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Integrated Sustainable Life Cycle Design: A Review

Product design is one of the most important sectors influencing global sustainability, as almost all the products consumed by people are outputs of the product development process. In particular, early design decisions can have a very significant impact on sustainability. These decisions not only relate to material and manufacturing choices but have a far-reaching effect on the product's entire life cycle, including transportation, distribution, and end-of-life logistics. However, key challenges have to be overcome to enable eco-design methods to be applicable in early design stages. Lack of information models, semantic interoperability, methods to influence eco-design thinking in early stages, measurement science and uncertainty models in eco-decisions, and ability to balance business decisions and eco-design methodology are serious impediments to realizing sustainable products and services. Therefore, integrating downstream life cycle data into eco-design tools is essential to achieving true sustainable product development. Our review gives an overview of related research and positions early eco-design tools and decision support as a key strategy for the future. By merging sustainable thinking into traditional design methods, this review provides a framework for ongoing research, as well as encourages research collaborations among the various communities interested in sustainable product realization. [DOI: 10.1115/1.4002308]

Keywords: *sustainable design, eco-design, product design, manufacturing, supply chain*

1 Introduction

The world is more crowded, more polluted, more urban, more ecologically stressed, and warmer than ever before in recorded history. During the 20th century, the human population increased from less than 2 billion to over 6 billion people. The number of cities with more than a million people has grown from less than 20 to more than 300, and in the last 75 years, many cities have grown 25 times or more. The largest cities in the world now contain a startling 30 million people in total. During the same time period, the number of automotive vehicles in the world has grown from a few tens of thousands to more than half a billion. The consumption of resources such as oil, water, and metals has increased more than ten times, while pollution has increased even more. Human activities worldwide now add as much as 7×10^9 tons of carbon dioxide to the atmosphere every year [1].

Growing environmental concerns, coupled with public pressure and stricter regulations, are fundamentally impacting the way companies design and launch new products across the world [2]. Therefore, companies are confronted with the responsibility of producing products in an environmentally friendly manner. This requires the next generation of engineers to be trained in the con-

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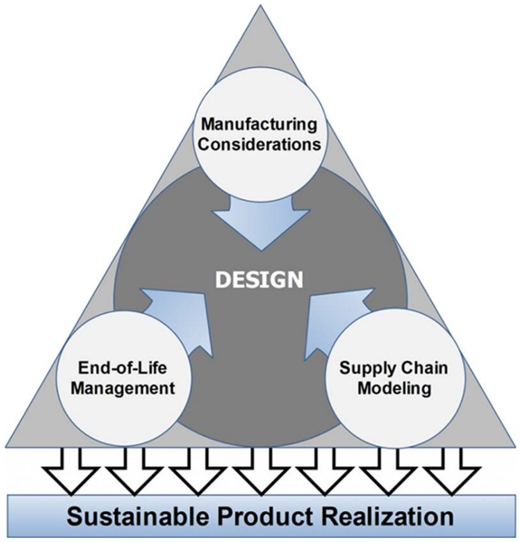

Fig. 1 Design decisions affect every stage of a product's life

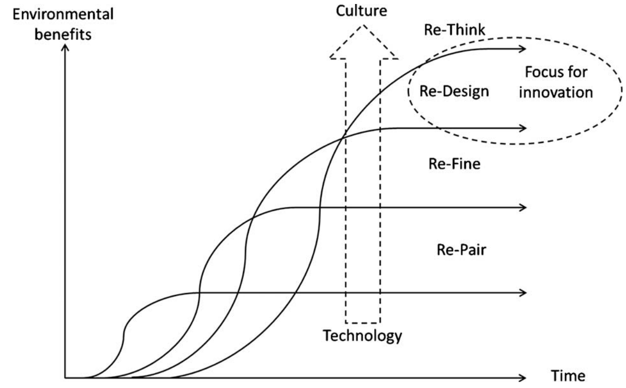

Fig. 2 Revised approach to DFS [15]

text of sustainability, along with a global perspective, in order to solve problems of sustainability on multiple scales [3].

The issue of environmental sustainability is extraordinary in both magnitude and complexity and as such is one of the greatest challenges faced by modern society [4]. Moreover, as a result of population growth and the improvement in the quality of life [5], more and more products are used to provide services or are consumed by people directly, further complicating the quest for environmental sustainability. In 2006, the total output of the U.S. manufacturing sector (in the form of a variety of products) had a gross value of $\$5.3 \times 10^{12}$ [6]. These products were responsible for about 84% of energy-related carbon dioxide emissions and 90% of the energy consumption in the industrial sector [7]. Therefore, reducing the environmental footprints associated with these products has critical importance in addressing the environmental sustainability challenge.

While many different enterprises and systems are involved from the concept to the end-of-life (EOL) and recycling of products, it also requires a shared responsibility to implement and realize sustainability throughout the life cycle. Ultimately, designers and product engineering management must understand possible designs for environment strategies. Innovation is an integral part that must balance business with other constraints to find the best strategy for product lines. Information requirements of engineering designers for eco-design have to be served in a manner such that both manufacturing and life cycle use of the product are eco-friendly. Figure 1 illustrates the necessary considerations during design to achieve sustainable product development. Also, the integration of downstream issues into design is a complex task. The ambiguity attributed to a concept during the early design phase creates grand challenges for the development of appropriate, accurate metrics related to sustainability. The purpose of this paper is to provide a map of the primary drivers, ongoing research, and future needs for researchers, educators, and practitioners. In addition, the paper also serves another purpose of providing foresight into gaps that are emerging in realizing the quest for more sustainable products [8]. This review also provides some specific research examples in terms of our position in developing early design strategies, which show promise to be effective in the long run.

2 Background

On Feb. 2, 2007, the United Nations scientific panel studying climate change declared that the evidence of a warming trend is "unequivocal" and that human activity has "very likely" been the driving force in this change over the past 50 years [9]. The last report by the Intergovernmental Panel on Climate Change, in 2001, had found that human beings had "likely" played a role. Subsequently, climate change, including the "cap and trade" possibilities, has been a major front page topic in various newspapers, Secretary Clinton's agenda for engaging Asian countries in solving global problems, the soot from millions of villages in India as a source of global climate change, the arctic melt unnerving scientists in the summer of 2007, the risk of inaction on climate change by the United Nations, and, most recently, the Aug. 9, 2009 article entitled "Climate Change Seen as Threat to U.S. Security," all paint a picture illustrating the far-reaching implications of climate change [10].

3 Sustainability and Product Design

The industrial sector has been responsible for emissions of 1235×10^6 metric tons of carbon dioxide in the United States as of 2007. This number is expected to increase to 1667 $\times 10^6$ metric tons by 2030 [11]. It is therefore imperative to design products and processes that are environmentally sustainable.

It is well known that although only 5–7% of the entire product cost is attributable to early design, the decisions made during this stage lock in 70–80% of the total product cost [12]. Correspondingly, one can hypothesize the same to be the case for environmental impacts. That is, whether or not a product is relatively sustainable is largely determined during the early design stage. Due to high levels of uncertainty regarding design embodiments at the early design phase, novel methods and tools are essential to providing designers a basis for ascertaining the degree of sustainability of a given product or process [13].

