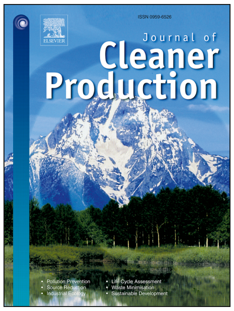

# Review of Life Cycle Assessment towards Sustainable Product Development

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Nowadays, environmental problems have aroused public awareness about the trade-off between economic growth and environmental conservation. In this regard, sustainable development plays a crucial role in striking a balance between the demands of social productivity and the reserves of natural resources. In the realm of sustainable development, life cycle assessment (LCA) is an important tool to assist in ensuring proper sustainability through assessing the environmental impacts of product designs. Unlike previous reviews, which mainly focus on LCA methodology, this paper presents LCA related studies from the perspective of product development applications. In this article, the approach on how LCA can be used in product development is introduced step by step, from concept design, part design, and process design to decision making. The applications of LCA come in different forms such as impact assessment, selection, classification and decision support. The issues or challenges with respect to the four steps of LCA (i.e. goal and scope definition, life cycle inventory, life cycle impact analysis, and interpretation) have been examined and investigated. Corresponding models and theories for coping with these challenges are reviewed. In particular, widespread and popular analytical tools are identified and highlighted. Considering the vague measurement of environmental impact in an agile manufacturing system, it is suggested that the development of LCA should keep pace with the advancing complex product development system. Overall, this article sheds light on the trend of LCA applications in sustainable product development and provides the prospect of promising research directions for LCA researchers and practitioners.

# Review of Life Cycle Assessment towards Sustainable Product Development

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## Abstract

Climate change has become more visible and the average global anomaly of surface temperature change is increasing. The environmental problems have aroused public awareness about the trade-off between economic growth and environmental conservation. In this regard, sustainable development plays a crucial role in striking a balance the demands of social productivity and the reserves of natural resources. In the realm of sustainable development, life cycle assessment (LCA) is an important tool to assist in ensuring proper sustainability through assessing the environmental impacts of product designs. Unlike previous reviews, which mainly focus on LCA methodology, this paper presents LCA related studies from the perspective of product development applications. More than one hundred relevant research papers were studied and analyzed. In this article, the approach on how LCA can be used in product development is introduced step by step, from concept design, part design, and process design to decision making. The applications of LCA come in different forms such as impact assessment, selection, classification and decision support. The issues or challenges with respect to the four steps of LCA (i.e. goal & scope definition, life cycle inventory, life cycle impact analysis, and interpretation) have been examined and investigated. Corresponding models and theories for coping with these challenges are reviewed. In particular, widespread and popular analytical tools are identified and highlighted. Considering the vague measurement of environmental impact in an agile manufacturing system, it is suggested that the development of LCA should keep pace with the advancing complex product development system. Overall, this article sheds light on the trend of LCA applications in sustainable product development and provides the prospect of promising research directions for LCA researchers and practitioners.

**Keywords**: Life cycle assessment, sustainable product development, environmental issue, LCA tool

## 1. Introduction

Over the last few decades, environmental issues (e.g. pollution and global warming, resource depletion, etc.) have attracted much attention. Natural resources of the earth are so finite that human beings are being urged to take proper action to ease the situation. In response, life cycle assessment (LCA) is a tool that was developed to measure such environmental impacts.

