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Review Article

Environmentally Conscious Manufacturing and Life Cycle Analysis: A State-of-the-Art Survey

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Research on developing new methodologies on environmentally conscious manufacturing and way of reducing environmental impacts on product design was started over two decades ago. Environmentally conscious manufacturing has become a challenge to the environment and to the society itself, enforced primarily by government regulations and the customer expectation on environmental issues. In both industry and academics, there is a sizable following for environmental-related issues which are aimed at finding answers to the problems that arise in this newly emerged area. Problems are widespread including the ones related to the life cycle of products, disassembly, material recovery, and remanufacturing and pollution prevention. Only very few researchers have concentrated on ecofriendly products. This paper investigates the literature by classifying more than 200 published references into four categories, viz., design for environment checklist, environmentally conscious manufacturing, life cycle analysis, and material selection.

1. Introduction

Increasing customer demands has led to the present manufacturing industries to continuously evolve in meeting all the needs of end customer due to factors like competition and profit. But in this evolution process, environmental issues were neglected. This has resulted in serious environmental disputes like global warming, acid rain, changes in weather, and water shortages around the world. As a result of these environmental consequences from fast-paced industrial evolution, the ecofriendly Industrial Revolution has begun. While developing a product, the environmental performance of these products has become a vital issue. Bearing 5this issue in the mind, some industries are investigating ways to minimize their effects on the environment by providing products with high-level reusability. In recent scenario, a manufacturing facility was specifically designed in solar energy sector by a unique manner for utmost efficiency in terms of production and energy. The global earth warming is being mitigated by providing solar panels developed by NASA that utilizes sun energy. In another scenario, novel invention of a product, ecoconscious-based materials, reusable packaging products, etc. to name a few pave a good way for eradicating environmental pollution and maximizing resources. Remanufacturing is an economically viable and environmentally friendly way to achieve many of the goals of sustainable development. Remanufacturing forms an essentially closed-loop manufacturing system by concluding ends of the material use cycle. It primarily focuses on value-added recovery, rather than just material recycling. There are estimated to be in excess of 73,000 firms engaged in remanufacturing in the United States directly employing over 350,000 people (Lund, 1998). Environmentally conscious remanufacturing is fundamentally an industrial process wherein worn-out products are restored to like-new condition. The discarded product is completely disassembled through a series of industrial processes in a factory environment. The reusable parts are cleaned, refurbished, and put into inventory based on product development.

In another study, it was revealed that major hindrances faced by Western Europe are waste management and landfill space. The overseas manufacturers are incorporating more and more postlife considerations into their product design and development process. Both in industries and academia, under the influence by European governments, a considerable attention has been drawn towards material recycling. The material recycling focuses on leading constituent materials from the disposal of the product or its associated value into a new cycle of usage. Arguably, a drastic reduction in impact on environmental factors can be attained by reuse of product and remanufacture by which geometrical aspect of the product is retained and is reutilized for the same purpose as during its original life cycle for secondary purposes. With remanufacturing, the energy and matter consumption during manufacture is eliminated as the existing components are facilitated. The monetary expenditure incurred for producing or acquiring new product components are reduced elastically with remanufacturing. On the other side, the disadvantages incurred in remanufacturing are as follows: requirement of channels for collecting worn-out products, identification of product design and restructuring of product design for remanufacturing, need to redistribute and retail reprocessed products, etc. The four categories, design for environment checklist, environmentally conscious manufacturing, life cycle analysis, and material selection, play a vital role in sustainable manufacturing.

1.1. Design for Environment Checklist. Several researchers have given an overview on environmental design checklist as a method or tool to help manufactures to achieve an optimized design for ecofriendly development. A sustainable environmental design also contributes towards development of green manufacturing disciplines in the world. The primary objective of ecofriendly manufacturing process is to minimize environmental degradation effects in the product development perspective, viz., taking recyclability, reusability, and degradability into account, rather than to boost economic benefits. The design methodology for environmental design and development is attributed to energy efficient lighting, heating, and cooling systems. This energy-reliable manufacturing as an element of environmental design check suits lower operating costs as well as longevity in the product lifetime. In day-to-day scenario, the constructions of buildings in accordance with environmental principles provide enhanced occupant productivity and sense of wellbeing. Recycling and waste management are another aspect of environmental design.

1.2. Environmentally Conscious Manufacturing. Environmentally conscious manufacturing abbreviated as ECM is associated with producing methods for manufacturing new products from conceptual design to final delivery as well as ultimately to the end-of-life (EOL) disposal with respect to environmental standards and requirements. Product recovery, on the other hand, is aimed at minimizing the amount of waste sent to landfills by recovering materials and parts from old or outdated products by means of recycling and remanufacturing. ECM is driven by the escalating deterioration of the environment. With the aftereffects of both fast depletion of the raw materials and an increasing number of various forms of waste, viz., solid waste, air, and water pollution, in order to design and develop a product which is environmentally benevolent, the life cycle of the product should be very well understood. Figure 1 shows the flow process of environmentally conscious design.

1.3. Life Cycle Analysis. Life cycle assessment (LCA) stands as the preeminent tool for estimating environmental impacts caused by products from “cradle to grave” or “cradle to cradle.” It exists in multiple forms, claims a growing list of practitioners, and remains a focus of continuing research. Presently, this system of LCA is often used by decision-makers to study an entire product system in a very detailed way and still remains the focus as if the whole products were a single process. Therefore, LCA is started to prove that it is an excellent guidance tool for the industrial world to make their processes environmentally friendly. In LCA, useable parts are cleaned; then, the new product is reassembled from the old and, where necessary, new parts to produce a product that is fully equivalent and sometimes superior in performance and expected lifetime to the original product. Life cycle analysis (LCA) spans over the development, manufacturing, use, and disposal stages of the product. At these stages individually, decisions based on environmentally friendly techniques need to be made and have prompted methods like design for environment (DFE), design for disassembly (DFD), and design for recycling (DFR). LCA has proven to provide most important solution to environmental problems; its adjacent effect is with the birth stages of novel product development. However, the greatest impairment to nature occurs when the product completes its lifetime utility. Therefore, understanding and developing innovative techniques for end-of-life management of the products by means of product/material recovery would be a suitable solution for eradicating environmental or natural degradation. LCA is extremely crucial considering the millions of products that have already been developed without incorporating their undesired effects on the environment.