3.1 DFE. Design for environment (DFE) is a practice by which environmental considerations are integrated into product and process engineering design procedures. DFE practices are meant to develop environmentally compatible products and processes while maintaining product, price, performance, and quality standards [14]. Sherwin and Bhamra [15] suggested that the real focus for innovation should be around stages 3 and 4 (redesign and rethink), as can be seen in Fig. 2 and in the original revised four-step approach by Charter [16]. Indeed, sustainability is inextricably linked with economic and social considerations that differ across cultures and technology, and combined with improved design, they can greatly aid this quest [5].

Design for the environment enables consideration of environmental issues as business opportunities. These opportunities may exist for new products, processes, or manufacturing technologies [17]. The extent of the product's environmental friendliness depends on the level of DFE implemented by the company. Therefore, most of the levels of DFE have to be set up before companies start to implement their own DFE. In general, because of the complexity of today's products and the departmental organization

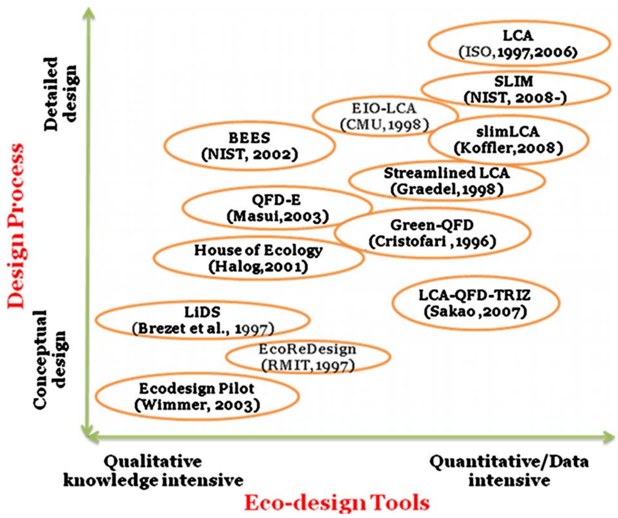

Fig. 3 Map of current ecodesign tools

of most companies, DFE is essentially a cross-functional activity [18]. Although DFE suggests a number of ways in which one can include environmental considerations in design, it is prescriptive. It does not reflect reality, which is simply that the considerations and decisions at design time have to be informed by knowledge that comes from a detailed analysis. However, such analysis takes a long time and is done at later stages of the product design process. Projection of life cycle data to the design phase would enable key decisions at the early design phase. New interfaces and design methods must be developed and tested using appropriate information/knowledge models to accomplish this task.

3.2 Eco-Design Tools. During the past ten years, numerous eco-design tools have been proposed and developed. In fact, ISO-TR 14062 [19] suggests the use of some 30 various tools. The current eco-design tools vary in data presentation and design process implementation. Figure 3 illustrates some of the recent eco-design tools and their individual application to the design process. These tools can generally be classified into three categories: tools based on checklists, tools based on life cycle assessment (LCA), and tools based on quality function deployment (QFD) [20].

3.2.1 Tools Based on LCA. Engineered products interact with the environment through energy and material flows at every stage of their life cycle, from raw material extraction and acquisition, manufacturing, transportation, and distribution, all the way to use and maintenance, reuse and recycle, and, ultimately, disposal and waste management. LCA has emerged as the most objective tool available for evaluating the environmental profile of a product or process [21,22]. Figure 4 illustrates the steps for identifying the environmental impact of a product system in a LCA context [8]. In order to conduct a LCA detailed product design, information is required, which makes it unsuitable for use in the early design process when a detailed specification is not available yet [23]. This is especially true for a new product design since even information from reference products (previous generation or competitors) is not available. Also, LCA could be very costly and time-consuming, so only large companies can afford to do it. There have been some efforts in addressing these issues by developing simplified or streamlined LCA for screening purposes. But again, these methods tend to ignore environmental impacts from certain life cycle stages, certain material/energy flows, or certain impact categories [24,25]. As recent efforts have been made to implement LCA during the early design phase [26], uncertainties about the early design embodiments (i.e., shape, component interactions, etc.) have become a major obstacle. To what level the fidelity can be maintained remains largely unaddressed. Another serious obstacle associated with applying LCA-based tools to early design lies in the fact that, inherently, LCA is not design oriented; i.e., it is designed to analyze certain structures and components, not environmental costs associated with functions required by customers or the technologies used to achieve those functions. Allocating environmental impacts across functions is one method of assessing the greenness of concept embodiments [27].

3.2.2 Tools Based on Checklists. These qualitative tools are the easiest to use and are among the tools most prevalent in the industry, especially in small and medium size companies [28]. A common feature of these tools is the checklist, which is a set of items used for assessing a product from the environmental perspective over its entire life cycle. These items include, for example, "is less energy consumed during the use phase of the product than the existing ones?" or "are less toxic materials used in the product?" [29]. These tools are developed particularly for the early stages of the product development process. Compared with LCA-based tools, these tools are much more subjective. The proper use of the tools requires extensive experience and knowledge. Even with these, there remains a challenge when trade-offs exist between different life cycle stages or different environment impact categories. Moreover, these tools can rarely offer concrete solutions.

3.2.3 Tools Based on QFD. The objective of a traditional QFD is to convert customers' needs into engineering characteristics and, at the same time, to improve the quality level of the product. By introducing the environmental impacts of the product itself and over its life cycle into QFDs as new customer needs, a set of ecodesign tools has been developed. These include QFD for the environment, green quality function deployment, and House of

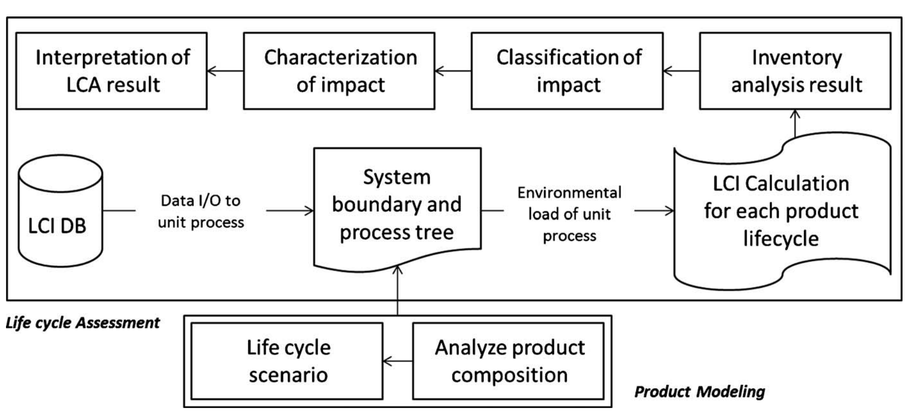

Fig. 4 Steps for identifying environmental impact

Ecology [23,30]. In general, application of these tools starts from collecting both customer needs and environmental needs and developing correlations between these needs and quality characteristics. A functional analysis is then performed to identify how quality characteristics are correlated with engineering characteristics (including structure or components) and hot spots from both environmental as well as traditional quality points of view. It can be seen that QFD-based tools are significantly different from LCA-based tools since the focus here is on the product specification development stage. One serious drawback of these QFD-based tools (similar to traditional QFD) is that the development of correlations between environmental needs and quality and engineering characteristics is totally on the designers, and usually the correlations developed are based on knowledge from the traditional environmental engineering discipline without the consideration of life cycle [31].

