INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING Vol. 13, No. 7, pp. 1259-1272
DOI: 10.1007/s12541-012-0169-1

Review of Sustainable Product Design from Life Cycle Perspectives

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KEYWORDS: Sustainable design, Sustainable product development, Life cycle assessment, Environmental impact

Design stages have been widely recognized as a key phase in a product's life cycle in implementing sustainability. Since the late 1990s, various sustainable design methods and techniques have been developed in response to the requirements of sustainable product development. Understanding what types of sustainable methods have been applied in which design phases is advantageous for determining future research directions. The main purpose of this study is to systematically review past studies on sustainable product design. These studies are categorized into different types according to a two-dimensional framework. The ideas and limitations of representative approaches in each category are discussed. The results show important findings and implications.

Manuscript received: March 13, 2012 / Accepted: June 5, 2012

1. Introduction

Environmental issues such as global warming and energy consumption have become the most critical challenges faced by the contemporary world. To consider sustainability in product development is imperative for modern enterprises. Because of increasing scarcity of resources and raw materials, environmental regulations have emerged with potentially drastic impacts on manufacturing and logistics.[32] A consensus in industry and academics is the need to implement sustainability at early stages of a product's life cycle. Unfortunately, current product development activities in manufacturing companies are still predominantly driven by quality/cost concerns. These companies worry that implementing eco-friendly means into product development plan could incur additional costs and thus reduce their competiveness. It is not surprising that environmental requirements are mostly treated as an afterthought.

The World Commission on Environment and Development defines sustainable development as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Elkington[36] indicated that the concept of sustainability should cover economic, societal, and environmental aspects. This concept is also known as the triple bottom line (Fig. 1), where profit, planet, and people are considered simultaneously. Therefore, the scope of sustainable design covers all spectrums of product life. Sustainable design is generally the process of developing a product that performs functions successfully, generates profits for the company, is socially acceptable, and uses minimum energy and material without producing hazardous waste.

Proper sustainability tools and techniques are required to implement sustainable development in a company. They are critical to making environmentally friendly decisions during the development process. However, studies[33,35] have highlighted that many usable sustainability methods and indicators are extremely complex and foreign to typical workers and, in many cases, management as well. What is worse is that no "one size fits all" method exists and techniques that stand alone are often misleading and may lack the technical depth needed to truly assess progress. This inhibits their ease of implementation and understanding.[34]

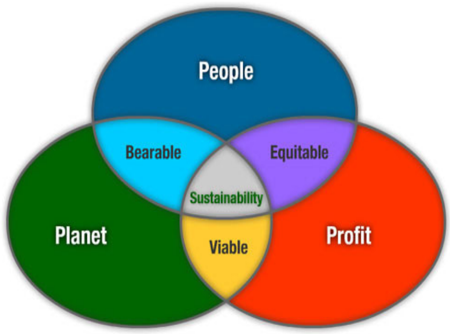

Fig. 1 Triple bottom line of Sustainability[36]

Life cycle assessment (LCA) is a method used to evaluate the environmental impact of a product through its life cycle, including extraction and processing of the raw materials, manufacturing, distribution, use, recycling, and final disposal. A full assessment, often referred to as cradle-to-grave, is extremely time consuming and needs specific data. Many scholars have used simplified or partial LCA methodologies for the early estimation of the environmental impact of a product. In this study, a typical product's life cycle has four phases: material extraction, production, operation, and retirement (Figure 2).[15]

2. Classification Framework

The goal of this research is to systematically compile, evaluate, and summarize past studies on sustainable product design. Our focus is to highlight what types of sustainable methods have been applied in their respective design phases, and to discuss the concepts behind and limitations inherited by each method. We propose a two-dimensional framework to classify those studies and compare their characteristics. The result helps identify future research directions in sustainable design.

This section presents a categorization framework to distinguish different efforts in sustainable design. This framework consists of two metrics. Along the ordinate, Guideline provides easy to follow general operational instructions to product development team members. Metrics involves simple qualitative and quantitative criterion for environmental assessments. DfX refers to Design for X perspectives and this study is focused on perspectives related to sustainability such as manufacturing, environmental, dis-assembly, and recycling. LC Costing denotes techniques that compute life cycle costing. Finally, Methodology tackles sustainable design issues from a systematic viewpoint, which considers interdependencies among various stakeholders in product development.

The abscissa delineates the time line for a typical product design process. Such a process can be roughly classified into four stages: problem definition, conceptualization, preliminary design, and detail design (Ogot & Kremer, 2004;[40] Ulrich & Eppinger, 2004;[41] Pahl & Beitz, 1996[42]). The problem definition stage identifies customer needs and product functions. The conceptualization phase generates product architecture (a.k.a.