LCA was first proposed in Europe and the USA in the late 1960s and early 1970s, mainly concerning the environmental effects of beverage containers (Hunt and Franklin, 1996). Subsequently, major practical applications were contributed by the chemical industries aiming at toxicant examination and pollution abatement. Later, significant efforts to broaden the application of LCA came from the Society of Environmental Toxicology and Chemistry (SETAC) in 1990 to promote LCA over the world and to extend LCA definition (Fava et al., 1991). Nowadays, LCA has evolved to be an effective and prevailing quantitative tool to measure environmental impacts (Ekvall, 2002; Russel et al., 2005). According to International Standards Organization (ISO) (ISO 14040, 14044) (ISO 2006; Hauschild and Wenzel, 2001), LCA consists of four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (Hauschild, 2005; ISO, 2006). It covers the whole product (goods/services) life, and has been applied in different industries such as manufacturing, construction and even education (Boks and Diehl, 2006; Westkämper et al., 2000; Zheng et al., 2009). Moreover, the research directions of LCA studies have been extended from simply the environmental aspect to comprehensive study integrating social and economic concerns (Norris, 2001; O'Brian et al., 1996; Rebitzer and Hunkeler, 2003; Schmidt, 2003).

Sustainable product development (SPD) is a core issue for the manufacturing industry, and has been a target of designers to make products more sustainable (Kloepffer, 2003). As LCA is such a useful tool, more and more effort has been devoted to help the product development process achieve the goal of SPD (Veshagh and Obagun, 2007). Based on study of a large number of relevant research works, we found that there are still some limitations in previous work:

- Previous review work paid more attention to LCA theories and methodologies rather than applications.
- Product design and development (PDD), which is actually one of the major platforms for LCA, receives relatively little consideration in LCA research.
- There is a lack of resources and guidance for new users to adopt LCA simply and quickly.

In order to tackle the above problems, this article proposes three objectives as follows:

- Present the state of the art of LCA research comprehensively, from the applications perspective.
- Formulate the problems in applying LCA in SPD (Section 4) and provide a simplified collection of commonly used LCA tools as references for new users (Section 5).
- Highlight the SPD process (Section 6). Firstly, LCA applications in SPD are analyzed. Secondly, an explanation of some practical examples, which aims to develop more sustainable products through LCA measures, is given.

Therefore, the purposes of this article are to fill up the gaps and present an overview of LCA practices. The remaining sections are organized as follows. Section 2 briefly describes the research methodology used in this paper. The framework of this article is illustrated in Section 3. Problems in LCA applications and solutions to these problems are respectively presented in Section 4 and Section 5. Section 6 introduces LCA practices in SPD. Discussion in Section 7 reveals the limitations and proposes some suggestions on future research directions. Finally, conclusions are drawn in Section 8.

## 2. Research Methodology

A large number of research papers on LCA have been published in multiple journals and conference proceedings. In this study, research papers related to the model, concept and techniques of LCA in SPD were studied. These academic papers were extracted from the following online databases:

- Academic Search Premier
- Emerald full-text
- IEEE Xplore
- Science Direct

- Springer link

A text mining approach was used to search for relevant literature. The screening procedures are presented as follows:

1) Text gathering and pre-processing – Based on the documents and data extracted from above e-databases, noisy data (e.g. figure, table, formula) were cleaned up, and unstructured texts such as figures and charts were not considered. Through unsupervised learning, all these papers were clustered into two main categories: A=articles related to LCA and PDD, B=others.
2) Attribute identification – The attributes of a document are the important words/strings which can characterize the document in the following procedure. In our case, basically the attribute words are the keywords of that document. Based on the frequency and significance of the attribute words, three sets of keywords were chosen as centroids for further mining: {problem, data quality, variability, uncertainty…}, {solution, data mining, analytical method, mathematical method, simulation…}, and {practice, application…}.
3) Data mining – At this stage, the classic data mining approach was adopted. Through the computation of the semantic similarities between the centroids and attribute words of each document, these documents were clustered into three groups. The first round began with “problem, data quality, variability, uncertainty”. The articles related to problems of LCA were extracted. Attributes such as ‘Data quality’, ‘Uncertainty’, ‘Variability’, and ‘Evaluation’ were used to identify problems of LCA in SPD. For this list of articles, solutions were often given simultaneously. Then “solution, data mining, analytical method, mathematical method, simulation” was used to do the next clustering. The papers related to the solutions of LCA problems were sorted out. Finally, the following keywords were selected to describe LCA application practices in SPD: ‘Product design’, ‘Concept design’, ‘Process design’, ‘Product selection’, ‘Product classification’, and ‘Decision making’.