3.2.4 Integrated Tools. Though most eco-design tools fall within the three categories mentioned above, there have been efforts to provide a more holistic approach to the design process. Lofthouse described a web-based framework for eco-design tools, a combination of guidance, education, and information, along with well considered content, appropriate presentation, and easy access [32]. Furthermore, Dewulf et al. presented an alternative web-based platform for a novel eco-design tool, Eco-PaS [33]. Robert et al. suggested that the discontinuity between these various tools has slowed the progress toward achieving sustainable development [34]. Moreover, these tools generally take the form of a stand-alone application, which further limits their use in the conceptual design stage of product development. There are some efforts to bridge this limitation by integrating various technologies such as life cycle costing with LCA [35], multicriteria decision making with LCA [8,36], and mathematical decision modeling with constrained optimization approaches [36,37]. An integrated decision support tool that minimizes information-related barriers is likely to significantly enhance the capability, simplicity, and willingness of decision makers to pursue sustainable product design activities.

3.3 Challenges for Eco-Design Tools. There is no single silver bullet eco-design tool that can handle all aspects of sustainable product realization since there are a variety of limitations associated with all types of eco-design tools discussed in this section. For example, despite the important contributions of LCA tools in eco-design, various levels of uncertainty sources reside within LCA. These sources of uncertainty are usually generated by (1) empirically inaccurate parameters in the life cycle inventory (LCI) originally caused by imprecise, outdated measurements or lack of data and/or by (2) the life cycle impact assessment (LCIA) model caused by utilizing simplified factors, which do not consider the spatial and temporal characteristics. Generally, variations in environmental interventions over a relatively short period of time, such as short disastrous emissions, are not considered in LCA. The high uncertainty present in the implementation of LCA may introduce a crucial limitation when interpreting the environmental impact, as well as implementing the result in eco-design. There are some methodologies that mitigate the uncertainty issue by introducing probabilistic simulation, correlation, and regression analysis [38]. Monte Carlo simulation is one of the most popular tools to use for analyzing the uncertainty through assigning the probabilistic distribution to each source of uncertain data. Most LCA software packages at least consider parametric uncertainty via sensitivity analysis; however, efforts for standardizing LCA data collection and including uncertainty have not received much attention. The relevance of Bayesian methods for LCA has been recognized in recent research [39].

LCA provides information about an average product or process. However, to use such information in improving design and manufacturing, it is necessary to also account for detailed information about a specific process [40]. The need for integration of socio-economic modeling with ecodesign and LCA is recognized [41]; however, there is a lack of systematic methods to satisfy this necessity. Products with multiple embedded technologies require a collaborative design and development process across corporate, global, and disciplinary boundaries.

By using eco-design tools, designers can conceptualize a sustainable product. However, product design is simply the first stage of product development. Thus, there are further opportunities for improvements from an environmental perspective. Cleaner manufacturing, a more efficient infrastructure (i.e., transportation and internal logistics), and more thoughtful end-of-life scenarios could all contribute to a better eco-design.

4 Product Manufacturing

4.1 Environmentally Conscious Manufacturing. The product manufacturing process is the main stage in the life cycle that consumes resources directly and produces environmental pollution as well as being the main factor that affects the result of enterprise performance in terms of sustainable development [42]. Efforts to minimize the environmental impacts of manufacturing processes can roughly be classified into three categories: (1) process improvement and optimization, (2) new process development, and (3) process planning. Traditional manufacturing processes are generally designed for high performance and low cost with little attention paid to environmental issues. For example, metalworking fluids are widely used in a variety of machining operations, and flood delivery is the common practice. Skerlos et al. reviewed advances in the development of alternative metalworking fluid delivery strategies for sustainable manufacturing. It was pointed out that it is possible to design more sustainable metalworking fluid systems either by extending dramatically the in-use lifetime of water-based fluids or, better yet, by switching to gas-based (air or supercritical carbon dioxide) minimum quantity lubrication systems [43].

Besides process improvement and optimization, many new "green" processes have been developed to replace conventional processes. One example is the development of laser-based manufacturing processes. One of such processes is laser cutting, which has become a popular alternative to oxy-fuel cutting. Laser cutting usually leads to much narrower widths of cut (thus less material waste) and does not emit metal oxide fumes. Similarly, laser shock peening has become competitive with conventional shot peening for certain aerospace and aeronautic applications, where high residue stress and long fatigue life are desired. Compared with shot peening, laser shock peening does not consume a shot medium; thus, no particulate emission is involved. It should be noted that LCA needs to be conducted to confirm the "greenness" of the new processes [44].

One of the most important steps in converting a design concept into a manufactured product is process planning [45]. The manufacturing plan outlines the selection of the manufacturing processes, sequencing of the processes, and parameters for each manufacturing process. Similar to in product design, one can argue that in the early stage of process planning, selection and sequence of major processes are more critical than the parameter optimization of processes involved, with regard to performance, including that of sustainability. Process planning is conventionally completed manually from scratch by experts who retrieve and manipulate a great deal of information from many sources, including established standards, machinability data, machine capabilities, tooling inventories, stock availability, and existing practice. Much research and development has been devoted to developing computer-aided process planning (CAPP). Similar to computer-aided design (CAD), CAPP when combined with computer-aided manufacturing (CAM) is effective in optimizing processes in a selected sequence but usually offers limited help at the early stage of process planning. Moreover, most of these CAPP efforts have been focused on production efficiency, cost, and product quality, but few efforts have been focused on environmental sustainability.

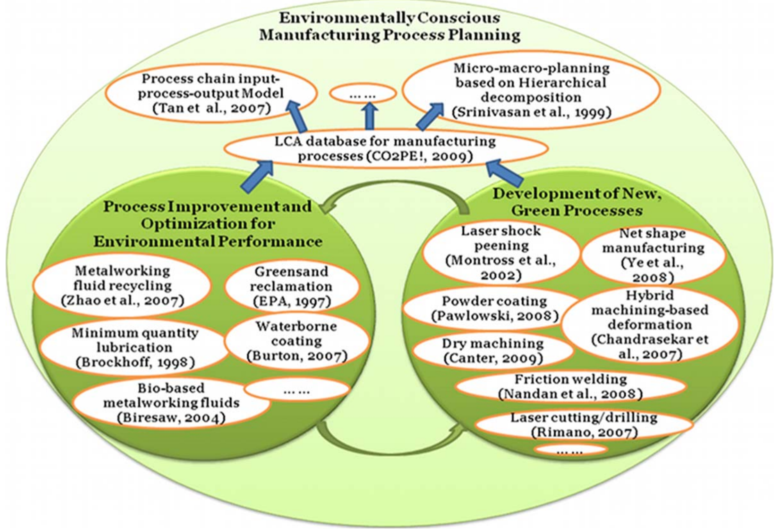

Fig. 5 Sustainable manufacturing research map

To date, only a handful of papers have been published, which focus on the integration of environmental considerations into process planning [46–49]. Due to the lack of life cycle data of manufacturing processes, almost all of the papers have directed their efforts to framework or methodology development. The integration of environmental considerations into process planning will allow for more sustainable manufacturing process selection and inventory management (Fig. 5).