Recovery of products can be done in binary methods as discussed in the former sections, viz., remanufacturing and recycling. The difference between recycling and remanufacturing is based on recovering ability of material content. Recycling is aimed at recovering the material content of retired products by performing the necessary disassembly, sorting, and chemical operations. On the other hand, remanufacturing preserves the product’s (or the part’s) identity and performs the required disassembly, sorting, refurbishing, and assembly operations in order to bring the product to a desired level of quality. Disassembly has proven its role in material and product recovery

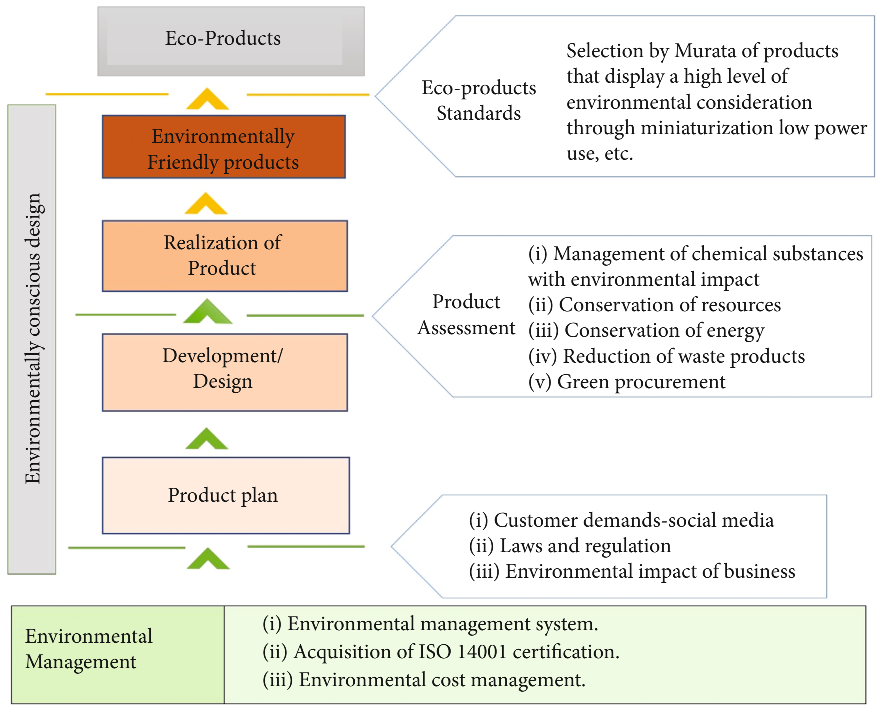

Figure 1: Flow process of environmentally conscious design.

by allowing selective separation of desired parts and materials. Besides being able to recover valuable precious materials by material recovery, good component removal via disassembly could provide parts for discontinued products and reduce the lead times in the assembly of new products. Life cycle analysis (LCA) spans over the development, manufacturing, use, and disposal stages of the product as depicted in Figure 2.

1.4. Materials for Environmentally Friendly Usages. Two common primary objectives arise as a momentum with the result of fast depletion of the raw materials and an increasing number of different forms of waste (solid waste, air, and water pollution). They are creating environmentally friendly materials (i.e., green products) and developing techniques for product recovery and waste management. Ecofriendly materials pave their way to the top among other class of materials. The primary reason for this ranking is due to its recycling and biodegradation aspects as well as zero degradation on disposal. The green materials are taking huge strides replacing toxic waste in the market place with organic materials. The trend of this green or ecofriendly materials has been escalating drastically to meet the demand of consumers for renewable and reusable resources. The materials used for environmentally friendly needs are diversified and spread in various regimes like constructions, waste water treatments, biodegradable materials, manufacturing, and packaging to name a few.

In this review article, many issues have been captured based on environmental issues with the attention of industries, academia, and manufacturing sectors. This article comprises detailed review about the effects of product design and development on ecofriendly aspects. Our objective is to offer an up-to-date literature review on product development based on environmental aspects, materials for recycling and reusable purposes, design for environment, etc. Basically, our surroundings have limited resources, viz., materials that convert into product, energy, water, and air supply. The areas for waste disposal and treatments are scarce in the society. The thrust for providing a sustainable environment for the next generation is of utmost privilege as the resources available in the globe are used for raising the living standard. This paper focuses on various literatures associated with the former mentioned aspects as the need to cultivate a viable solution for ecofriendly aspects related to product design development and manufacturing as well as recycling is of greater importance. The identification of extent of product issues and corrective actions given on research articles are also summarized in this paper. Moreover, the problems or issues sorted by the researchers in various dimensions affecting environmental degradation are also explained in this literature review article. The material selection criteria based on environmentally friendly aspects, degradation, and reusability are also given primary importance, for a better future. Lots of review researches have been carried out on green materials for environmentally conscious manufacturing aspects involving design and production.

Material selection should be a crucial consideration when building a product with environmental benefits. The environmental features of a product are very much fixed once the design decisions are made and the materials used to make it are known. In order to accomplish a complete ECM concept, concerns such as energy source selection, cooling systems, and handling of hazardous byproducts, among others, must be regulated during the production process.