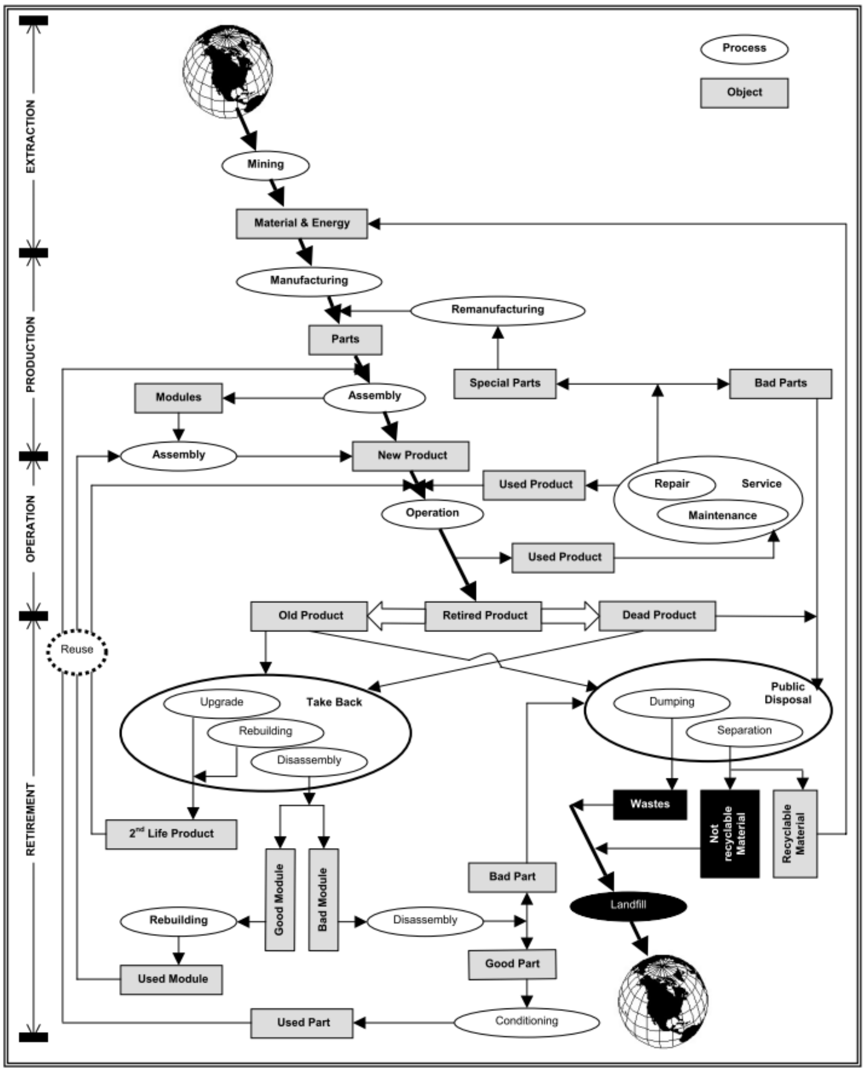

Fig. 2 Product Life Structure[15]

system-level design), specifications, and selects components that satisfy customer needs. The preliminary design stage (a.k.a. embodiment design) presents components, related motions, and form. The design stage finalizes the physical prototype and detail specifications of processes and materials. The reviewed sustainable design efforts are structurally categorized into the framework below (Figure 3).

3. Literature Review

3.1 Guideline

Spangenberg et al.[21] applied SCALES (Skills, Creating change agents, Awareness, Learning together, Ethical responsibilities, and Synergy and co-creating) principles to support design for sustainability in design education and practice. The overall goal of SCALES principles is to achieve consumer satisfaction with less resource activated. This goal can be further decomposed into satisfier efficiency, supply/use efficiency, product efficiency, production efficiency, and provision efficiency.

Waage[27] suggested a guideline based “roadmap” to integrate the sustainability conflicts among economic, social, and environmental aspects. The road map has four phases. Phase 1 establishes sustainability context that can raise sustainability issues in relation to client and product. In Phase 2, sustainability issues are defined through mapping and sustainability analysis. Phase 3 assesses which considers potential pathways forward in relation to a vision of a sustainable solution. Finally, phase 4 is to act and receive feedback so as to create and roll-out sustainability oriented product/service and to evaluate and (re)assess in terms of sustainability definition and context. The whole sustainable design processes is achieved by asking designer sustainability questions. Ljungberg[37] presented a sustainable product design guideline considering whole product life spanning and emphasized that materials are the key to achieve sustainable design. Bhander et al.[71] suggested design strategies which can enhance sustainability at end-of-life phase of product. These guidelines[21,27,37,71] begin at problem definition stage.

Santana et al.[23] constructed a guideline based reference information system for sustainable design. This software covers life cycle assessment, product service systems, social, and economic

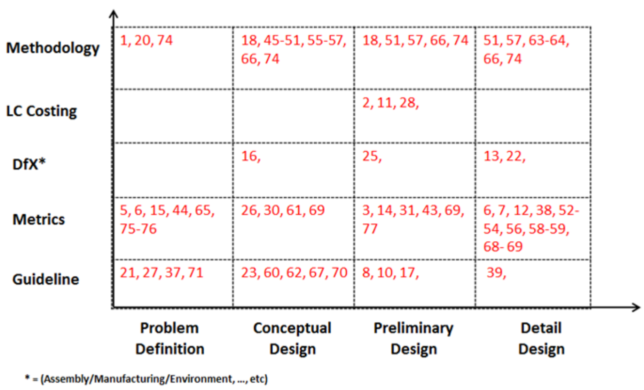

Fig. 3 Sustainable design efforts categorized by the framework

aspects. Six steps of reference process during product life cycle are: functionality conception, raw material acquisition, manufacturing, trade and delivery, use and maintenance, and reuse, recycling, energy recovery and disposal.

Anastas and Zimmerman[60] asserted that innovation must be used to design sustainability into products, processes, and systems in a scalable way. They proposed 12 principles of green engineering that provide scientists and engineers to create and assess the elements of design relevant to maximizing sustainability. By using these principles, the conversation that must take place between designers of molecules, materials, components, products, and complex systems can occur using a common language and a universal method of approach.

LCA requires detailed product development data that may not be available at the early conceptual stage of product design. To overcome this difficulty, eco-design principles and guidelines are created to help designers improve environmental impacts of products by making better early design decisions. However, existing methods for creating environmentally conscious design guidelines are largely undisclosed and do not offer a thorough process for extracting actionable guidelines and determining their environmental impacts. Thus, Telenko and Seepersad[62] presented a systematic method based on reverse engineering techniques and LCA for extracting environmentally conscious design principles and guidelines from existing products. A case study of reducing energy use for an electric kettle demonstrates how this method works step by step. One major advantage is that resulting guidelines can be used during the conceptual stages of designing similar products without repeating the steps of the method. Applying the method to other classes of products and other environmental concerns, such as the supply chain, is needed to make it a generic approach.

Most recently Bovea and Pérez-Belis[67] review and classify tools that have been developed to evaluate the environmental requirement of products and to facilitate its integration into the product design process. Their focus is to provide designers a guide to selecting the eco-design tool that best fits a specific case study. A taxonomy framework was made according to criteria such as (1) the method applied for the environmental assessment (2) the product requirements that need to be integrated in addition to the environmental one (multi-criteria approach) (3) whether the tool has a life cycle perspective (4) qualitative or quantitative (5) the stages of the design process where the tool can be applied, and (6) whether the tool has been applied to a case study. Veshagh and Obagun[70] conducted an empirical survey to identify life cycle design benefits as well as drivers in industry. This study pointed out that cost and time are the main barrier of sustainability while design for recyclability and minimization of hazardous materials can be introduced as sustainable strategy of enterprise. The above four guidelines[23,60,62,67,70] will enhance sustainable design at the conceptual design stage.