If it is necessary to broaden the review coverage and improve comprehension, more papers can be added to our database. In total, about one hundred papers have been analyzed in this article.

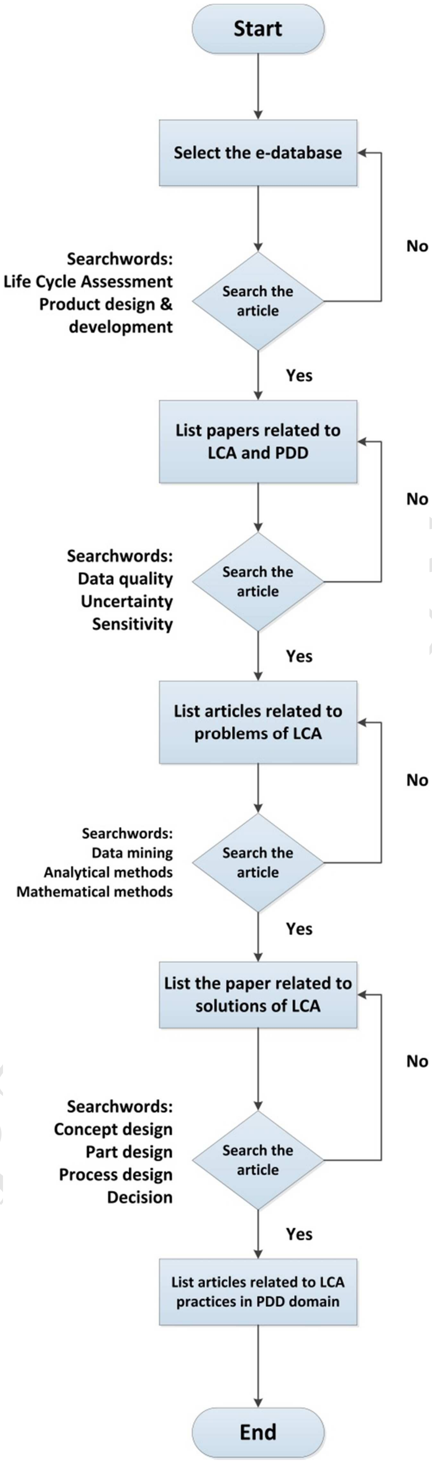

Fig. 1 Information extraction process

## 3. Proposed Research Framework of LCA in Product Development

Relevant research papers usually cover four levels: theories, research outcomes, research methods and practices. Papers presenting LCA concepts, theories or philosophies help to define our topic clearly and identify explicit research intentions. Research outcomes can reflect LCA effects and the challenges while applying LCA. Research methods provide diverse conceptual/analytical models and solutions to improve LCA in product development. The work concerning practices is regarded as material to outline the LCA application status in product development. Therefore, this paper presents LCA practices in product development by studying particular problems and the corresponding solutions (Fig. 2).

With respect to the operations of LCA, problems are proposed around the definition, inventory, impact and interpretation. Considering each phase, various kinds of obstacles are examined. Vague definitions, uncertain data, fuzzy environmental impact and inaccurate interpretation are identified as the most significant problems and deserve deeper learning.

Accordingly, solutions are emerging to cope with these problems. Qualitative methods are employed to define the goal and scope, numerical and analytical methods are used to tackle inventory data, data mining techniques and sustainability tools are utilized to handle environmental impact issues, and decision support tools are applied to facilitate decision making. Detailed elaboration is given in Section 5.

For LCA practices, we focus on the main activities of product development (i.e. concept design, part design, process design and then decisions) to present how LCA is integrated to help new product/service development. Depending on the particular characteristics of different product development processes, LCA has different practical application cases.