When the product structure is large and complex and the number of components to examine expands, the LCA problem becomes more complicated. LCA demands contributions from all parts of society, including public pressure organizations,

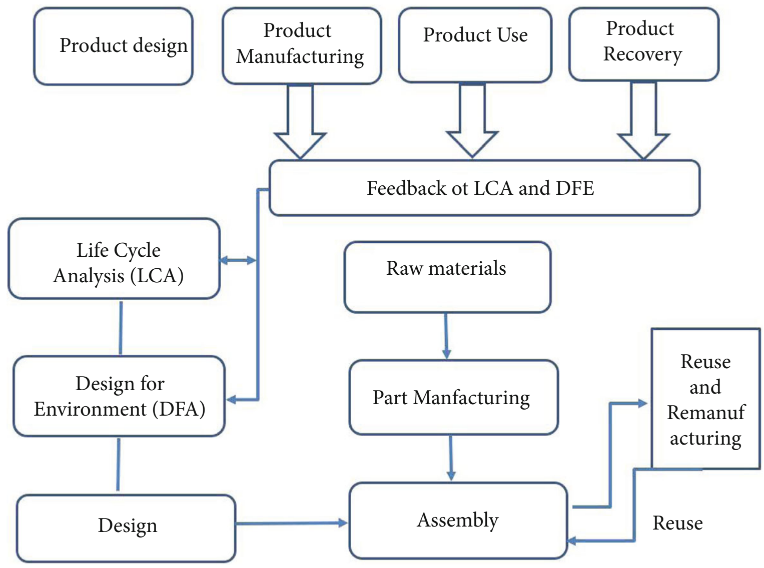

Figure 2: Flowchart representing LCA.

educational institutions, companies, and government agencies, according to a number of LCA-related researches.

2. Review Status of the Ecofriendly-Based Manufacturing Process

2.1. Design for Environment Checklist. DFE checklists are widely used tools for supporting product analysis at the design stages. Some checklists are intended for certifying ecolabels such as Ecomark [1]. By using a checklist, the designer can design good-quality, desirable, and cost-effective products to reduce the impact on the environment. Preparation of ecodesign checklist adds value or supports the designer for designing ecofriendly products. One of the most prevailing checklists called "the ecodesign checklist" covers the entire life cycle of a product from need analysis to the recovery and disposal stage [2]. Japanese manufacturers adopted the use of checklists and LCA for assessing the environmental aspects of their manufacturing products [3]. Many researchers have done lots of work with the help of the ecodesign checklist, and some of the findings are described below. Kishita et al. [4] framed a checklist that reduces CO_2 by 8% for a digital duplicator.

Ketchatturat [5] developed a self-evaluation checklist with each set consisting of 3 check points, 14 subcheck points, and 70 items to increase the value of educational provision processes. The author analyzed the data by employing content analysis, cross-case analysis, and analytical description methods. The PDCA cycle was used in the implementation of the self-evaluation checklist. "The ten golden rules," which is a powerful tool for integrating realistic environmental demands into the product development process, was introduced by Luttrop and Lagerstedt [6]. The product developers/designers can use these general guidelines as a base and guideline for the development of situation-specific product design challenges. Wimmer [7] developed an ecochecklist method that supports engineers in product development to produce ecofriendly products. The checklist is prepared based on a holistic view of the product in three analysis levels, namely, part, function, and product. Checkpoints show where the weak points of a product are and how to reuse and recycle the parts, where to integrate, omit, or create functions, and where to increase efficiency and reduce consumption and the usability of the whole product.

A method for incorporating ecodesign into product design and development in an automobile company was proposed by Wimmer and Zust [8]. The application of the twelve-step approach of ecodesign is implemented for the fuel tank unit of a car. This indicates that the approach can be a viable ecodesign method for manufacturers to integrate the environmental aspects of their products into their product design and development processes.

A variety of ecodesign checklists presenting a system to assist product designers in selecting the appropriate ecodesign checklist for product development were investigated and analyzed by Masoudi et al. [9]. Byggeth and Hochschorner [10] proposed that ecodesign tools can be used in both product development and purchasing, i.e., to prescribe design alternatives, assess environmental impacts, or compare environmental improvement alternatives. In this study, the authors analyzed 15 different ecodesign tools to ascertain whether a valuation is included in the tools, in what way the tools give support in different types of trade-off situations, and whether the tools provide support from a sustainability perspective. And it is concluded that nine of the 15 tools analyzed provide support in trade-off situations, but the support is not sufficient. The authors suggest that an ecodesign tool should contain a valuation if it is designed to support a user in a trade-off situation. The valuation should include a life cycle perspective and a framework for sustainability to give an accurate result from a sustainability perspective.

For industrial designers, Lofthouse [11] developed a more holistic framework for building ecodesign tools. The author has provided his result that "information/inspiration" makes ecodesign much more accessible to designers who intend to consider ecodesign strategies within their design work. It is a more user-friendly, design-specific service to designers, guidance providers, supplier information, and educators and allowed browsing source-specific data for interesting ideas. Two handbooks with recommendations and procedures for developing environmentally friendly vending machines were created by Vezzoli and Sciana [12]. To achieve these results, an LCA has been developed and a system to prioritize guidelines has been adopted. Finally, these tools have been integrated within the company procedure to consistently reduce the overall environmental impact of products throughout their entire life cycle.

Telenko et al. [13] made a compilation of designs for environmental guidelines. A total of 6 DFE strategies and 76 DFE guidelines were reconciled from 20 sources, and a subset was illustrated with examples. The guidelines are intended to be used in the early stages of design to reduce the environmental impacts of products and systems. The guidelines can be used as prompts for ideation, as expert knowledge in automated design guidance, and as criteria for evaluating early-stage design alternatives.