Heijungs et al.[8] pointed out a eight-aspect framework as guideline that should be considered with an aim to improve sustainability. These aspects include technical models, physical models, environmental models, micro-economic models, meso- and macro-economic models, cultural, institutional and political models, ethical and societal values, and models for integrated environmental, economic & social analysis. Kasarda et al.[10] adopted the rational of control feedback system in order to simulate possible environmental changes in the future and modify current design to be sustainable. A eight-step guideline is provided in this study. Ma et al.[17] developed a guideline based method that contains four steps: optimized product and process optimization, product life cycle modeling, life cycle analysis and lifecycle optimization. The above three methods start at preliminary design stage.

Ijomah et al.[39] proposed a Design for Re-manufacturing (DRrem) guideline that can enhance the product re-manufacturability by coordinating material, assembly technique, and product structure. This guideline is considered at the detail design stage.

3.2 Metrics

Fargnoli and Kimura[5] provided a metric based method for appreciate tools on different design objectives. Several Quality Func-tion Deployment (QFD) based, LCA, and checklist tools are evaluated using six criteria, which are the ability to correctly define the product's requisites/performances, usability, effectiveness of the method in assessing the environmental performances of the product, ability to provide new solutions, possibility to review the design activities allowing designers to perform a correct design management, and ability of the method in fitting into a certain design process. Therefore, appropriate techniques can be adopted for different product and circumstances.

Fargnoli and Kimura[6] proposed a Screening Life Cycle Modeling (SLCM) method to achieve sustainable product design. Four steps of SLCM are: Base Scenario (BS) definition, Alternative Scenarios (ASs) definition, Simulation and Analysis of results. An indicator which is product of energy consumption, life span, efficiency improvement rate and recycling ratio is defined as judgment criterion.

Bovea and Wang[44] propose a novel redesign approach that integrates QFD, LCA, life cycle cost (LCC), and contingent valuation (CV). This approach identifies environmental improvement options and at the same time compares the increase that the incorporation of these options produces on the life cycle cost of the product, to the additional money that the customer is willing to pay for perceiving environmental benefits. A case study of office furniture re-design shows that re-designing products with a significant improvement in their sustainability without compromising other customer requirements is possible. To estimate customer willingness to pay (WTP) is crucial in product eco-design.

Sakao[65] argued that current eco-design methods support manufacturers to satisfy necessary conditions but not sufficient conditions so as to obtain competitiveness in their markets. These methods may sorely help companies deal with regulations or legislations which their products must comply with, instead of helping understand what kinds of environmental characteristics contribute to the economy. This paper aims to propose the application of quality engineering in the early phase of environmentally conscious design. A framework was proposed for classification of environmental characteristics of products/services in two dimensions based on the Kano model and willingness to pay. This framework is connected to product design and external communication with the company strategies given. It is applied to three environmental characteristics against Japanese markets and the test results show its effectiveness as much richer implication than other existing methods can be obtained. This research, in a broader sense, exists in integration of marketing and design disciplines.

Lu and Gu[15] proposed a sustainable product development method that includes three design requirements, two design tasks, and three comprehensive assessment streams. The design requirements, which are functional purpose, environmental requirement, and economic requirement. The functional purpose is derived from the customer needs to reflect the product's major purpose; the environmental requirement reflects the society's needs of protecting natural resources and environment; and the economic requirement denotes the producer's basic business motivation. Accordingly, two design tasks compose of physical structure and life cycle structure. These design parameters need to be determined for the product's physical structure and lifecycle structure. Three comprehensive assessment streams consist of lifecycle quality analysis, life cycle assessment, and lifecycle costing. In the assessment phase, LCQ (lifecycle quality), LCA, and LCC are three assessment streams in respect to the functional, environmental, and economic evaluations. Kobayashi[75] proposed a QFD based design support tool to evaluate eco-design solutions by extend the horizon of product life to multiple generations. Fitch and Cooper[76] developed Life- Cycle Modeling for Design (LCMD) that can generate different design scenarios and serves as a communication tool of design trade-offs to a design team. These metrics based methods[5,6,15,44,65,75,76] are applied at problem definition stage.

Vinodh and Rathod[26] integrated environmentally conscious quality function deployment (ECQFD) and LCA approach in sustainability study. In ECQFD, the environmental Voice of Customers(VOC) include less material usage, easy to transport and retain, less energy consumption, easy to disassemble, harmless to living environment. Accordingly, the environmental engineering metrics contain number of types of materials, physical lifetime, rate of recycled material, biodegradability, and insulation strength. Based on the environmental engineering metrics, environmental sustainable products are developed. This method starts at problem definition phase.

Yang[30] also coordinated QFD and LCA method to address sustainable product design. QFD first translated sustainability requirements to product characteristics. Three metrics: generic resource metric model, generic energy metric model, and end of life metrics are adopted to evaluate the sustainability of design concept. Subramaniyam et al.[61] reported that green products focused solely on reducing environmental impacts may not be favorable in the market, because these products fail to consider customer needs and product costs. They proposed a QFD-based methodology to solve this problem. This method defines the phases to be followed by a company that incorporates design for recycling into product design. Consumer appliances are used as an example to describe the recycling process of various materials and the issues need to be considered for improving sustainability in the process. De Silva et al.[69] proposed quantifiable sustainability metrics to aid design and manufacturing of sustainable consumer electronic products. These methods start at conceptualization phase.