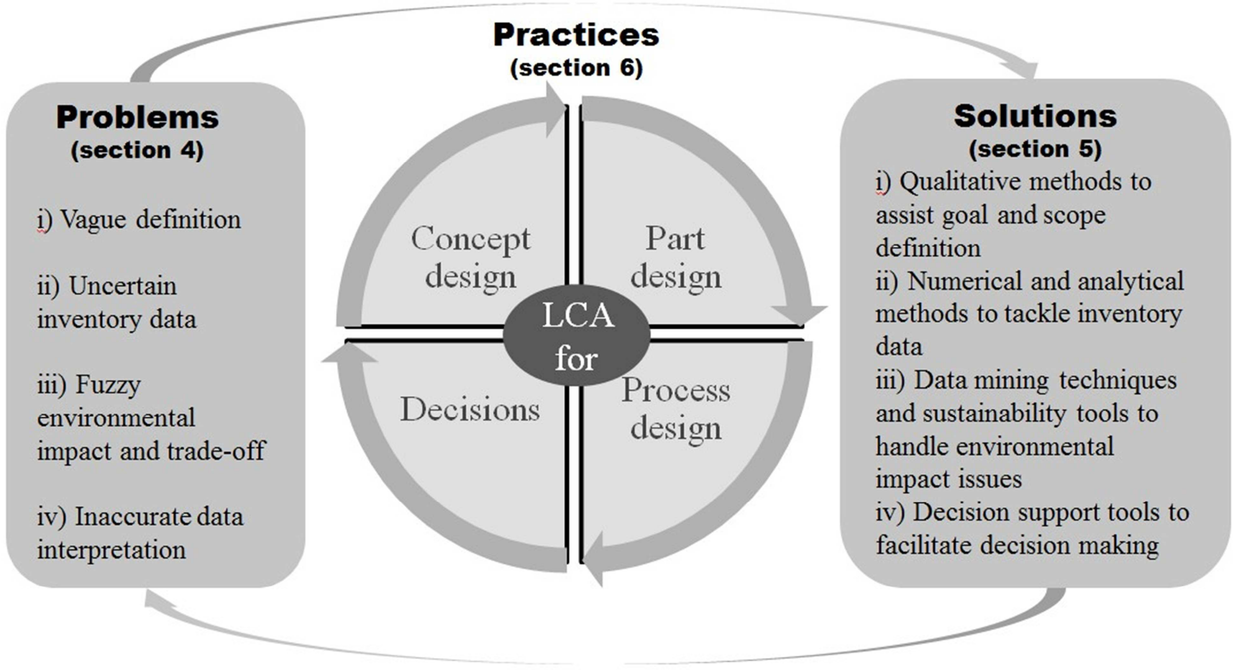

Fig. 2 The overall structure of the proposed research framework of LCA in product development

## 4. Problems of applying LCA in Product Development

Problems need to be identified so as to find suitable solutions for coping. The main challenges faced by practitioners include vague definitions, uncertain inventory data, fuzzy environmental impacts and trade-offs, and inaccurate interpretations.

### 4.1 Vague definition of goal and scope

Goal and scope definition is the first step of LCA. In this step, the ‘system boundaries’, including what is being studied, the quantity of materials, energy or impacts being studied, and allocation methods to partition the impacts caused by the same process and the ‘functional unit’, which is a measure of the performance of the functional outputs of the studied system, should be defined precisely (Reap et al., 2008). However, the early stage of product development is the fuzzy front end, and there is not enough specified information to support the goal and scope definitions. Actually a whole LCA scope can be very complex and contains a wide range of information about materials, energy and properties. Therefore, users often prefer partial/local LCA.

On the one hand, the concepts of ‘functionality’ and ‘product’ are different (Field et al., 2001). Functionality relates to specific inputs and outputs, the time range and the impact categories. To some extent, the functional unit is to demarcate the elements and information of a product concept into detail. Huijbregts (1998) holds the view that choices of functionalities have influences on the final analysis. However, users often assume the system under study is the product and do not distinguish ‘product’ and ‘functionality’ clearly. If only a clear definition is obtained and the boundary is set unambiguously, the later procedures could be properly interpreted. Therefore, the initial scenario should be set properly to give unambiguous system boundaries (Field et al., 2001). On the other hand, assumptions also need to be defined properly. For instance, the products to be compared are assumed to be independent or dependent of launch time (independent: the launch time of products has no influence on each other; dependent: the former launched products have certain influences on others) will affect the assessment process. Unfortunately, the proper assumption at the stage of goal and scope definition has received less attention than it deserves.