2.2. Environmentally Conscious Manufacturing. Environmentally conscious manufacturing involves producing products with minimized environmental effects [14–17] [16, 17]. ECM consists of two important issues. The first one is described that it understands the life cycle of the product and its impact on the environment at each of its life stages. Next, it will make better decisions during product design and manufacturing so that the environmental impacts of the product and the manufacturing process are kept at a minimum level. The issues in environmentally conscious manufacturing were addressed by Gungor and Gupta [18]. During the design stages of the product, there are different objectives that the designers should focus on. ECM designs the product which increases recyclability ([19][19–25], manufacturability [26, 27], and disassemblability ([28–30]; Lambert & Gupta 2005) in order to minimize the effect on the environment.

Ayes et al. [31] discussed the role of government regulation as a driver of change by reviewing several specific cases from European firms, with emphasis on the potential for internalizing the product by recovery, remanufacturing, and material recycling. The authors conclude with the views that the economics, the regulatory environment, and the organizational and management aspects are the problem. In light of environmental concerns, Brennan et al. [32] explain why manufactured parts must be disassembled. The authors emphasize the important point that the products and machines are to be designed in terms of disassembly and part recycling. The increased awareness of the state of the environment by both the consumer and the producer, recycling regulations, and resource conservation needs are leading to new challenges and dictate a fundamental reappraisal of the traditional manufacturing paradigm. A heuristic algorithm, referred to as the Acyclic Assembly Time (AAT) algorithm, which is based on the asynchronous model for concurrent machines in electronic assembly was developed by Moyer and Gupta [33]. The developed AAT algorithm increases the utilization of the individual mechanisms, and the efficiency of the overall system is naturally improved. The ultimate goal of reducing the total assembly time is achieved.

Mittal and Sangwan (2014) stated that the reliable, valid, and tested model has three types of drivers—internal, policy, and economic. It has been found through hypothesis testing that internal drivers for the implementation of ECM are positively related to policy and economic drivers, and policy drivers are positively related to economic drivers. This research is expected to help the government and industry in developing policies and strategies for the successful implementation of ECM. Argument et al. [34] examine academic research and industrial requirements in the area of environmentally conscious design. The authors wish to explore the perceived gap that exists between academic research and industrial requirements. Duhan et al. [35] in their paper on environmentally conscious manufacturing have used an analytical network process (ANP) decision tool in ECM and have concluded by saying that the manufacturing control process plays the most important role for environment-conscious manufacturing, and then, waste control comes next in the priority while quality control and research and design process comes next in hierarchy, and packaging control is the least important among the factors selected.

Yusuff et al. [36] have discussed the importance of the manufacturing process and environmental considerations which must be in place, from the design, production, use, and disposal. It is no longer viable to consider reduction measures of environmental problems after it has been produced.

The authors have found a way of strong disagreement, by suggesting the existence of a gap, and conclude that the most significant gaps are in the area of environmental concerns and research preferences. Many other researchers have also provided their perspectives and scope on environmentally conscious manufacturing which have been tabulated in Table 1.

2.3. Life Cycle Analysis. LCA is a process for assessing and evaluating the environmental and occupational health and resource consequences of a product through all phases of its life, i.e., extracting and processing raw materials, production, transportation and distribution, use, remanufacturing, recycling, and final disposal [44, 45]. To reduce ecological burdens, Alting and Legarth [46] introduce a conceptual framework of integrating life cycle engineering into designing low energy consumption in the use phase of a product. An economic input-output life cycle analysis model which was used to generate a large array of indicators for analyzing the economic and environmental impacts of a product was developed by Maclean and Lave [47].

The assessment was investigated in the application of a midsized automobile. Focusing on the manufacture and the use stage, Joshi [48] performed a life cycle inventory analysis by presenting a new model for performing product life cycle assessment. The proposed model is a matrix, which consists of environmental impact categories in conjunction with about five hundred economic inputs and outputs. The scope of LCA involves tracking all the materials and energy flows of a product from the retrieval of its raw materials to the disposal of the product back into the environment [49]. Most of the

Table 1: Author scope on ECM.

Author review	Scope
Lisa et al. (1998)	Environmentally conscious design
Bras & McIntosh [37]	Remanufacturing
Zhang et al. [38]	Environmentally conscious design and manufacturing
Guide et al. [39]	Production planning and control for remanufacturing
Guide [40]	Production planning and control, inventory management and control, disassembly, reverse logistics
Tang et al. [41]	Disassembly modeling, planning, and application
Williams [42]	Electronic demanufacturing processes
Kim et al. [43]	Disassembly scheduling
Duhan et al. [35]	Analytical network process (ANP)
Yusuff et al. [36]	Disassembly design, production planning, and application

researchers use LCA within a DFE methodology as a tool to measure the environmental impact of a product design [38, 50–53] [50]. LCA is a powerful tool chosen from a large number of available tools for their suitability of product assessment (Finnveden & Moberg 2004). Several authors have applied LCA to different case studies in automotive [54], [55], construction (Banaitiene et al. 2006), and computer industry [56, 57], [57], to target the individual evaluation of technical, economic, and environmental aspects of products or systems.

Most of the literature on LCA focuses on the second stage of the study, namely, the selection and evaluation of various, noncomparable environmental consequences ("chalk vs. cheese"), according to Ayres [58]. This problem is, indeed, very difficult and may well be impossible to solve convincingly—even at the conceptual level. However, the only approach that can make progress utilizes monetization to the limits of its applicability, rather than one that seeks to bypass (or reinvent) economics. Nevertheless, the evaluation problem is second in priority, for the simple reason that LCA has utility even if the evaluation technique is imperfect. On the other hand, LCA has no (or even negative) utility if the underlying physical data is wrong concerning critical pollutants.