Bonanni et al.[3] established a visual web-based tool to address the sustainable design and design of supply chain. A simplified LCA method (Okala method) is applied to calculate the carbon footprint of a product. In the same manner, Leibrecht[14] utilized information technology and integrated Computer-Aided Design (CAD) tools and LCA assessment so that eco-logical assessment of product are be evaluated according to manufacturing processes, assembly processes, and transportation. Yang and Song[31] established a framework that consists of lifecycle sustainability metrics, inventory databases, and design support tools for design options comparison and decisions making. Vinodh[43] reports a case study in a manufacturing company in India. Sustainability analysis based on a CAD tool is conducted on the existing design of a sprocket for determining its environmental impacts in terms of carbon footprint, energy consumption, and air/water usage. The analysis reveals critical design features with greater environmental impacts. Design optimization is then performed to produce design variants with lower impacts, validated by interviewing manufacturing executives in industry. This empirical study demonstrates the effectiveness of re-design for developing environmentally friendly products. Newcomb et al.[77] developed correspondence ratio (CR) and Cluster independence (CI) to measure the degree of modularity regarding life cycle aspects. Therefore, the number of materials, similarity of materials within a module can be assessed before detail design stage. Above five methods[3,14,31,43,69,77] are applied at preliminary design phase.

Haapala et al.[6] addressed sustainable design and manufacturing issue with four aspects: energy use, resource use, resource consumption, waste production, ad human health using Eco-indicator 99. This method starts at detail design phase.

Harun and Cheng[7] investigated the manufacturing processes along with facility layout design and its environmental impact. This method applied energy and resource efficiency and effectiveness (EREE) as indicators of life cycle assessment. Gabi 4.3 is applied to evaluate life cycle inventory analysis. This method starts at detail design phase.

Koukkari et al.[12] selected 12 sustainable indicators to form a sustainable metric and the weight of these indicators is ranked by the degree of low, medium or high. These indicators are summarized as sustainable score. A spider chart is presented for comparing the environmental, economic, social, and functional performance of design concepts. This method starts at detail design phase. This method starts at detail design phase.

Howarth and Hadfield[38] developed a sustainable product design model that tackle sustainable product design from materials and design perspectives. 22 indicators are selected and evaluated according to their economic, social, and environmental impacts. Many eco-design methodologies were developed for simple products and did not consider the complexity of a product structure. Moreover, most existing methodologies cannot be applied parallel to the design process. Focusing on (EuP) Directive, Grote et al.[52] proposed a product hierarchy driven methodology for eco-design of new complex products. This methodology must be applied in a manner parallel to the product design process, consisting of three phases: early concept, advanced concept, and detailed design. The purpose is to avoid a time consuming redesign of the product if eco-design and LCA are only applied at the end of the design process. TRIZ is incorporated to enhance eco-performance of a product and aligning the DfX tools helps to bring together the product hierarchy and the life cycle thinking. The proposed methodology considers both the environmental and economic issues to avoid difficult trade-offs. However, its effectiveness can be limited by availability and accuracy of LCA information.

LCA analysis is both time and resource consuming, due to the collection of the product data needed to perform it. Thus, complete LCA can be carried out mainly to assess the environmental impact of an existing product. Simplified Life Cycle Assessment (SLCA) approaches try to increase LCA usability in the early design stages. In the design phase to perform an environmental consideration for the complete life cycle is not easy when not all product data is available and fixed. Therefore, it is important to evaluate simplified methods and to study what type of information they require and what kind of results they can produce.

Morbidoni et al.[53] evaluate and compare CAD-based SLCA solutions and complete LCA software tools, with a focus on the mechanical product design field. SolidWorks Sustainability (by Dassault Systems) and GaBi (by PE International) have been considered as references for the comparison. Their purpose is to demonstrate the inaccuracy of current CAD-SLCA solutions and identify the main causes of the inaccuracy. The analysis results show that the current SLCA systems based on the integration of CAD tools with LCA databases neglect the whole life cycle (in particular use and disassembly). The estimation of material used and manufacturing cycle impact are treated with too little detail. In addition, this work proposes an approach where the same system structure (CAD, machine and LCA databases) are more efficiently integrated by extracting the right amount of geometrical and non-geometrical data from the CAD data structure and PLM databases. However, validation of the proposed approach is lacking and sensitivity analysis is needed to determine the correct order of priorities for the data/parameters to be extracted for SLCA.

As mentioned previously, a full LCA can be difficult to apply at the design stage because of its tedious, expensive and time-consuming attributes. SLCA methods that involve less cost, time and effort, but yet provide insightful information are needed. Hur et al.[54] evaluated 11 simplified methods to determine which methods could identify those areas which can be omitted or simplified without significantly affecting the overall results for Electrical and Electronic Equipment (EEE) products. A semi-quantitative approach, the so-called environmentally responsible product assessment (ERPA) method, was analyzed. The effectiveness of SLCA and ERPA are evaluated and compared using the case studies of a cellular phone and a vacuum cleaner. The SLCA generated more information on the inherent environmental characteristics and most highly weighted environmental aspects of a product system. It might be useful for new design/eco-innovation when developing a new product where environmental considerations play a major role from the beginning. In contrast, the EPRA method can be used in eco-redesign to identify the potentials for improvement and alleviate harmful environmental impacts of an existing product or process, since it identifies areas where environmental improvements are needed considering the availability of alternatives. The conclusions may not be valid for products other than Electrical and Electronic Equipment, though.

Knight and Jenkins[58] discussed the adoption of eco-design techniques and how their applicability can be determined in relation to new product development processes. The compatibility of eco-design techniques with the existing design process is established through development of an applicability framework which has been used to identify three tools: checklists, guidelines, and a material, energy and toxicity (MET) matrix. They found out that checklists, guidelines and the MET matrix can be used both on a specific product, and also more generally in the design process. In particular, the MET matrix is shown as being used to successfully identify key environmental aspects of the product during its lifetime. This paper also argues that eco-design techniques may not have been more widely adopted by businesses because such methods are not necessarily generic and immediately applicable, but instead require some form of process-specific customization prior to use, which can in turn act as a barrier to adoption.

Russo et al.[59] applied TRIZ laws of evolution to assess the value of existing solution and explore the most promising directions of improvement and develop improved solutions according to sustainability requirements.