4.2 DFMA. Although efforts in improving the environmental performance of manufacturing processes discussed above can lead to significant reduction in environmental impacts associated with product manufacturing, it should be noted that these efforts alone may not be sufficient for sustainable product realization. As pointed out earlier, design choices, especially decisions made during the early design stage, can take up to 70% of the cost (including material and resource consumption) committed [12]. As a result, life cycle environmental impacts of a product are largely determined by design. To maximize product sustainability, it is more desirable to integrate environmentally conscious manufacturing efforts with design for the environment. Design for manufacturing and assembly (DFMA) has emerged as a framework to address the imperative need of accommodating manufacturing and assembly considerations within the design [50]. Although the focus of DFMA to date is on minimizing production cost and time to market, the framework has the potential to be expanded to include sustainability considerations and to integrate environmentally conscious design and manufacturing.

The main goal of current DFMA approaches is to obtain a product with a high level of manufacturability. That is, DFMA usually attempts at simplifying the product structure by reducing total parts count; optimizing for the best combination of materials, geometry, and cost-effective manufacturing methods for all parts; and simplifying manual assembly tasks [51]. Design guidelines, manufacture and assembly guidelines, and manufacturing process selection guidelines have been made available to designers to consider the manufacturing and assembly issue [52,53]. With the advances of computer-aided engineering software packages and the development/adaptation of Standard for the Exchange of Product Model Data (STEP), it is now possible to simulate manufacturing and assembly processes, to predict their performance, and to evaluate the manufacturability aspects of a specific part [54–58]. More recent efforts have attempted to develop a feedback mechanism linking product design decisions in a CAD system to actual manufacturing/assembly operations in CAM [59], with the ultimate goal of evaluating a product's design without building an expensive physical production system.

Ideally, DFMA must be applied at the conceptual design stage in order to obtain the maximum benefits. It is widely acknowledged that suitable methods and tools should be used to integrate manufacturing information into the design process as early as possible [60]. However, making sound decisions in the early design phase is rather difficult since this involves many unpredictable factors in manufacturability, quality/tolerance, and resource availability [54,61]. At the conceptual design stage, computer simulation based approaches cannot be applied since a detailed design is not available yet. DFMA tools in the form of guidelines or ranking indices are helpful, but proper use of these "subjective" tools requires extensive designer experience. Although the critical need exists for supporting DFMA in early design, a literature search only resulted in a handful of studies, and almost all of them take an information model or ontology-based approach [50,61–63]. This is not a surprise since experience or knowledge is critical in properly applying qualitative DFMA tools in early design.

In general, these efforts aim at enabling the reuse of DFMA knowledge embedded in previously solved problems, which is stored in a repository. Ontology is used to capture concepts and represent the knowledge in a hierarchical manner, which is preferred by designers. For example, Yim and Rosen used a description logic to encode ontology for parts to be produced through additive manufacturing processes and demonstrated the retrieval of archived DFMA problems that are similar to the specific problem at hand [62]. More recently, Chang et al. proposed a new process for DFMA ontology development and utilization, which can reuse existing relevant ontologies and can dynamically expand as new design alternatives are added to the repository [63]. To address the impreciseness associated with early design, Wang and Ceglarek developed a vector-based variation propagation model for a skeletal design of a truck cab made through multistation sheet metal assembly processes [64]. The model takes into consideration all the existing interactions between flexible parts and tools and can automatically generate product skeletal design to be fed into CAD systems. Potentially, this variation in the propagation modeling approach can be combined with knowledge retrieval through ontology to support preliminary and conceptual design.

It should be pointed out that until now, environmental or sustainability issues have not been considered in all the efforts in DFMA technique development. To bring manufacturing considerations into a design for an environmental approach, DFMA tools have to be expanded. Since DFMA tools suitable for early design are still at a premature stage, both challenges and opportunities exist. Given the current research efforts, the information model/ontology-based method represents a promising approach. Since the availability of manufacturing information and knowledge is key to achieving DFMA [52], developing an environmental life cycle inventory database for both existing and emerging manufacturing processes and integrating the database into the DFMA information model seem to carry the priority.

5 Supply Chain Considerations

5.1 GSCM. As a result of globalization, today a product assembled in one location can be comprised of many components from literally all over the world. After assembly, the product is shipped to distribution and eventually to the consumer. Therefore, efforts toward sustainable product realization must take into account manufacturing activities at three different levels: process, factory, and supply chain [65]. The supply chain can account for a quarter of the total manufacturing costs [66], making it likely to contribute to the environmental costs as well. The primary objective of traditional supply chain management approaches is to fulfill customer demands through the most efficient use of resources, including distribution capacity, inventory, and labor. Sonnemann et al. discussed the need for shorter industrial process chains, particularly geographically well-localized parts of life cycles [67]. Boons recognized that diminishing the ecological effects of products has become a significant focus of corporate environmental strategies [68]. Due to these mounting concerns for environmental sustainability, academic and corporate interest in sustainable supply chain management (or green supply chain management (GSCM)) has risen considerably in recent years, as illustrated by the number of papers published, particularly in special issues of journals [69].

Therefore, one can look at the reuse problem from a logistical perspective as well. Compared with the traditional supply chain management approach, a sustainable supply chain should be designed for cost and environmental impact minimization. The scope of GSCM practice implementation ranges from green purchasing to integrated life cycle management supply chains flowing from supplier, to manufacturer, and to customer, and then closing the loop with reverse logistics [70]. The problem not only involves the willingness and ability of customers to return products but also the existence of a streamlined reverse supply chain. The issue of reverse logistics has been approached in primarily two ways, independent and integrated [71]. In an independent approach, it is assumed that the forward supply chain works independently of the reverse supply chain and vice versa. On the other hand, an integrated approach considers them together, including the interactions. Demirel and Gökçen presented a mixed integer model for remanufacturing in a reverse logistics environment. They considered an integrated model in which forward and reverse flows are considered simultaneously, and they provided solutions in terms of optimal production volume as well as location of various facilities [72]. Neto et al. proposed a multi-objective programming-based framework for the design and evaluation of sustainable logistic networks, in which profitability and environmental impacts are balanced [73]. Sarkis developed a strategic decision framework for GSCM practice implementation to evaluate alternatives adopted by companies that would affect their external relationships with suppliers and customers [74]. Sheu et al. developed a linear multi-objective programming model that optimized the operations of both forward and reverse logistics in a given green supply chain [75]. A leasing approach, as presented in Mangun and Thurston, promised to simplify the logistics issue but requires participation from customers [76]. Modularization of product has also been found to facilitate reverse logistics [77] as well as product reuse in general [78]. In the end, a closed-loop manufacturing system, which manages a reverse logistics network, is preferred.