2.3.1. Environmental Life Cycle Assessments. The idea of comprehensive environmental life cycle assessments (LCA) was conceived in the U.S.A. in the late 1960s and early 1970s. The first study of the life cycle perspective was focused on environmental impacts from different types of beverage containers [59], [60]. However, the formal analytical scheme to become LCA was first conceived by Harry E. Teasley, Jr. in 1969. At that time, he was managing the packaging function of the Coca-Cola Company. One of the interesting findings of the Coca-Cola Company is switching from glass bottles to plastic bottles [61], [62]

After the Coca-Cola study, there was a steady flow of resource and environmental profile analysis (REPA) studies at Midwest Research Institute (MRI). In the early 1970s, the driving force became solid waste issues. People were very interested in the total life cycle manufacturing system aspects of solid waste in comparison to postconsumer solid waste. The role of recycling and the use of reusable products to reduce solid waste were of particular interest. The inclusion of energy and other environmental emissions was not considered as important as solid waste. The second REPA study to be completed at MRI was sponsored by the Mobil Chemical Company [61], [63].

In the 1970s, the various calculations for performing an LCA were done without the aid of electronic computing equipment. The umpteen numbers of calculations were done on a mechanical calculator that did not even have a paper tape printout. It consisted of electric motors and rotating wheels [61], [61]. In 1973, the first LCA computer program was funded by an MRI client. The data filled several boxes containing many hundreds of punched cards. The information on the cards had to be loaded into the computer with a mechanical feeder at any point in time we wished to do calculations. Often the feeder would not read one or two cards correctly, and we had to start all over. The computer would often just indicate the error "somewhere," which meant the people would have to hand sort through the boxes of cards and try to find the card error. From 1970 to 1974, the modern concept of REPA/LCA took shape. Also, during that time, a framework for impact assessment was developed [62], 1973)[59].

In 1985, the major report was completed for Goodyear Tire and Rubber Company [60], [64]. The purpose of this report was to provide a database that the container presented no more threat to the environment than competitive containers. This was a study on 2-liter plastic (PET) soft drink containers and played a pivotal role in the initial marketing of that container. In 1992, there was a dramatic reawakening of environmentally consciousness, and it did not have a single source, but rather several factors were converged to create national debate and extensive media attention. Several consecutive international Society of Environmental Toxicology and Chemistry (SETAC) working groups moved the methodology development and international consensus building to a good step forward [65–67].

Presently, many automotive and manufacturing industries lead their research and developmental activities in response to the negative environmental developments. The new European Ford model, Mondeo, is designed to be 85% recyclable [68], [68]. Mercedes Benz implemented a total vehicle recycling program with vehicle design and vehicle recycling [69]. The highlight of the recycling program is reducing the variety and volume of plastics used, avoiding composite materials, and making logos with plastic parts. Mercedes and Swatch jointly designed a prototype car with vegetable fibers instead of metals. BMW announced a pilot program to test the feasibility of recycling BMW automobiles under the compulsion of German laws for recycling [70], [70]. Similar contributions were made by General Motors [69], Volkswagen [71], Nissan Motors [19], and Volvo Car Corporation [72]. The manufacturing industry adopted this technique to perfect their processes to make them more productive and environmentally friendly. Many researchers have worked on ecodesign for product development through the implementation of various tools and techniques. Table 2 presents various authors dealing with the application of life cycle analysis of various product designs and manufacturing processes and the results achieved.

From the above literature review process, a detailed study has been envisaged about life cycle analysis. LCA-based studies have been focused on development of performance-based manufacturing process suitable for reducing environmental degradation. Several researchers have also reported about LCA related to welfare assessment works. A prototype-based LCA has also been incorporated to estimate rapid assessment of conceptual design for environment.

2.4. Material Selection. The main concern in today's manufacturing industries is to bring out the products that are ecofriendly, and therefore, ecodesign is widely incorporated in the material selection [132]; [112]. Material selection influences more while designing a product. To reduce the environmental burdens of products, ecodesign is incorporated with material selection [113]. Tseng et al. [114] performed a green material cost analysis to recommend materials that cause less environmental impacts. The enormous types of materials are available for engineering application which makes the designer complexity in deciding the most appropriate materials. Several systematic methods have been proposed to help the designers in the selection of materials and processes [115, 116].

One of the most commonly used quantitative selection methods introduced by Ashby and Cebon [117] was based on the definition of the material index, and it consists of sets of physical-mechanical properties to maximize some performance aspects of the components. Defining the indexes, it is possible to produce selection charts reviewing the relation between properties of materials and engineering requirements [118]. Environmental information about materials is a must for the completion of product LCI. The different industrial sectors have developed environmental profile database for material based using the LCA approach [119, 120].

Holloway [121] introduced material selection charts called Ashby's method and shows how this methodology can be extended to take environmental factors into account. By implementing these charts and extending their range to include environmental concerns, designers may consider them the same way they consider the other material and process properties. A new life cycle cost analysis methodology with the goal of building a new sustainability model to quantitatively evaluate the overall direct cost of a vehicle over its complete product life cycle was proposed by Ungureanu et al. [122]. Evaluation of environmental impacts caused by a lightweight material and aluminum alloy used for autobodies was presented. Implementation of a life cycle engineering approach was done by Ribeiro et al. [123] to determine the material selection for a fender. The authors evaluated the best choice of material from mild steel to ultrastrength steel and aluminum alloys for the automobile fender. Three different methods—LCC, LCA, and a conventional approach—were applied for the sustainability performance of the product. The study by Zhou et al. [124] depicts that optimal material with the highest total fitness value was selected for a drink container. Genetic algorithms (GA) and artificial neural networks (ANN) were used to achieve the optimized mechanical, economic, and environmental properties.