Therefore, LCA requires clear system boundaries and specified inputs, outputs and impact categories. Otherwise, the final impacts are hard to be partitioned and the mapped-relationship between the system studied and the environmental effects may be controversial. However, the ambiguous nature of conceptual design leads to difficulties in defining the goal and scope.

### 4.2 Uncertain inventory data

As a quantitative method, LCA has high requirements for data quality and is sensitive to uncertainties. In LCA, data are collected and stored at the LCI stage. Firstly, regarding the data source, collecting site-specific data (with respect to a specific geographic location) or general data (the average data covering a larger geographical area), should be defined clearly. Normally, the inherent uncertainty of a specific data set is typically low, while the uncertainties of average data (e.g. resulting from the variation in management between individual plants) are relatively difficult to predict (Weidema et al., 2003). In addition, making appropriate assumptions on the selection of data sources is important. For data collection methods, records of material consumption and customer buying behavior are examples. However, improper data collection methods may lead to errors, and these errors can affect the LCI results drastically (Jacquetta et al., 1995). For example, data on actual materials and energy consumption are more reliable than questionnaire feedback.

Basically, input and output data of materials, energy, and all detailed levels of property need to be detected in LCA (Dale et al., 1997; Frischknecht et al., 2004). However, incomplete inventory data often leads to difficulties in achieving reliable LCA results. For all industries, it is shown that the inventory data quality is an important concern in electricity production (May and Brennan, 2003; Maurice et al., 2000). On the other hand, data quality is an important indicator of LCA quality (Weidema and Wesnaes, 1996). Properties such as sensitivity and uncertainty have immediate influences on the final result and affect the output quality. When these two parameters are correctly measured, they can be strong indicators for the selection of products or processes (Grimes-Casey et al., 2011). Particularly for the electricity and biofuel industries, uncertainties often occur because transmission constraints and efficiency losses are difficult to estimate in the transmission and distribution systems (Weber et al., 2009; Zhai and Williams, 2009). Uncertainties in LCA can be categorized into 6 types (Huijbregts, 1998; Field, 2001; Reap, 2008):

- Parameter uncertainty: Lack of data in a collection and lack of knowledge about specific processes, materials, and emissions, together with incomplete and outdated measurements.
- Model variability: Original drawbacks in the calculation algorithms exist. In addition, not all data features are suitable to be modeled within the LCA structure.
- Uncertainty due to choices: Choices of functionalities and choices of procedures both can affect the final analysis.
- Spatial variability: It is caused by the spreading property of environmental impacts. Regardless of spatial context (e.g. location), it could result in inappropriate LCA results and introduce uncertainties.
- Temporal variability: For inventories, emissions and impacts not only spread spatially but also last for a certain period. For impact assessment of LCAs, environmental interventions over a relatively short time period are often not taken into account, which leads to variability.
- Variability between sources and objects: In LCA, the inherent differences in inputs and emissions can cause variability. Furthermore, variability between objects also exists in the characterization phase.

From data collection to computation, each step has potential bias, and consequently the result will be an accumulation of all the former errors. Hence, when problems occur, it is important to be able to detect the source of uncertainty so that diagnosis can be facilitated (Björklund, 2002; Seager et al., 2008). Thus, statistical analysis of LCA is especially important for examining data quality and eliminating bias.