The impact of reused products on sales of new products is also

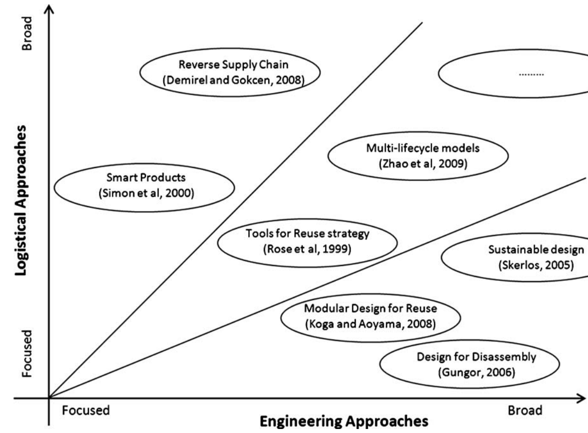

Fig. 6 Research map for product end-of-life management and logistics

an issue of concern. Thomas showed how the increase in demand for reused products could have a positive or a negative effect on new product demand depending on the availability of waste goods [79]. Joint considerations of new and remanufactured products were considered in Guide and Wassenhove, where the authors looked at this issue and provided insights into cannibalization of sales of new products by remanufactured products [80]. Additionally, Simon et al. evaluated the cost benefits of self-contained data acquisition features in products, which could help in product reuse [81].

The product's entire life cycle has to be carefully considered in supply chain management. A company can select those suppliers that generate the least pollution in each individual phase. In fact, Gehin et al. introduced a method to deconstruct the supply chain in order to target the product's phase (distribution, packaging, etc.) that carried the most environmental impact [82]. This paved the way for a concerted effort to reduce the total environmental load of the product in cooperation with suppliers, distributors, users, recycling companies, and waste-processing firms. However, similar to the case of environmentally conscious manufacturing process planning, lack of life cycle data on products has seriously limited the use of the sustainable supply chain management approach. Recently, Walmart™ funded the Sustainability Consortium, which brings together universities, businesses, nongovernment organizations (NGOs), and governmental agencies to design and develop a sustainable product index for consumer products [83]. One of the key tasks is to develop scientifically grounded tools to create life cycle inventories and analysis for thousands of products that are manufactured and used in places around the globe. It is expected that there will be similar efforts initiated that can eventually be shared, yet secure databases will be developed to allow retailers and consumers the ability to compare one product with another in a variety of areas, besides enabling green supply chain management in enterprises of different sizes. Another important aspect is that consumers are becoming more sensitive to the life cycle costs of the product, and the notion of product and services are being merged [84]. Figure 6 illustrates the numerous paths of research within life cycle management.

5.2 Projecting Supply Chain Knowledge to Design. Though there has been some recent work attempting to predict supply chain data at the early design stage, this research area is still well in its infancy. The ambiguity associated with an embodiment design gives little insight into the dynamic networks associated with transportation, distribution, and other supply chain related costs. Additionally, linking product attributes and features directly to supply chain costs is challenging without having fully developed relationships among designers and manufacturers and/or suppliers. Efforts, such as the Walmart™'s Sustainability Consortium mentioned above, aim to gain insight into these issues.

Though modularization and part/subassembly commonality across separate product lines or pipelines could significantly reduce the environmental costs of supply chain networks, innovative metrics and decision making tools for the product's early development stages are essential to deliver the necessary eco-savings. Regardless of this need, there has been some relevant research. In a 2009 paper, Thomas proposed barcodes on products (in addition to packaging) that can lead to their clear identification [85]. Here, logistical issues are facilitated within the product design by including specific features that inherently provide knowledge about their performance level and/or usability. Krikke et al. coupled a volume-based mathematical model with optimization techniques to improve supply chain eco-costs for the design of refrigerators [86].

Life cycle simulation (LCS) has emerged as a promising field to narrow the gap between supply chain cost estimation and design feature decisions. As of now, there has been little work with regard to DFE in simulating supply chain networks. However, there have been recent studies within LCS specifically for optimization of supply chain eco-costs [87–89]. The potential benefits of LCS with regard to environmental cost savings and application to decision making are significant. The supply chain's relative impact on sustainability within design remains as a potentially rich avenue for innovative research.

6 Product End-of-Life Management

Managing end-of-life products has become a field of rapidly growing interest for product manufacturers. As environmental regulations urge stronger stewardship for product retirement, disposal can no longer be the primary retirement strategy for end-of-life products. Manufacturers need to find more proactive ways to reduce waste and save resources. EOL management of used products is a promising solution to this problem.

EOL management is the process of converting end-of-life products into remarketable products, components, or materials. It enables manufacturers to comply with legislation while gaining some economic advantage as well. As a result, more companies have become interested in EOL management, and successful cases have been reported by various industries, including IT and consumer electronics, household appliances, industry equipment, and automobiles.

Environmental regulations are strong motivators for companies to undertake product recovery. However, in order to facilitate EOL management and sustain its growth, another positive motivator is essential, i.e., profit. Accordingly, engineering methods for maximizing (or improving) profit from EOL management have seen to increase demand in both academia and industry.

Product design is the most important factor in achieving profitable EOL management. Product design features, such as product architecture, material properties, functional performance, and reliability, greatly affect what types of used products can be collected, what kinds of recovered items can be produced, what recovery operations are necessary to produce them, and how profitable the recovered units can be. Therefore, EOL management should be considered at the design stage in order to facilitate efficient and effective take-back and recovery. In this regard, a large number of studies have been conducted seeking optimal or at least better product design from the EOL-management standpoint.

6.1 Design for End-of-Life Management

6.1.1 Processes for End-of-Life Management. EOL management starts from product take-back, which is the process of collecting products that reach an end-of-life status. White et al. presented an overview of challenges in end-of-life management at each stage of the product recovery process and showed that better information about product design, product quality, and timing can improve the end-of-life opportunities [90]. Since product take-back determines the volume, type, and quality of feedstock processed later in the recovery process, how many cores and which types of cores should be acquired are major concerns for the manufacturer.

After product take-back, the collected products move to a recovery plant and pass through an end-of-life recovery process. After testing functional and cosmetic quality, unrecoverable units move to disposal sites for landfill or incineration. Recoverable products are reprocessed with various options, including reuse, refurbishing, remanufacturing, and material recovery. When component-level recovery is more worthwhile than product recovery, disassembly is performed in advance of other recovery processes. In disassembly, a product is dismantled and turned into a set of "child" subassemblies, and individual child subassemblies continue their recovery as independent units. Finally, recovered units are sent to various demand sites, such as manufacturing plants, second-hand markets, or component markets.

