare earth products. *ACS Sustainable Chem Eng* 2018;6:3311-20. DOI
126. Akcil AA, Pillai A, Akcil A. Critical and rare earth elements: recovery from secondary resources. Available from: https://www.researchgate.net/publication/336265917_Critical_and_Rare_Earth_Elements_-_Recovery_from_Secondary_Resources [Last accessed on 28 Mar 2023].
127. Khazdozian H. Driving reuse, recycling, and more efficient use of critical materials. Available from: https://usea.org/sites/default/files/event-/Khazdozian_Reycling and Reuse.pdf [Last accessed on 28 Mar 2023].
128. Binnemans K, Jones PT, Blanpain B, et al. Recycling of rare earths: a critical review. *J Clean Prod* 2013;51:1-22. DOI
129. Priya A, Hait S. Comparative assessment of metallurgical recovery of metals from electronic waste with special emphasis on bioleaching. *Environ Sci Pollut Res Int* 2017;24:6989-7008. DOI PubMed
130. Brierley CL, Brierley JA. Progress in bioleaching: part B: applications of microbial processes by the minerals industries. *Appl Microbiol Biotechnol* 2013;97:7543-52. DOI PubMed
131. Brewer A, Dohnalkova A, Shutthanandan V, et al. Microbe encapsulation for selective rare-earth recovery from electronic waste leachates. *Environ Sci Technol* 2019;53:13888-97. DOI PubMed
132. Reed DW, Fujita Y, Daubaras DL, Jiao Y. Thompson VS. Bioleaching of rare earth elements from waste phosphors and cracking catalysts. *Hydrometallurgy* 2016;166:34-40. DOI PubMed
133. Thompson VS, Gupta M, Jin H, et al. Techno-economic and life cycle analysis for bioleaching rare-earth elements from waste materials. *ACS Sustainable Chem Eng* 2018;6:1602-9. DOI
134. Curran MA. Life cycle assessment student handbook. Available from: https://books.google.com.hk/books?hl=zh-CN&lr=&id=-rcOCgAAQBAJ&oi=fnd&pg=PT8&dq=Life+Cycle+Assessment+Student+Handbook.+John+Wiley+%26+Sons&ots=OFHFSkJEoU&sig=MIIokUIs3pDtHYA7IeVgVytNVnY&redir_esc=y#v=onepage&q=Life%20Cycle%20Assessment%20Student%20Handboo [Last accessed on 28 Mar 2023].
135. Cong L. Product design for value recovery in support of closing material loops. Available from: https://docs.lib.purdue.edu/dissertations/AAI10845107/ [Last accessed on 28 Mar 2023]
136. Mathur N, Sutherland JW, Singh S. A study on end of life photovoltaics as a model for developing industrial synergistic networks. *Jnl Remanufactur* 2022;12:281-301. DOI
137. Kumar V, Sutherland JW. Development and assessment of strategies to ensure economic sustainability of the U.S. automotive recovery infrastructure. *Resour Conserv Recycl* 2009;53:470-7. DOI
138. Choi JK, Fthenakis V. Design and optimization of photovoltaics recycling infrastructure. *Environ Sci Technol* 2010;44:8678-83. DOI PubMed
139. Sariatli F. Linear economy versus circular economy: a comparative and analyzer study for optimization of economy for sustainability. *Visegrad J Bioecon Sustain Dev* 2017;6:31-4. DOI
140. Pearce DW, Turner RK. Economics of natural resources and the environment. Available from: https://www.researchgate.net/publication/31662420_Economics_of_natural_resources_and_the_environment_DW_Pearce_RK_Turner [Last accessed on 28 Mar 2023].
141. EPA. Sustainable materials management: materials management and the 3Rs initiative. Available from: https://archive.epa.gov/oswer/international/web/pdf/3rs-initiative-082907.pdf [Last accessed on 28 Mar 2023].