Lenau and Bey[68] studied the requirements of the tools and methods for environmental evaluation. Designers need to discuss with other people about environmental consequences and the design decisions to be made. The procedure of applying eco-design tools should allow comparison of different products. These tools should not presuppose detailed environmental knowledge. The quantitative

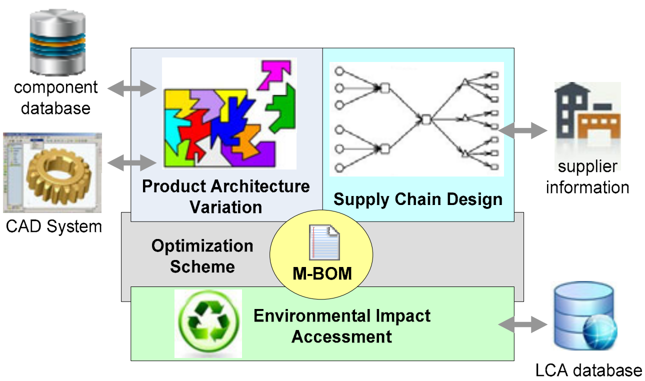

Fig. 4 A concurrent product design approach to reducing environmental impact

results of environmental impacts, as they are documented in a formal LCA, are not of major interest to the designers. Instead, they prefer to be able to identify the critical part in a product design responsible for the majority of the environmental impacts and to estimate the order of magnitude of such impacts. They proposed to adopt indicator-based methods for eco-design, and argued that LCA also employs indicators: as many correlations between causes and subsequent effects in the environment are not fully understood. An indicator-based Oil Point Method (OPM) was developed to enable users to generate missing evaluation data based on various available sources. The OPM described in this paper uses product-related primary energy consumption as an indicator of the extent of environmental impacts. Case studies of real products demonstrate how the developed method helps designers conduct "quick-and-easy" overviews of their design decisions. The above methods are applied in the detail design stage.

3.3 DfX

Luh et al.[16] presented a methodology that can identify green product development by using generic modularized product architecture. This method contains four levels, which are product family, product model, option control, and physical component level. By mapping the modules and option items, green design can be viewed as another option in the Product Data Management (PDM). A LCD TV product family case study is demonstrated using PDM software "TeamCenter". This method provided answer for customers with different green standards. Therefore, Green product development can be achieved at conceptual design stage.

Vinodh and Rajanayagam[25] applied CAD and Design for Manufacturing (DFM) principles to achieve sustainable product design. This software will compute carbon Footprint, water eutrophication, air acidification, and total energy consumed during material extraction, manufacturing, use and end of life phase. This method starts at preliminary design phase.

Lee and Xu[13] addressed environment burden on product packaging issues considering energy consumption, biodegradable materials, and intelligent packaging with an aim to minimize the amount of materials while maintaining function of product protection.

Tabone et al.[22] applied green design principles on the selection of materials. Every principle serves as an indicator and all indicators are ranked with order. Therefore, sustainable design concepts are presented. The above two methods[13,22] both begin at detail design phase.

3.4 Life Cycle Costing

Bevilacqua et al.[2] evaluated the environmental impact of circuit board design based on both LCA technique and economic aspects. Based on the ratio on reduction of energy dissipation, economic and environmental break even points are presented as support information for decision makers. Kloepffer[11] proposed a new direction to Life Cycle Sustainability Assessment (LCSA), which summarizes environmental LCA, LCC, and Social LCA.

Wang[28] proposed a metrics method that integrated life cycle costing, multiple criteria, and group decision making. All design concepts are evaluated with cost and risk criteria and displayed using feasibility score. The feasibility score is a 3 by 3 matrix regarding environmental benefit (x-axis) and ease of implementation (y axis). The values are +1, 0, and -1 on both axes. Decision maker select one among nine blocks according to their evaluation. The group decision making here is simply averaging value of all decision makers. These methods[2,11,28] start at preliminary design phase.

3.5 Methodology

Azapagic et al.[1] incorporated sustainable considerations into every design process as shown in Figure 5. At each stage, it asked designer to consider sustainable criteria and indicators as part of design process. This methodology can identify sustainability issue in the early design stage, but didn't provide suggestions while different aspects of indicators are conflicted.

Robert et al.[20] applied systematic thinking to build a top-down framework that contains five levels for strategic sustainable development. Level 1 is the overall system — the ecosphere. Level 2 describes principles for sustainability. Level 3 identifies related principles for sustainable development that can achieve sustainability. Level 4 set up concrete measures according to level 3 and finally, level 5 is monitoring and auditing of the process.

Sakao[74] developed an environmentally product design method that contains Quality Function Deployment for Environment (QFDE), LCA and TRIZ to mitigate environmental impact of a new product which still satisfies original functional requirements. The above methods start at problem definition phase.

Yan et al.[45] proposes a sustainable product conceptualization system (SPCS). Domain experts first generate the product platform of a specific product using general sorting and design knowledge hierarchy (DKH) techniques. Initial design options can be produced using morphological configuration. The Hopfield network is then used to narrow down initial design space based on design criteria solicited by domain experts. The sustainability and cost pairs can be obtained for selecting environmental friendlier design options using the rated sustainability and cost criteria solicited using repertory grids by domain experts. A case study of cellular-phone design illustrates how the system works.

Umeda et al.[46] propose a modular design methodology that derives modular structure based on both life cycle properties and geometric information. The method aggregates attributes related to a product life cycle by using self-organizing maps (SOM) and evaluates geometric feasibility of modular structure. SOM is a neural network based technique applied to cluster components according to similarity of their life cycle attributes such as constituent materials, physical lifetime, and value lifetime. The components classified into groups that should form a module from the integrated view of life cycle options of each component, including recycling, maintenance, reuse, and upgrading. On the other hand, the proposed method derives geometrically appropriate modular structure using module density represented by a convex hull. A case study of ink jet printer demonstrates the feasibility and advantages of the proposed method.

Yu et al.[47] proposed a modular design method by which modular structure can be generated based on both life cycle issues and original product function-structure information. This method first selects proper Modular Driving Forces (MDFs) based on the life cycle objectives. A matrix that shows connective intensity of each component pairs is constructed for each driving force. A comprehensive matrix which shows the component-component relations affected by all MDFs is then generated. Finally, product modular structure is reconfigured and optimized by Group Genetic Algorithm (GGA). The objective is to maximize the interactions between components within modules.