6.1.2 Method for Evaluating Product Design. The engineering challenge in EOL management is to be able to improve the design of the product after learning from the EOL strategies undertaken. EOL strategies involve a combination of decisions on the disassembly level (i.e., the extent to which a product is disassembled), disassembly sequence, and end-of-life options for resultant parts, such as reuse, remanufacturing, material recovery, incineration, and disposal [91]. These strategies are influenced by the product's attributes, manufacturer capabilities, and other constraints such as the cost and environmental impact of these decisions.

A number of methods have been developed to evaluate product designs based on their optimal EOL strategies. The optimal EOL strategy reveals the maximum recovery potential of the current product design. This information is helpful in answering various design questions. For instance, how good is the current design, which design is better than others, why, what is the limitation of current EOL management, and how can the product design be improved for better EOL management?

Early works in this field have focused on EOL management of a single type of product. Ishii and Lee proposed the reverse fishbone diagram to model the disassembly and processing sequence [92]. Penev and De Ron [93] and Pnueli and Zussman [94] used an AND/OR graph to represent a product structure and suggested algorithms to find optimal disassembly and recovery plans for the product. Kwak et al. proposed a linear programming model to achieve an optimal EOL strategy and discussed what insights can be gained for redesigning products [95]. Some methods, such as those developed by Krikke et al. [96] and Gonzalez and Adenso-Diaz [97], have focused on optimizing the disassembly level rather than the disassembly sequence.

Several studies have considered an extension problem of multiple types of products. Jayaraman [98] and Franke et al. [99] developed methods to manage a number of units of multiple products in end-of-life recovery. These models optimize the EOL strategy considering component commonality. Behdad et al. elucidated process commonality across multiple products in end-of-life recovery. The model is applicable to multiple products that do not share any components except disassembly operations [100].

For sustainability, establishing closed-loop system, i.e., a cradle to cradle system, is the most important goal. However, there have been only a few studies suggesting a systematic way to consider multiple life cycles. Zhao et al. presented a multi-life-cycle model to identify optimal life cycle lengths in the multiproduct case [101].

6.1.3 Design Method for Improving Processes. *Modular design.* In order to improve overall processes, modular design, where similar components sharing common characteristics are designed into a module, is frequently recommended. Marks et al. [102], Ishii et al. [103], and Feldmann et al. [104] proposed a modular design when the EOL strategy for the product is known. Qian and Zhang [105], Gu and Sosale [106], Sand et al. [107], Seliger and Zettl [108], and Umeda et al. [109] attempted to design modules by considering various life cycle attributes, such as compatibility of materials, similarity of lifetime, maintenance cycle, and ease of disassembly.

Part standardization. End-of-life management involves multiple types of end-of-life products. Accordingly, product take-back and end-of-life recovery are influenced by individual product designs and the interactions among designs. As Simpson [110], Perera et al. [111], and Bras [112] stated, increasing part commonality across product variants can benefit end-of-life management in two ways. First, the economies of scale in the recovery operation increase. Necessary tools and worker skills and setup time decrease in various recovery operations, including disassembly, repair, and reassembly. Second, the interchangeability of components across product variants increases, which in turn facilitates part reuse. Many studies have been conducted aiming at improving a specific area of EOL management.

Take-back management. Product take-back is emerging as a critical area to ensure sustainable product design and EOL management. Product take-back has been examined mainly from business and operational perspectives. Uncertainty of quality, quantity, and timing of end-of-life products makes EOL management difficult [113]. Active take-back can be used to mitigate such uncertainties. The active take-back system provides consumers with economic incentives if they return EOL products in good condition in a timely fashion. In this vein, pricing of used products and designing a trade-in or buyback program are of interest, and these concepts need engineering design involved for better decisions [114–116].

In the past, most product take-back models were focused on optimizing facility locations and resource allocation in order to minimize costs [117–120]. Recently, however, novel supply chain models started adopting product design focused variables in addition to location and allocation information in order to optimize LCA results [121,122,86].

A set of works addresses the problem of scheduling take-back. The demand for parts or recovered products triggers product take-back, and the objective is to fulfill the demand at minimum cost. Key decision variables are the amount and type of cores to acquire and the amount and type of parts to externally procure [123–127]. Research connecting the design perspective to business and operational perspectives is necessary. Also, product design for a timely take-back is necessary.

DfD. Design for disassembly (DfD) is a design method that makes a product easy to disassemble. Various DfD approaches have treated DfD with the assumption of a fixed recovery plan. They focused on evaluating the disassembly time and cost of a product [128–131]. When finding design weaknesses that counter the fixed recovery plan, one can improve it so that the recovered product can be effectively disassembled [132]. More innovative ways of DfD have also been discussed in academia, such as product-embedded disassembly using a snap-fit type of connector, active disassembly using smart material, and a heat-reversible connector [133–137].

Design for reuse and remanufacturing. Hammond and Bras (1996) [138] introduced design metrics for assessing the remanufacturability of product designs. In order for profitable reuse and remanufacturing, a product design should have efficiency in assembly, disassembly, testing, repair, cleaning, inspection, refurbishing, and replacement. In particular, easy repair and upgrade are emphasized in many studies. To render a product that has such characteristics, several concepts have been highlighted, including modular design [139,140], platform design [141,142], design for upgradability [143,144], and design for adaptability [145,146].

Design for material recovery. The economic viability and environmental impact of material recovery are directly influenced by the materials used. Reducing material diversity in a product, using less toxic materials, and employing biodegradable material are well-known design guidelines applicable in the design stage. Many approaches have been developed to help designers choose the proper material by considering all economic, environmental, and technical perspectives [147–149]. Product structure is also an important factor affecting material recovery. To be specific, modular design is desired, which supports easy separation of different material types. Williams provided a comprehensive review of demanufacturing for material recovery [150]. Mat Saman et al. proposed a method for evaluating the ease of recycling of a product [151]. Gutowski and Dahmus investigated the material mix in a product and predicted the likely end-of-life path of a product [152]. Finally, material recovery is also greatly affected by the process. Many analytical models for planning of material recovery have been developed; they include Choi et al. [153–155], Sodhi and Reimer [154], and Spengler et al. [155]. Product design is one of the most important inputs in these models.

6.2 Product EOL-Management Model. Who conducts take-back and EOL recovery is an important factor that must be considered in design for EOL management. EOL management can be conducted by the original equipment manufacturer (OEM), subcontractor, or independent remanufacturer [156,157]. OEM represents the original product manufacturer, while the subcontractor represents the remanufacturing company working for OEM under a contract, and independent remanufacturer represents the third-party remanufacturer. A comparative summary of the three business types—OEM, subcontractor, and independent remanufacturer—is provided in Table 1 with an insight for sustainable product design.