Zarandi et al. [125] emphasize life cycle engineering (LCE), and it is one of the best approaches of material selection for sustainable products. The authors proposed a new methodology that supports the preliminary filtering of alternatives from an environmental viewpoint. Moreover, a prototype hybrid expert system based on the proposed methodology called material selection expert system for sustainable product design is developed to support the task of preliminary filtering. Five distinct life cycle effect assessment methods to study the use of different polymer materials used for packaging reasons were employed by Bovea and Gallardo [112]. He concluded that during material selection for a product design, decisions are based on a variety of factors such as cost, properties, performance, and environmental aspects. Katsukiya and Kevin (2001) presented guidelines for the ecological design of engineering products and processing of iron and steel through the application of automobile manufacture and its use. They concluded that the improved application of iron and steel enables the environmental burden to be reduced.

Zuo-ren et al. [126] introduced several representative case studies such as life cycle analysis of civilian buildings and metal production in China by reviewing the recent developments of LCA methods and application of materials via life cycle assessment. The possibility of reducing environmental effect for automobile components by adopting alternative materials and production procedures was investigated by Vinodh and Jayakrishna [127]. Sustainability Xpress evaluates the environmental impact and the mean percentage reduction in carbon footprint, water eutrophication, air acidification, and total energy consumed estimated at 43.68, 99.58, 48.38, and 52.19, respectively, which are meant as a drastic reduction.

Jeya Girubha and Vinodh [79] used VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje in Serbian, which means Multicriteria Optimization and Compromise Solution) as an MCDM tool for the selection of alternate material for instrument panel used in an electric car. The authors finally concluded that polypropylene can be used as a suitable alternative material for ABS instrument panels. A structural optimization technique to determine the best foams to use as the core material for sandwiches with aluminum alloy faces that would be used as floor panels in a concept car's bottom structure was employed by Ermplaeva et al. [128]. In future minimization, a problem for the weight of the entire bottom structure under static load conditions, including stiffness, strength, and buckling constraints, is formulated and solved for the material application. More analytical tools should be developed for estimating environmental degradation effects

Table 2: LCA of various product designs and manufacturing process or overview of applied case studies in LCA.

Authors	Application	Achieved result
Rosa et al. [73]	Life cycle assessment of a composite component for automotive using SimaPro 7.2 software	A panel made of hemp fiber and processed through vacuum bag infusion reduces the environmental impact at the production phase due to the use of plant-based materials and the impact reduction in the use phase due to the weight reduction of 280 g
Premrudee and Naruetep [73]	Life cycle assessment of lead-acid battery using Eco-indicator 95	An assessment of the entire life cycle of the battery found that a calcium maintenance-free battery had 28% less impact on the environment
Song et al. [74]	Environment performance of Chinese TV sets using SimaPro software version 7.2	Increases the energy efficiency within the various life cycle stages which reduces the environmental impact of TV sets. It also reduces overall energy consumption
Andersson et al. [75]	Life cycle assessment of tomato ketchup using CML provisional method	Packing and food processing were found to be hot spots, and the critical parameter was found to be the storage time in a refrigerator
Paris & Museau [76]	Quantification of environmental impacts of self-vibratory drilling (SVD) over traditional drilling (TD) using CML 2 baseline 2000 V2.04	Self-vibratory drilling is an innovative technology that increases productivity without coolant. Lifespan increases for twist drill to 200 m could contribute to the reduction of the environmental impact of the SVD process by 25% to 30%
Mayyas et al. (2012)	Life cycle assessment-based design approach to assess the performance of vehicular body-in-white is an analysis of the material to be used in the vehicle	It shows that magnesium and aluminum are used because of less energy consumption; however, advanced high strength steel (AHSS) has very less energy consumption than both of the above
Curran [73]	Life cycle assessment-based design approach to assess the performance	Ten important often overlooked or misunderstood aspects of LCA methodology and descriptions of what users should be aware of when setting out to conduct an LCA or when reviewing an LCA conducted by someone else
Vinodh & Rathod [77]	Integration of environmentally conscious quality function deployment (ECQFD) and life cycle assessment (LCA)	The analysis of the response of executives indicates that the suggested tools/techniques are practically feasible and compatible for sustainable product development
Eliceche et al. [78]	Minimization of environmental life cycle impact as a tool for process optimization of utility plants	Significant reduction in the environmental impact, operating cost, natural gas, and electricity consumption has been achieved simultaneously, increasing the efficiency of the plant
Vinodh et al. [79]	Application of life cycle assessment on the instrument panel of an electric car using CML methodology	The sustainability index of the instrument panel has been computed before and after implementing the EIA methods, which has shown a notable improvement level from 6.09 to 7.73. Also, the improvements have been statistically validated and found to be 90% satisfactory after the implementation of EIA into practice
Kharel & Charmondusit [80]	Ecoefficiency evaluation of iron rod industry in Nepal using LCA	It is noteworthy to mention that the ecoefficiency of the iron rod industry has been improved in all respect of energy intensity, material consumption, water use, waste generation, and CO_2 emission

Table 2: Continued.