Product architecture, primarily determined at the system design stage, has a profound impact on the entire product lifecycle and has been identified as the crucial factor that links product design and supply chain activities for environmental decision makings. The study of Feldmann et al.[48] was one of the first attempts to reduce environmental impacts of a product by computer-aided design of product structure. A computational framework was developed for product structure analysis regarding the end-of-life behavior of a complex product. This framework computes an overall score for environmental impact using multi-attribute value theory, considering metrics related to the number of materials, materials used in the product, disassembly and recyclability of the product, for various product structures. The results help product designers to determine the economically optimal end-of-life strategies and improve their designs. The proposed framework serves as a decision making tool for eco-design, but cannot automatically produce design alternatives with reduced environmental impact or compliant with sustainable directives.

Tseng et al.[49] added engineering attributes to the liaison graph model for sustainable evaluation of part connections, referred to as

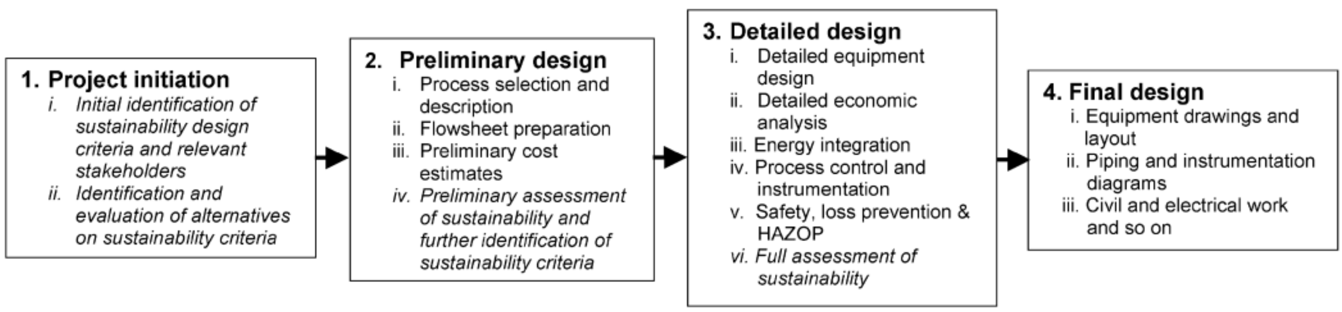

Fig. 5 Stages in process design for sustainability[1]

the component liaison intensity. They applied a variant of Genetic Algorithm, GGA, to cluster components into groups with lower green pollution index and cost. Better green designs are produced through the GGA-based optimization process. Most product modularization methods based on GGAs have the same problem that when the number of components in a product increases, computational time increases significantly.

To overcome this limitation, Smith and Yen[50] proposed to solve the modular green product design problem using the concept of atomic theory. They defined a module as a subassembly of a product determined by the component spatial locations, structures, and lifecycle options. The proposed method provides more control and finer sensitivity with respect to green constraints in the initial stage of product lifecycle design. Product designers only need to build a touch matrix and define green constraints to form modules. They can establish a desired number of modules by selecting the minimum number of positive charges that will form atomic nuclei. Different module solutions can be developed and considered by merging non-full loading modules. Existing designs can be adjusted based on the results of modularization to make them even greener.

Kang et al.[51] studied the EuP directive and proposed a computer-aided design system based on the EuP guidelines. Designers can upload a product design to this three-tier system and receive various environmental information required by EuP, including ecological profile (energy, water consumptions, waste, and emissions to air and water), eco-reports in the format of bills of material for five product lifecycle stages (material extraction and production, manufacturing, distribution, use, and disposal and recycling), economic life cycle costs, and eco-design guidelines. Designers can identify critical stages in the product lifecycle in terms of reducing environmental impacts. Strictly speaking, this system is not considered a real design tool, because it cannot automatically generate design options based on the information it provides.

Yung et al.[55] presented a case study to show how an LCA of a personal electronic product is conducted subject to the requirements of the EuP Directive. A commercial software tool, GaBi, was employed to determine the lifecycle inventory of a heart rate monitoring sensor. They reported that the bill of material (BOM) usually provides high-level information only and is not sufficient for a detailed LCA. There is a gap between the information that can be retrieved from the BOM or received from the manufacturer and the input interface to the software. Substantial effort was put into filling this gap by transforming the information, gathered from factory visits and face-to-face meetings, into useful input from the software perspective. In this case study, the material selection process, which occurs at the very beginning of the product, development cycle, is a dominant phase in reducing environmental impact. Several managerial insights are provided for implementing a proper eco-design strategy in a company. Cross-functional cooperation is of vital importance in success of eco-design product development, due to the complexity of the LCA in terms of its data collection and modeling. LCA modeling can, in fact, and should be reused so that the modeling effort is dramatically reduced when considering similar products. Top management also plays a role in supporting the eco-design strategy as part of the company's business strategy. Similar studies must be extended to other product types so that the derived insights can be made more generic.

Chu et al.[56] proposed a CAD-based approach that allows automatic variation of 3D product structure by means of changing the combination of parts, selecting the assembly method, and rearranging the assembly sequence. A computational scheme based on Genetic Algorithm (GA) produces an optimal product structure from the design alternatives generated by this approach, corresponding to lower assembly/disassembly costs, while complying with specified recycling and recovering rates. It also chooses a small set of parts to be disassembled to meet with the green directives and suggests an economical disassembly process. This scheme has been implemented in a commercial CAD system as an eco-design tool. The implementation results show that automatic variation of product structure is a simple but effective means of economical green product design. This study adopted a simplified approach to product variation and thus more complex issues, like tolerance and the influence of product structure on the product quality, should be considered.

Most design for environment methodologies only facilitate decision making in the detail design stage. Supply chain considerations have to be incorporated early in the design process to ensure the greatest possible reduction in environmental impacts. However, fewer methods have been developed to reduce environmental impacts with approaches at the system design stage. Chu et al.[57] presented an integrated framework for product designers to make environmental friendly decisions in consideration of the product design, manufacturing, and the supply chain simultaneously. It incorporates a number of factors into the system design stage that ecologically influence the product development activities. These factors, including component selection, assembly sequencing, assembly method, component merge, and supplier selection, allow automatic variation of manufacturing BOM's. The variation result is guaranteed to provide all product functions and to be interference-free during assembly. A computational framework was proposed to search for better BOM's with minimized CO2 emission. An example of bicycle design was tested to demonstrate the capability of the proposed framework. The test results show that the system design stage offers feasible means that can significantly improve the environment impact of product development.