## 4.3 Fuzzy environmental impact and trade-off

Regarding environmental impact, the primary problem is the identification of the impact category. Referring to a survey by Reap et al. (2008), there is still a lack of standardization in several impact categories. A debate on the categorization of certain impacts, such as soil salinity and erosion demonstrates the necessity to standardize impact categories (Jolliet et al., 2004). Secondly, environmental impacts are assessed in terms of space and time (crossover time analysis) (Hauschild et al., 2005; Field et al. 2001; Udo de Haes et al., 2004). For instance, Green House Gas emissions are spreading and have a lasting effect within a certain period of time. During the assessment, LCA practitioners always make a prediction to estimate the possible influence of the phenomena. Moreover, the temporal distribution of environmental impacts is an indicator to reveal the environmental consequences caused by discrete stages (e.g. manufacturing, use, disposal). Comparison between products that are ‘clean’ to make but ‘dirty’ to use and those ‘dirty’ to make but ‘clean’ to use was carried out by Field et al. (2001), and the results showed that the former one is preferred with less total impact.

On the other hand, the environmental trade-off between different products is quite complex. Field et al. (2001) argued that environmental effects are aggregated results which cannot be reflected purely from a single product, and a series of similar products should be treated as a whole. However, many studies are conducted on individual products but ignore the effects caused by product-fleet (Field et al. 2001).

In addition, it is challenging to quantify the trade-off between economic benefits and environmental impacts. The trade-off between economic growth and environmental protection has been discussed for more than a decade. Until now, governments are still struggling for a balance between environmental legislation and economic growth policy. Particularly in developing countries, trade-offs against the Gross Domestic Product result in environmental degradation. In this respect, Arrow et al. (1995) proposed carrying capacity and ecosystem resilience to tackle this situation. However, it is mentioned that resilience is difficult to measure while adaptive management may be applied for detecting environmental problems.

### 4.4 Inaccurate data interpretation

Data interpretation is the last step in the LCA process. At this stage, results are analyzed and recommendations are given to decision-makers. While evaluating the overall performance, the effects actually contain accumulated errors throughout the whole actions, and it is thorny to prevent these errors. Based on results with cumulative bias, it is tough to distinguish clearly which element is the root cause of the impact.

Therefore, iterative analysis is required to provide a more scientific interpretation together with a comprehensive analysis of the underlying errors and uncertainties. By combining the detection of error sources, the actual influence of each component can be determined (Anna and Björklund, 2002; Seager et al., 2008). Based on knowledge of the error sources, the results can be verified and validated properly. Unfortunately, not all errors can match a causal source in practice. Especially in the mathematical analysis process, too many uncertainties arise. They may be due to mechanical failures, or due to the computation methods used. Although the assumptions and predictions have been stated, ambiguous uncertainties are unavoidable, and the exact confidence level is still difficult to find.

## 5. Solutions Generation for Reliable LCA

To tackle the problems stated in Section 4, qualitative and quantitative methods are emerging in recent years. The qualitative methods adopt empirical studies to support the data collection and data analysis. The quantitative methods use statistical or data mining techniques to analyze and extract the data to provide justification for a better eco-design.

### 5.1 Qualitative Methods to Assist Goal and Scope Definition

Design for X (e.g. Design for assembly, Design for disassembly) (Boothroyd and Alting, 1992; Jovane et al., 1993) and ‘3Rs’ (reduce, reuse, recycle) (Hrinyak et al., 1996) are good approaches to add additional value to products. These strategies can set the goal of LCA for lowering environmental impacts and help to extend the system boundaries with the concerns of prolonged lifespan.

Moreover, other environmental concepts work cooperatively with LCA and also play key roles in green product development, such as sustainability, which is defined by the United Nations' World Commission on Environment and Development (World Commission on Environment and Development, 1987): '… *development that meets the needs of the present without compromising the ability of future generations to meet their own needs*'. It has evolved to be a guidance to balance either the economy or ecosystem (Norton, 2005).