Authors	Application	Achieved result
Monteiro & Freire (2012)	Life cycle assessment of a house with alternative exterior walls using CML 2001 and EI'99	To sum up all results, the wood wall has been pointed out as the preferable solution by the three methods and the results for the remaining exterior wall scenarios are influenced by the life cycle impact assessment method applied, in particular for the toxicity categories
Marco et al. [81]	Validation of recycled materials using life cycle assessment methodology for the injection molding process	The study underlined the effective improvements of the environmental aspects by substituting the actual product with the one made of recycled PET (RPET). The research demonstrated a useful interaction between life cycle assessment and the conceptual design phase with the design supporting software packages used in the injection molding field
Li et al. [82]	Ecoefficiency approach to evaluating energy as well as resource efficiency of manufacturing processes in grinding case	The evaluation process shows the dynamic nature of the unit manufacturing process, whose ecoefficiency can be improved by accounting for all aforementioned aspects. The current application faces challenges to gather reliable data, such as life cycle inventory data for grinding wheel and coolant consumption/loss
Gonzalez-Garcia et al. [83]	Life cycle assessment of eucalyptus TCF pulp manufacture using CML baseline 2000 V2.1	The main contributors to the environmental impact are not related to the wood paper pulp manufacture that takes place inside a mill, the background process such as the upstream production of chemicals and fuels has been identified as the main contributor to impact categories related to toxicity and abiotic resource depletion
Puettmann & Wilson (2005)	Life cycle analysis of wood products: cradle-to-gate approach	The environmental performance of these products is measured by total energy and major emissions. LCI findings for the production of wood products, by the nature of the industry, show that the use of biomass as major fuel will decrease the environmental impacts
Duflou et al. [84]	Life cycle assessment of manufacturing process	Significant environmental impact (CO_2 PE!) reductions are identified in the manufacturing unit process
Frenette et al. [85]	Life cycle assessment of light-frame wood wall assemblies using IMPACT 2002+, Eco-indicator 99, and TRACI	The results of the case study, which are consistent with all the methods considered, show the relatively small contribution of the wood framing and other wood-based products on the total embodied impact
Cherubini & Jungmeier (2010)	LCA of a biorefinery concept that produces bioethanol, bioenergy, and biochemicals from switch grass using CML 2 baseline 2000 V.2.03	Significant GHG and fossil energy savings are achieved when the biorefinery system is compared with a fossil reference system. In the first 20 years of activity, 79% of GHG emissions and 80% of fossil energy were saved. After 20 years, the soil is in new equilibrium and atmospheric CO_2 is no longer sequestered; CO_2 emissions of the biorefinery system increase by 65 kt/a
Kaebernick et al. [86]	Life cycle assessment of product development using various tools	Environmental requirements must be considered as equal partners to the traditional requirements of cost and quality. Several tools and methodologies are available, and some others are still being developed

Table 2: Continued.

Authors	Application	Achieved result
Pecas et al. [87]	Life cycle assessment of plastic injection molds using Eco-indicator 99	The comparison of two alternative molds reveals that the “best mold” is the STM mold in terms of economic and environmental aspects, while conventional mold (CM) mold has a better technical performance
Zufia &Arana [88]	The life cycle of tuna with tomato food products using LCA-TEAM 4.0	Improvements are established for the concept of product, the reduction of the use of material, a material with less impact, transport efficiency, and replacement of raw material
Lombardi [89]	Life cycle assessment and energetic life cycle assessment (ELCA) of a semiclosed gas turbine cycle using SimaPro	The results show that the major energy destruction is due to the SCGT/CC cycle operating phase because of the conversion of chemical energy into thermal energy during the combustion process. The energy of all phases is negligible when compared with these terms
Wang & Sun (2012)	Life cycle assessment of CO_2 emissions from wind power plants	Sensitivity tests show that the measures taken to increase the CP would result in a significant reduction of emissions. The use of wind to produce electricity constitutes an environmental improvement, and more research on this technology is needed
Erol &Thoming (2005)	Ecooptimization of pretreatment processes in metal finishing	From this process, 74% improvement can be attained in terms of environmental indicators depending upon the weighting ratio; it represents the impact factor and cost objective
Andrae et al. [90]	Life cycle assessment of electronic products assessed using a generic compact model	The model has successfully been applied to a digital system telephone (DST) to partly quantify technospheric greenhouse gas emissions from the intermediate unit processes (IUPs) of the DST, in the upstream life cycle. The need for data gathering is great but not as extensive as it would be whereby the data collection can be reduced for silicon-containing electronic components
Busi et al.	Environmental sustainability evaluation of innovative self-cleaning textiles	This paper shows the whole “gate-to-gate” analysis; the innovative material shows decreased impacts
Cottle and Cowie	Allocation of greenhouse gas production between wool and meat in the life cycle assessment of Australian sheep production	This paper proposes PMA as a simple, easily applied allocation approach for use when attributional life cycle assessment (LCA) is undertaken
Manda et al. [91]	Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value	This paper supports LCA-supported decision-making of business functions to create sustainable value
Go et al. [92]	Multiple generation life cycles for product sustainability: the way forward	In this paper, design for multiple life cycles is defined as a combination of ecodesign strategies including design for environment and design for remanufacture, which leads to other design strategies such as design for upgrade, design for assembly, design for disassembly, design for modularity, design for maintainability, and design for reliability
Matsuyama et al. [93]	Simulating life cycles of individual products for life cycle design	This paper defined two types of information of products: nominal information and entity information. To support the design of such a product life cycle, this paper proposed a method for modeling the product life cycle by simulating the entity information at its design stage

Table 2: Continued.