By Kobayashi,[66] most current LCP methodologies are useful particularly in the situation of product improvement or redesign at the component level. At the product level, to detect and resolve conflicts between quality, cost, and environmental concerns is crucial but lack of support. The author also argued that few eco-design methods consider risks and the resultant uncertainty in design innovation. It is advantageous to select a design concept that increases eco-efficiency but reduces design risk. To overcome these deficiencies, this study proposed an innovative product eco-design framework consisting of three major functions. An idea generation support method enables the knowledge incorporated in TRIZ to be used for eco-design. Next, a concept evaluation method helps deal with design uncertainty in which uncertainties of a solution idea and a weighting factor are considered by using Monte Carlo simulation. Also, an eco-efficiency indicator comprehensively based on the specification framework in LCP is developed to facilitate estimating Factor-X value in the early phases of design and to find target values of quality and environmental characteristics that achieve the target value of Factor-X. A case study of a real refrigerator demonstrates the effectiveness of the proposed framework. The above methods are applied at conceptualization stage.

Matos and Hall[18] developed a grounded theory based method to explore issues while integrating sustainable development in the supply chain. To tackle the uncertainties and complexities in supply chain network, all stakeholders should provide Economic (which can break down to technological, commercial, and organizational aspects), Societal, and Environmental (ESE) parameters related to their job functions in all phases of product life cycle in Figure 6 below. These parameters become input of a design structure matrix and the interdependencies among all parameters are identified. According to the case study, the fewer independencies among ESE parameters, the more sustainable of supply chain network. These methods start at preliminary design phase.

Kuo[63] was focused on recycling of waste electrical and electronic equipment (WEEE). According to this study, to gain all the information necessary to plan for the recycling evaluation of a complex product is difficult because most design information is owned and kept by suppliers, rather than manufacturer or the product owner, in industry. Another difficulty in recycling EOL products is a lack of technologies to handle complex products that are being discarded today, because the knowledge of how to do so is owned by the recycler, not the designer. The author claimed that recycling planning should be estimated when a product's BOM is determined. This research demonstrates how to support WEEE recycling analysis with environmental information derived from bill of material. A collaborative design platform collects all the required information using CAD, enterprise resource planning (ERP), and product life-cycle management (PLM) systems. Suppliers can provide component information to enable the manufacturer's design for disassembly and recycling analysis through this platform. A case study of cellular phone recycling shows that designers can obtain disassembly and recycling information through the collaboration, so that desirable changes can be made in the early design stages. However, this research did not address how to conduct these changes and how to create incentives for suppliers to upload the required information.

Gaha et al.[64] were focused on improving sustainability in the detail design phase. They proposed a simple eco-design tool by integrating CAD and LCA. Geometric characteristics of a CAD model are analyzed to estimate their environmental influences during the phases of extraction of raw material, manufacturing, use, end of life, and transportation for development of the product corresponding to the model. The tool consists of a special geometric data base containing the impacts of all existing design options of a

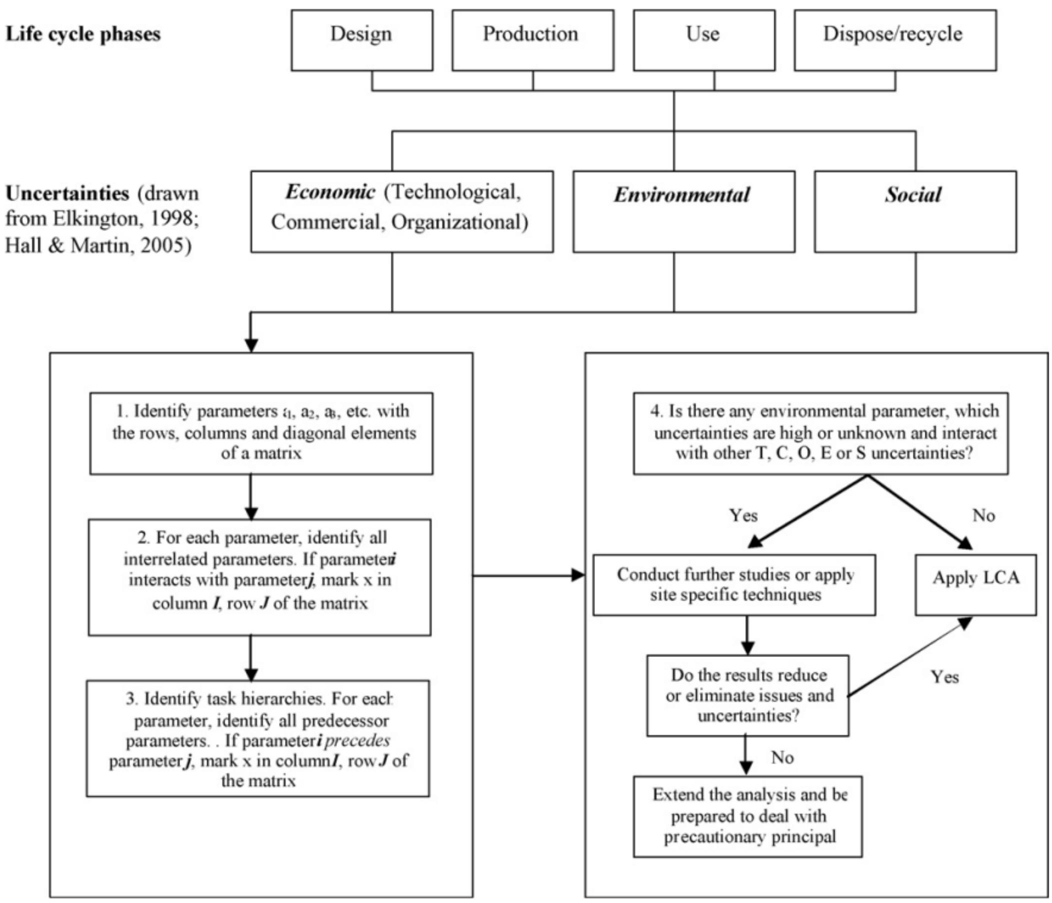

Fig. 6 Framework for LCA appropriateness s for sustainable development[18]

product. Critical geometric features and forms concerning environmental impact are identified and the result helps designers make design decisions in constructing a CAD model for reducing the environmental impact. This research suffers from a major drawback as most CAD-based eco-design methods do. Since CAD model cannot provide all the necessary information for LCA, the assessment result may be misleading for making environmental benign decisions when the entire product lifecycle is concerned. These two methods[63, 64] begin at detail design phase.