### 5.1.1 Recommendations to specify a functional unit and system boundaries

As mentioned above, the functional unit is vital to ensure that the function is complete and to enable product comparison. According to a study by Weidema (2003), product properties are classified into three categories, obligatory, positioning, and market-irrelevant. This classification can be used as the starting point for a proper definition of products. A functional unit often involves obligatory and positioning properties. If extra functions are entailed, these should be considered, and the system boundaries should be expanded. One recommendation to define the functional unit was proposed to include system expansion when feasible and to use a mass-based functional unit. If the properties of the product cannot be completely described by a mass-based functional unit, a combination of physical and economic parameter units is suggested (Schau and Fet, 2008).

Regarding the system boundaries, boundaries relative to production capital or personnel, as well as the boundaries in relation to the other products' life cycles, are included (Hospido et al., 2010). Generally, the boundaries relative to production capital or personnel are disregarded. However, when infrastructure acts as a relevant parameter on the lab scale and on the industrial scale, a sensitivity analysis is recommended so as to evaluate the possible implications of infrastructure exclusion. When the same process(es) is shared by several products or functions, boundaries related to other product life cycles need to be considered. Subdivision, system expansion, and allocation are hierarchical recommendation by ISO standards (ISO 14044, 2006). What should be included or excluded is heavily dependent on the functional unit.

Moreover, scenario development affects the definition of system boundaries. Identical processes in different scenarios can only be excluded if the reference flows corresponding to these processes are strictly equal (i.e. total output of the system must also be identical).

### 5.1.2 Design for X

Design for X (DFX) is a collection of guidelines. Generally, DFX includes Design for Assembly (DFA), Design for Disassembly (DFD), and Design for Recycling (DFR), to name but a few. Among these guidelines, two should be emphasized:

- Design for Environment (DFE). It considers design issues from an environmental viewpoint as an overall evaluation (Joseph, 2009) and includes a set of principles that provides guidelines and references for manufacturers and designers:
    - Embed life-cycle thinking in the product development process
    - Evaluate the resource efficiency and effectiveness of the overall system
    - Select appropriate metrics to present product life-cycle performance

  - Maintain and apply a portfolio of systematic design strategies
  - Use analysis methods to evaluate design performance and trade-offs
  - Provide software capabilities to facilitate the application of DFE practices
  - Seek inspiration from nature for the design of products and systems

  Basically, LCA is highly similar to Design for Environment since they have a common target and share lots of similar tools. Some researchers try to distinguish them as two discrete concepts. Actually, it is unnecessary because LCA can be regarded as a routine to realize DFE (Tukker, 2000). Environmental impact assessment (EIA) is one concept of DFE and its process makes use of the major steps of LCA.
- Design for Disassembly (DFD) is different from Design for '3Rs' (Alting, 1995). It considers ease of disassembly at the design stage. Basically, it cares more about production efficiency which influences economic benefits and social effects. Meanwhile, reducing disassembly complexity helps to control energy consumption and work load. Generally speaking, DFD is an important consideration when used to simplify LCA (Hauschild et al., 2005). For example, Glazebrook and Coulon (2000) suggested a combination of DFD and LCA to develop a design tool which could satisfy the design requirements. In addition, the process with the focus of DFD can be defined through LCA approaches (Westkamper, 2003).

Integration of LCA into Design for 'X' optimizes the manufacturing and satisfies the integrated product policy. Although the definition and application of these rules and techniques are different, the objectives are the same, which is to achieve a more efficient product development process.

### 5.1.3 End-of-life Options

To define the scope of LCA, end-of-life options are considered, as they can extend a product's usable life, with the same material and energy consumption. Generally, end-of-life options involve a series of strategies to assist post-treatment of products, such as: reducing, reuse, and recycling. For '3Rs' (Reduce, Reuse, Recycle), the environmental load is reduced by dividing the environmental impacts into longer time spans. Reducing is to minimize waste. Reuse is to use an item again after it has been used. 'Reuse' can help to prolong the lifespan of the materials or parts. Recycling is to make use of used materials in new products. Therefore, 3Rs, which should be considered at the beginning stage of product development, can improve the result of LCA.