Clear distinctions among these cases are often hard in the real world. For a product, sometimes all actors are involved at the same time. In addition, sometimes the actors are collaborative and sometimes competitive. Geyer et al. [158] modeled the economics of remanufacturing for an OEM company, which conducted remanufacturing, and the remanufactured item was a perfect substitute for the new products. Many papers, including those of Majumder and Groenevelt [159] and Ferrer and Swaminathan [160] focused their attention on the competition between an OEM and an independent remanufacturer especially when OEMs involved remanufacturing in their business. Jung and Hwang [161] and Mitra and Webster [162] considered the competition between an OEM and an independent remanufacturer as well, but the OEMs were assumed not to be performing remanufacturing. This case shows the competition in the secondary market due to the cannibalization. Unlike others, Atasu et al. [163] and Heese et al. [164] considered the competition between OEMs that conducted remanufacturing.

Depending on the situation, optimal EOL management and optimal product design vary. In general, most design studies have assumed a simple setting of OEM remanufacturing. Understanding possible cases and variations is essential in order to identify possible directions for new research.

6.3 Insights for Sustainable Product Realization. It is difficult to recommend a specific product recovery model over another since this relates to different types of products and industries. However, OEM's direct product take-back and remanufacturing may be the most preferred model in the context of sustainable product design and recovery. In practice, it is unrealistic to expect OEMs to take feedback from remanufacturers for design innovation and changes, as pointed out by Ref. [157].

From the life cycle perspective, this research area has gained a new wave of interest that can be seen in recent works: product end-of-life decision making for multiple life cycles [101], linking product recovery with design decisions [76], merging recovery network with product design chain [165], sharing components or disassembly operations, etc [100,166]. However, an analysis of individual products is necessary to evaluate the efficacy of product recovery. Skerlos et al. [167] found that the extent of environmental impact of product take-back depends largely on situational issues such as transportation and energy grid technology.

Table 1 Remanufacturer business types and examples

Remanufacturer	Structure	Characteristics	Examples
OEM	OEM has full control over design and recovery.	• Effective compliance with environmental regulations. • Economic benefits (if return volume is high). • Reuse of remanufactured parts and components. • Protection of OEM's proprietary design information.	Kodak, Fujifilm (single-use cameras), Caterpillar, Perkins engine (engine/transmission), Milliken (carpet), BT industries (Forklift trucks), Swepac (soil compactors), Electrolux (white goods, commercial cleaning equipment), Xerox (printers, copiers), HP, IBM (PC)
Subcontractor	Subcontractor provides remanufacturing service.	• OEM maintains product brand and warranty. • OEM can facilitate design improvement based on subcontractor's feedback. • Subcontractors can receive assistance from the OEM for parts, designing, and tooling.	Flextronics InfoTeam (Sony, Game console)
Independent remanufacturer	No or little partnership exists between OEM and third-party remanufacturer.	• Remanufacturers often become competitors with OEM. • Remanufacturers need to purchase parts for recovery process.	Recellular (cell phones), 24 Hour Toner (toner cartridges), MKG Clearprint (toner cartridges), Turbo tech (turbochargers)
			Sources [157,169–172]

A logical progression of research will be in the area of sustainable product portfolio realization by embedding product recovery decisions early in the product design stage. Manzini and Vezzoli [168] argued that design should shift the business focus away from developing single products, toward managing systems of products that are jointly capable of fulfilling environmental demands. New aspects in the end-of-life decision model should include energy, enterprise-level strategy, environmental impact, emerging market conditions, disruptive changes, etc., as well as the conventional enterprise profit.

Potential research areas are summarized as follows, which reach beyond the engineering design community.

1. Establishing a mutual link between product design and recovery for a portfolio of products. Previous approaches have shown limited one-way influence (as opposed to mutual influence) either by proposing an evaluation method of design under a given recovery plan or by identifying an optimal recovery plan under a given product design. A new research direction is needed that captures prelife and end-of-life in a simultaneous manner by closing the loop of prelife, usage life, and end-of-life, thus enabling sustainable, multi-life-cycle product design and recovery. This research will logically combine well-established areas such as engineering design, operations research, optimization, and logistics.
2. Utilizing the evolving, massive-scale preference/usage/recovery data that can capture a dynamic trend in the design and recovery process. Utilizing data in product design and recovery process has been limited to small-scale, single-product cases to date in the context of product recovery. As the complexity of product design grows with volatile market conditions, a new research direction is needed to overcome the issues of scalability. This research will lead to a new area that combines data management, data mining, visualization and computing, as well as marketing and statistical preference analysis.
3. Component sharing decision making for product portfolio design and end-of-life recovery in a simultaneous manner. This leads to (1) the identification of the effect of sharing components on the recovery operations and (2) the effect of sharing disassembly operations on the design process. As a result, product portfolio design will be better, not only from the design perspective but also from the recovery perspective.
4. Embedding environmental regulations and policies in product design and recovery in the enterprise context. Recent studies suggest product design, and recovery decisions are closely related to the environmental regulatory policies. Regulatory enforcement, however, must be justified in the sustainable economic front for voluntary adoption in the industry. In other words, policy alone may not justify the economic shortfalls under the current challenging global economic environment. A new research area is needed to identify and characterize the interactions among design, recovery, environmental impact, and regulations, which will lead to potentially a new business model in industry.

7 Challenges

Early design decisions can have a significant or even dominant impact on the sustainability of product realization. The decisions have to be made based not only on structure, material, and manufacturing choices, but also on transportation, distribution, and end-of-life logistics and management. That is, the product's entire life cycle has to be included. Although LCA has been established as the most widely used methodology (and deemed as the most objective one) to evaluate the environmental sustainability of a product, applying LCA to support design decision making in general remains a significant challenge. Consequently, LCA is used more often as a compliance tool in practice. A design strategy toward sustainability could also be new product or machine designs leading to innovative designs in areas for which we have not envisioned products yet. Some coupled sustainability-energy-related products and processes are also attractive.

Another challenge lies in the fact that, until now, relatively comprehensive databases used to support LCA have only been developed for EU scenarios. The U.S. databases are under development, but the scope is very limited so far. Considering that product realization has been globalized, there is a clear need to develop inventory databases for all major countries involved due to their varying levels of technological development. Also, it should be noted that the current EU databases have been developed for product evaluation and not product design. The databases cover major industrial processes (called unit processes, such as producing 1 kg of stainless steel and generating 1 kW h of electricity). The unit process is treated as a black box, and there is no correlation between inputs and outputs specified, which makes the exploration of "what-if" scenarios (e.g., process changes/updates such as efficiency improvement) difficult. Probably, the drawback is most obvious for manufacturing processes where the unit process is based on the weight of the part being machined or deformed. Moreover, very limited processes have been developed for "infrastructure" (e.g., machines, devices, and components), which makes it tedious to identify environmental impacts of some commonly used product components (e.g., motors). The current methods, both repetitive and time-consuming within industrial application, force designers to start from the raw materials and manufacturing processes involved. Sharing of standard data for LCA may be envisioned as a future scenario.