142. Okorie O, Salonitis K, Charnley F, Moreno M, Turner C, Tiwari A. Digitisation and the circular economy: a review of current research and future trends. *Energies* 2018;11:3009. DOI
143. Awan U, Sroufe R, Shahbaz M. Industry 4.0 and the circular economy: a literature review and recommendations for future research. *Bus Strat Env* 2021;30:2038-60. DOI
144. Rosa P, Sassanelli C, Urbinati A, Chiaroni D, Terzi S. Assessing relations between circular economy and industry 4.0: a systematic literature review. *Int J Prod Res* 2020;58:1662-87. DOI
145. Bag S, Yadav G, Dhamija P, Kataria KK. Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: an empirical study. *J Clean Prod* 2021;281:125233. DOI
146. Wu H, Huang A, Sutherland JW. Layer-wise relevance propagation for interpreting LSTM-RNN decisions in predictive maintenance. *Int J Adv Manuf Technol* 2022;118:963-78. DOI
147. Padilla-rivera A, Russo-garrido S, Merveille N. Addressing the social aspects of a circular economy: a systematic literature review. *Sustainability* 2020;12:7912. DOI
148. Padilla-rivera A, do Carmo BBT, Arcese G, Merveille N. Social circular economy indicators: selection through fuzzy delphi method. *Sustain Prod Consum* 2021;26:101-10. DOI
149. Moreau V, Sahakian M, van Griethuysen P, Vuille F. Coming full circle: why social and institutional dimensions matter for the circular economy: why social and institutional dimensions Matter. *J Ind Ecol* 2017;21:497-506. DOI
150. Reich-Weiser C, Vijayaraghavan A, Dornfeld DA. Metrics for sustainable manufacturing. In: ASME 2008 International Manufacturing Science and Engineering Conference;2008:327-335. DOI
151. Mani M, Madan J, Lee JH, Lyons KW, Gupta SK. Review on sustainability characterization for manufacturing processes. National Institute of Standards and Technology, Gaithersburg, MD, Report No. NISTIR 7913. 2013. DOI
152. Jawahir IS, Dillon OW, Rouch KE, Joshi KJ, Venkatachalam A, Jaafar IH. Total life-cycle considerations in product design for sustainability: a framework for comprehensive evaluation. Available from: https://www.researchgate.net/publication/285360999_Total_life-cycle_considerations_in_product_design_for_sustainability_A_framework_for_comprehensive_evaluation [Last accessed on 28 Mar 2023].
153. Dow Jones Sustainability World Index Available from: https://www.spglobal.com/spdji/en/indices/esg/dow-jones-sustainability-world-index/#overview [Last accessed on 28 Mar 2023].
154. OECD. Oecd key environmental indicators 2004. Available from: https://www.oecd.org/environment/indicators-modelling-outlooks/31558547.pdf [Last accessed on 28 Mar 2023].
155. Wulf-peter schmidt ford of Europe, vehicle environmental engineering. Available from: https://www.un.org/esa/sustdev/marrakech/schmidt.pdf [Last accessed on 28 Mar 2023].
156. General motors metrics for sustainable manufacturing - laboratory for sustainable business. Available from: https://www.readkong.com/page/general-motors-1822704 [Last accessed on 28 Mar 2023].
157. Towards environmental pressure indicators for the EU. Available from: https://op.europa.eu/en/publication-detail/-/publication/80ce03d9-fc51-4bb6-a6fc-c3997efa3525 [Last accessed on 28 Mar 2023].
158. United Nations. Indicators of sustainable development: guidelines and methodologies. Available from: https://sustainabledevelopment.un.org/content/documents/guidelines.pdf [Last accessed on 28 Mar 2023].
159. Walmart. Fact sheet: sustainability index. Available from: http://cdn.corporate.walmart.com/4e/07/2822e9e94695815f70ef54d49c09/china-sustainability-supplie-index-fact-sheet_129955748580825248.pdf [Last accessed on 28 Mar 2023].
160. Dornfeld D. Green Manufacturing. Vol 9781441960. (Dornfeld DA, ed.). Springer US; 2013. DOI
161. Laurent A, Olsen S, Hauschild M. Carbon footprint as environmental performance indicator for the manufacturing industry. *CIRP Annals* 2010;59:37-40. DOI
162. Singh RK, Murty H, Gupta S, Dikshit A. An overview of sustainability assessment methodologies. *Ecological Indicators* 2012;15:281-99. DOI
163. Sarkar P, Joung CB, Carrell J, Feng SC. Sustainable manufacturing indicator repository. In: 31st Computers and Information in Engineering Conference, 2011:943-950. DOI
164. Chai SYW, Phang FJF, Yeo LS, Ngu LH, How BS. Future era of techno-economic analysis: Insights from review. *Front Sustain* 2022;3:924047. DOI
165. Thomassen G, Van Dael M, Van Passel S, You F. How to assess the potential of emerging green technologies? *Green Chem* 2019;21:4868-86. DOI
166. . Van Dael M, Kuppens T, Lizin S, Van Passel S. Techno-economic Assessment methodology for ultrasonic production of biofuels. In: Fang Z, Smith, RL, Qi X, editors. Production of Biofuels and Chemicals with Ultrasound. Dordrecht: Springer Netherlands; 2015. pp. 317-45. DOI
167. Huang T, Pérez-cardona JR, Zhao F, Sutherland JW, Paranthaman MP. Life cycle assessment and techno-economic assessment of lithium recovery from geothermal brine. *ACS Sustainable Chem Eng* 2021;9:6551-60. DOI
168. Shade SA, Sutherland JW. Energy efficient or energy effective manufacturing? In: Sutherland JW, Dornfeld DA, Linke BS, editors. Energy Efficient Manufacturing. Hoboken: John Wiley & Sons, Inc.; 2018. pp. 421-44. DOI
169. Advanced manufacturing office. 2018 Manufacturing static energy sankey diagrams. Available from: https://www.energy.gov/eere/amo/2018-manufacturing-static-energy-sankey-diagrams [Last accessed on 28 Mar 2023].
170. Feng S, Joung C, Li G. Development overview of sustainable manufacturing metrics. Available from: https://www.nist.gov/

publications/development-overview-sustainable-manufacturing-metrics [Last accessed on 28 Mar 2023].

171. Cohen S, Bose S, Guo D, et al. The growth of sustainability metrics 1/3. earth institute research program on sustainability policy and management. 2014;(May):1-16. https://spm.ei.columbia.edu/sites/default/files/content/Publications/SPM_Metrics_WhitePaper_1.pdf.