4. Findings and Discussion

General findings can be obtained from our literature review. The implications of each finding and their potential research directions also discuss the following:

- The result of literature review shows that a larger portion of sustainable design techniques belongs to metrics-based approaches. However, deriving useful metrics from life cycle assessment that fits the product design process is a challenging task. The major difficulties lie in data collection of life cycle inventory and reliable database of materials and processes. Current LCA tools and techniques calculate the life cycle impact without considering uncertainties involved in the data sources. How these uncertainties affect implementing sustainable design remains unsolved. Uncertainty in sustainable design involves two critical tasks: (1) to quantify the imprecision in life cycle data inventory in the proper metric forms; and (2) to develop robust design methods based on these metrics.
- CAD tools play an essential role in modern product design. Thus, to implement sustainable design in CAD software is advantageous and a more natural approach for design engineers in their daily work. Past literatures indicate that integrating CAD and LCA is ineffective and problematic. LCA involves extra information relating to processes, machines, purchasing and suppliers, which CAD systems cannot support. The mainstream of CAD technologies is based on feature modeling. However, to link design features with life cycle inventory data may be an unfeasible approach. Most feature-based sustainable design methods suffer from oversimplification by failing to fully consider the other phases of a product's life cycle. A feature represents the final result of intentional design (form), whereas environmental impacts are mostly estimated through a product's life cycle (process).
- Most sustainable design methods developed in the past failed to address the interdependencies among different stages in a product's life cycle. This deficiency may result in biased estimation and wrong decisions. An emerging need is to develop a systematic method that integrates the scopes of product, process, system, and ecosystem, while balancing conflicting product development perspectives.
- A crucial factor that links product design and other lifecycle activities for environmental decision making is product architecture. Most past studies investigated the influence of product architecture from the perspective of design for assembly/disassembly. Supply chain considerations should be incorporated early in the design process to ensure the greatest possible reduction in environmental impacts. Product modularization, component reuse, and product platform serve as good design handles to improve product sustainability from the perspective of product engineering. No case studies have reported sustainable design using product engineering techniques. Developing quantitative tools for achieving this goal is a potential research topic.
- An interesting observation is that the majority of the reviewed studies were accomplished in developed countries. Developing and emerging countries that consume a large fraction of energy and resources should be encouraged to conduct more sustainability research. Detailed analysis is needed to collect, validate, and complement the life cycle inventory data to the level of nations or regions. Product life cycle activities occur frequently in various countries. Collaborative product development has become a norm for the modern business world. International collaborations on sustainable development are urgent and inevitable.
- Several past studies mentioned that LCA tools may be unable to analyze environmental impacts of new or derived products with newly developed processes and/or materials. This is because their life cycle inventory data comes from existing products, processes, and case studies. Developing design methods that maintain high sustainability in the development of new products based on the knowledge and experience learned from past practice is a promising research topic. Few sustainability studies emphasized the pivotal role Small and Medium Enterprises (SME) play in reducing environmental impacts from the supply chain perspective.
- To date, most eco-design studies are focused on evaluating environmental impacts. Social impacts and long term factors are rarely studied. Proper aggregation and weighting methods on economic, societal, and environmental indicators do not exist, especially when they are conflicting with each other. Life cycle assessment should be expanded to account for these heterogeneous concerns and provide support for product design methods in a broader context.

5. Conclusion

To reduce environmental impacts is the grand challenge facing the cotemporary world. Governmental regulations and social initiatives have requested enterprises endeavor to increase the sustainability of their businesses. Sustainable product development has become imperative for modern companies. Both practitioners and academicians assert that decisions made at early stages of a product's life cycle have a profound impact on improving product sustainability. Environmentally conscious design practices contribute to sustainability by considering global ecology and resources in addition to traditional consumer and cost requirements. Many studies have reported on sustainable product design from multiple perspectives and with various techniques since the late 1990s. It is necessary to revisit those works and to identify where research directions should go from there based on the experiences and understandings learned. This paper systematically reviewed past studies concerning sustainable product design. A two-dimensional framework consisting of two metrics was proposed to categorize those studies. We distinguish them from *Guideline*, *Metrics*, *Design for X*, *LC Costing*, and *Methodology* in the ordinate. Each method can be applied to different phases during the product design process, from *Problem Definition*, *Conceptualization*, *Preliminary Design* to *Detail Design*. The ideas and limitations of representative methods in each category were discussed. The result leads to important insights for sustainable design research.

- All the works emphasized the effectiveness of early design decisions on reducing the environmental impacts induced by the later activities of a product's life cycle.
- A larger portion of design methods belongs to metrics-based approaches. Useful metrics derived from life cycle assessment must fit the product design process and consider uncertainty inherited from existing LCA data.
- Integration of CAD and life cycle inventory remains ineffective and problematic. CAD systems do not support LCA data related to processes, machines, purchasing and suppliers. Feature-based modeling represents the final form of design intent, while environmental impacts are estimated from a process perspective.
- An emerging need is to develop a systematic method that can integrate the scopes of product, process, system and ecosystem, while balancing conflicting product development perspectives.
- Product architecture has been identified as a crucial factor that connects product design to other lifecycle activities for environmental decision makings. The improvement of product sustainability by product engineering techniques such as product modularization, component reuse, and product platform is a potential research topic.
- The majority of the studies reviewed were conducted in developed countries. However, developing and emerging countries that consume a large fraction of energy and resources play an important role in the global supply chain. International collaborations on sustainable product development are urgent. More sustainability studies should focus on small and medium enterprises (SME).

Life cycle assessment should be expanded to a broader context by accounting for heterogeneous factors like economic, societal, and environmental, impacts.

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