Additionally, product family design has gained significance in the design community as a well-established design paradigm for designing a portfolio of products. Most research so far has focused on the design stage, while the role of the product family in product recovery is not known to date. Future work in sustainable product family design involves assessing the effect of platform sharing in product family design and recovery, optimal decision making in multigeneration product portfolio design and recovery, and end-of-life product/component decision making for maximum profit and sustainability, to name a few.

Another important area is to quantify the impact of regulatory and business decisions in product recovery. Current low rates of product take-back might be improved by strategic business decisions such as product buyback programs or regulatory enforcement in the form of a financial penalty. By quantifying these decisions, a new business model may arise through linking new product marketing and used product take-back in an incentive-driven environment.

One of the issues associated with low levels of product take-back is the high variability of incoming feedstock (i.e., end-of-life products) to product remanufacturers. Analytic methods for identifying design trends and corresponding recovery options will become a critical component for simultaneous design/recovery decision making. The effort should focus on design/recovery differences in various types of products such as PCs, cell phones, white goods, and automotive vehicles. Once the trend and corresponding recovery options are identified, OEMs can strategically focus on design issues such as component sharing across multiple generations and active product take-back by enforcing product usage terms, for example. Research in more sophisticated models for dealing with uncertainty during the remanufacturing process is also needed.

8 Future Trends

In the realm of sustainable product development, there is a strong indication that future research will address the issue of integrating information from subsequent life cycle stages into the early design phase. As a result, research in the fields of information modeling, uncertainty quantification, and decision making as applied to sustainability will be of key importance. Another area of future importance is the seamless integration of sustainability into design practices. Hence, research in design cognition and in developing natural interfaces such as the sketch-based interface, FEAsy [173], will come to the forefront. Tools such as the function impact matrix and Eco-Pas [29,35] explore this same idea. Sustainability, unlike many other design parameters, is a global constraint. Therefore, design tools in the form of life cycle simulation for sustainability need to be developed. Efforts in this direction have already been seen in the form of the development of Sustainability Xpress™ by Dassault Systems.

With regard to businesses, imminent regulations have forced companies to search for quantification methods to assess their eco-footprint. Therefore, some businesses, specifically Walmart™, have begun to map their entire supplier network and have pushed to convert traditional business models toward more sustainable practices. Efforts to minimize eco-costs by business leaders will force others to follow suit to secure a competitive advantage in the market. Thus, the area of carbon footprint evaluation and sharing is expected to become a key area for all businesses in the future. After significant compliance throughout businesses is realized, research areas, such as industrial ecology, risk assessment, and life cycle simulation, will all be further adopted in real industrial applications. Sustainability will become a key consideration in shaping business models employed in product design as well [8]. Research will be focused on developing design methods for selling a service (rather than a product), including leasing systems. Additionally, research into customer motivations for making new purchases will be required. In addition to the traditional cost versus performance trade-off information, information about why customers are replacing functioning products with newer models will help designers better meet customer needs. Related research on residual product value at the end of the first consumer use phase will also be needed. Design methods, which take this value into account for product design, material choice, manufacturing process design, take-back, and remanufacturing, could potentially improve both the economic and environmental efficiency of the entire life cycle.

To summarize, future research in the realm of integrated sustainable design will be directed toward the following:

- development of uncertainty models that are representative of LCA data used in the interpretation of environmental impact; implementation of these results with regard to ecodesign
- integration of socio-economic modeling with ecodesign and LCA
- integration of environmental considerations into process planning for more sustainable manufacturing process selection and inventory management
- development of a feedback mechanism linking product design decisions in a CAD system to actual manufacturing/assembly operations in CAM with the ultimate goal of evaluating a product's design without building an expensive physical production system
- development of an environmental life cycle inventory database for both existing and emerging manufacturing processes and integrating this database into the DFMA information model
- development of shared, yet secure databases that will allow retailers and consumers to compare one product with another for sustainability
- using LCS with regard to environmental cost savings and application to decision making
- development of a systematic way to consider multiple life cycles
- utilizing the evolving, massive-scale preference/usage/recovery data that can capture dynamic trend in the design and recovery process

9 Conclusion

Increasing the amount of research coupled with practical implications is required to make sustainable design decisions early in the product realization cycle. The early design strategy offers the highest impact on sustainability. During early design, the designer has significant power to shape the design intent of the project to influence consumer behavior [174]. This is particularly important in the realm of sustainability in which regulatory policies and consumer consciousness have yet to be fully developed. It is also necessary to include uncertainty in assessment of these decisions supported by appropriate metrics for sustainable design decisions. Integration with product life cycle management, along with addressing interoperability in the environmental knowledge models, is needed. Providing nonintrusive interfaces for sustainable design

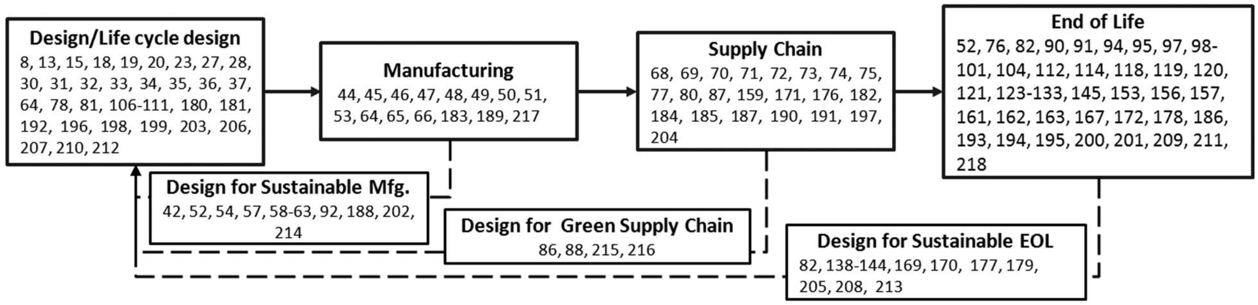

Fig. 7 Classification of research papers according to life cycle stages

decisions will enable the designer to interact with the knowledge models and design data as well as view data acquired from the past products. These varied efforts should be coupled with models and databases that can support sustainable decisions. The lack of standards and best practices in all domains from discrete products to buildings will increase life cycle costs with regard to sustainability. To limit the environmental impact in product development, "rigorous, clearly-defined measurements are essential" [175]. A community-based approach combining university research, national institutes, private enterprises, and even entrepreneurial eco-companies, together with larger enterprises, is needed to realize sustainability. Figure 7 illustrates the limited research in interfacing multiple life cycle stages with design. Thus, collaborations among the various disciplines of product realization (i.e., design, manufacturing supply chain, etc.) are essential to tackle this increasingly challenging task of sustainable development [176–218].

Of course, to realize these high-arching goals, research leaders must implement a complex systems approach for sustainable design decision making in product systems, in which manufacturing, global supply chain, and energy consumption are all linked. This integrative outlook on the interdependencies of these networked systems is currently outside the scope of existing engineering design and practice. Understanding and controlling multiscale, complex, coupled designed systems is essential to facilitating economic growth and improving health and societal well-being.

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