Authors	Application	Achieved result
Miranda de Souza and Borsato [94]	Combining Stage-Gate™ model using set-based concurrent engineering and sustainable end-of-life principles in a product development assessment tool	Their paper presents a development example using the proposed tool and compared it with a product designed with normal Stage-Gate
Scheepens et al. [95]	Two life cycle assessment- (LCA-) based methods to analyze and design complex (regional) circular economy systems. Case: making water tourism more sustainable	The conclusion from this paper is that the approach of ecoefficient value creation helps to avoid many pitfalls of the design of circular business models
Wiedemann et al. [96]	Application of life cycle assessment to sheep production systems: investigating coproduction of wool and meat using case studies from major global producers	This paper provides a functional BA method based specifically on protein requirements for application in attribution to LCA studies
Hicks and Theis [97]	A comparative life cycle assessment of commercially available household silver-enabled polyester textiles	The paper discusses the lifetime environmental impact of the three textiles considered varied as a function of the silver content and environmental impact category
Piontek and Muller [98]	Literature review: life cycle assessment in the context of product-service systems and textile industry	Analysis of the literature focused on the following aspects: The impact categories: while some categories appeared quite often (e.g., global warming potential, energy usage, and water depletion), others are less common and therefore difficult to compare to other studies
Roman et al. [99]	Development of LCA benchmarks for Austrian torrent control structures	This paper determines the range of LCA results, where an estimate of environmental impacts in early planning stages becomes possible
Morales-Gonzalez et al. [99]	Life cycle assessment of vitamin D_3 synthesis: from batch to photo-high p, T	This paper explains how continuous manufacturing of vitamin D3 is faster, requires fewer steps, and uses fewer solvents compared with the industrial synthesis using LCA
Joyce [99]	Computer vision for LCA foreground modeling—an initial pipeline and proof of concept software, Icopt–cv	This paper demonstrates that it is possible to generate a fully functional LCA model from a picture of a flowchart This has potentially important implications not only for LCA practitioners as a whole but also in particular for the teaching of LCA
Budzinski et al. [100]	Consequential LCA and LCC using linear programming: an illustrative example of biorefineries	This article shows that linear programming can be used to extend standard LCA in the field of technological choices
Gediga et al. [101]	Life cycle assessment of zircon sand. The international journal of life cycle assessment	In this paper, the LCA has quantified the potential environmental impacts associated with the production of the zircon sand ($ZrSiO_4$). With this study, a sound dataset for downstream users of zircon sand has been provided
Peters et al. [102]	A Swedish comment on review: the availability of life cycle studies in Sweden	Rather than being a review of the available data, the article lists a tiny sample of the many Swedish LCAs available from the included sources and provides some descriptive statistics and comments on this particular sample
Crenna et al. [99]	Global environmental impacts: data sources and methodological choices for calculating normalization factors for LCA	This paper discusses the quantification of the current levels of environmental pressures that entails the critical aspects, as it consists of an accounting of emissions and resources, relying on data often incomplete or based on modeling

Table 2: Continued.

Authors	Application	Achieved result
Heijungs et al. [103]	Everything is relative and nothing is certain. Toward a theory and practice of comparative probabilistic LCA	This paper puts the elements discussed in a structure that provides a research agenda for dealing with comparative uncertainties in LCA
Pelletier et al. [104]	Interpreting life cycle assessment results for integrated sustainability decision support: can an ecological economic perspective help us to connect the dots?	This paper supports a reinterpretation of LCA as a true sustainability decision support tool, in particular by enabling unification of historical development/practice with recent methodological developments
Vrasdonk et al. [105]	Reference situations for biodiversity in life cycle assessments: conceptual bridging between LCA and conservation biology	The paper recommends that reference situations for biodiversity in LCIA models should be developed based on biodiversity targets aligned with society's conservation frameworks
Corona and San Miguel [99]	Life cycle sustainability analysis applied to an innovative configuration of concentrated solar power	The methodological approach described in this investigation provided flexibility in the selection of objectives and analysis tools, which helped to quantify the sustainability effect of the system at a micro- and mesolevel in the three sustainability dimensions
Borridon et al. [106]	Development of LCA calculator to support community infrastructure codesign	A prototype version of an LCA calculator software tool has been developed to enable rapid assessment of the conceptual design of engineering systems
de Laurentlis et al. [64]	EATS: a life cycle-based decision support tool for local authorities and school caterers	This article focuses on the potential offered by the public food sector for a transformative reduction in the environmental impact of urban food consumption
Loppolo et al. [107]	Integrating strategic environmental assessment and material flow accounting: a novel approach for moving towards sustainable urban futures	The proposed SEA-MFA framework has the potential to unify and standardize the processes of categorizing and quantifying data to improve the understanding of urban metabolic principles and scale effects
Allacker et al. [108]	Energy simulation and LCA for macroscale analysis of ecoinnovations in the housing stock	The authors concluded that LCA integrated with dynamic energy simulation may help to unveil the potential improvements and burdens associated with ecoinnovations
Tallentire et al. [99]	The challenge of incorporating animal welfare in a social life cycle assessment model of European chicken production	In this paper, a methodology that incorporates animal welfare indicators into S-LCA was developed that is both scalable and related to welfare assessment frameworks
Prathap and Senthilkumaran [109]	Reduction of environmental impact by incorporating performance-oriented life cycle analysis	This paper discusses how incorporating performance-oriented life cycle analysis can impact environmental reduction
Prathap and Senthilkumaran [110]	Quantitative evaluation for reduction of environmental impact in the product life cycle of a monoblock pump	In this paper, the authors have given insight into how selective materials for a monoblock pump can have an impact on environmental evaluation
Prathap and Senthilkumaran [73]	Production life cycle studies based on design for environmental checklist for product enhancement	In this paper, the authors have studied the various environmental checklists for product enhancement
Prathap and Senthilkumaran [111]	Environmental cautious design of subassemblies in 0.5 hp pump	This paper discusses how various materials selected for subassemblies of pumps have an impact on the environment

during manufacturing. Ecofriendly manufacturing process should be projected towards development of recyclable products. Also, develop strategic models for the analysis of eco-friendly products concerning technological and organizational dynamics.

3. Conclusions

This paper presented a view of the state-of-the-art literature on environmentally conscious manufacturing of products published during 1999-2018; the following general conclusions could be drawn from the literature review.

(i) Environmental issues are gaining acceptable popularity among society, government, and manufacturing industries due to the negative environmental influences

(ii) Researchers proved that the manufacturing of environment friendly products is crucial to minimize the use of virgin resources, which can be achieved by studying the life cycle tool implementation. Reclamation of materials and parts from outdated products is equally crucial in fighting against environmental issues

(iii) The firmer implementation of environmental laws and regulations globally will bring our society to think of our environment as a global issue rather than an individual nation's problem. Although the modern development in environmentally conscious manufacturing of products research is encouraging, researchers' collaboration is highly needed to develop interrelationships and determine the global effects of this sphere

Data Availability

There are no relevant data to be made available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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