LCA has been applied to assess the total environmental impacts after reuse, and the result is compared with the process without reuse. To further explore this issue, Simon et al. (2001) described two models: a steady-state model used by previous authors and a more sophisticated transient original model. The results showed greater savings could be obtained by reusing more components rather than recovering end-of-life parts (Simon et al., 2001). Moreover, Latin Hypercube sampling was conducted by Huijbregts (1998) in the matrix (inventory) method of open-loop recycling to detect global warming potentials. LCA was also applied to achieve global sustainability through material recycling (Hanssen, 1999).

## 5.2 Numerical and Analytical Methods to Tackle Inventory Data

Another main challenge is to deal with LCI data. Having reviewed existing work on LCA, it appears that many sophisticated mathematical theories could be employed to improve LCA by dealing with LCI data. Using advanced analytical techniques and other theories, it is more convenient to reorganize the data.

### 5.2.1 Statistical techniques

To resolve data quality issues (e.g. sensitivity, uncertainty), statistical algorithms such as the microaggregation approach (Lin et al., 2010) and the visual assessment based data partitioning method (Chen et al., 2013) are oftentimes used. For instance, Multivariate Regression analysis has been applied to analyze data quality (Wang et al., 2010). Weibull analysis and regression analysis are tools to detect system reliability and failure (Mazhar et al., 2007; Wang et al., 2010). These two methods are used for parameter analysis. With all parameters fixed except the one being studied, the system performance can be observed by changing the free parameter. Statistical theories are also applied to modify defective data and avoid errors. Possibility theory mainly deals with data uncertainty problems (Tan et al., 2002). All these mathematical methods are to provide a quality test of inventory data which can be used to evaluate the quality of LCA results and to improve data reliability.

Furthermore, Monte Carlo (MC) Simulation is a simulation method which is commonly used to fix data quality problems (Maurice et al., 2000). According to LaGrega et al. (1994), Monte Carlo is a method that replaces point estimates by random variables drawn from probability density functions. To carry out MC simulations, the software Crystal Ball is used (LaGrega et al, 1994). Firstly, LCI data is prepared for MC simulation. Next, essential factors are selected and the distribution of data is determined. Then the possibility distribution is set in a spreadsheet cell and loaded into the MC simulation system. The data will be recalculated based on the random variable selected from the distribution, a process that is iterated more than 10,000 times. Finally, the simulation generates the output and analysis results of the data quality from sensitivity and uncertainty perspectives. Simulation is a very traditional but useful tool for LCA users. Moreover, Discrete Event Simulation, Latin Hypercube Simulation and Probabilistic Simulation are also applied widely to deal with uncertainty problems.

In addition, simulation techniques can verify uncertainties and check the result qualities. Several simulation models are shown in Table 1. Through reorganization of the inventory data and iterative selections/computations, random and stable trials are obtained and loaded into corresponding simulation systems. In this process, data are transformed. Through simulations, data can become more stable, and more reliable results can be guaranteed. Moreover, data mining is also an efficient method to evaluate data quality (Feeldersa et al., 2000). Additionally, possibility theory is implemented to estimate the uncertainty of data and improve the final accuracy (Raymond et al., 2002). Fuzzy set theory and Rough set theory are often integrated with clustering or neural networks to gain more stable and reliable results.

Users can select a proper stage for modification (e.g. preventing errors during calculation or rectifying the results after calculation), and then choose a suitable method, according to the characteristics of the statistical tools.

### 5.2.2 Data Gathering Techniques towards Reliable Inventory Data

Doing surveys is a common method for data collection. Björklund (2002) organized a survey to investigate the commonly used approaches of data quality management, sensitivity analysis and uncertainty analysis. Moreover, Bruce et al. (1995) conducted a questionnaire survey in North America and Europe to solicit suggestions and recommendations from LCA practitioners. The data collected are used to verify the commonly used LCA particles and assist the evaluation of LCA data sources. Normally, a survey is an effective method to get valid data. Based on the responses from LCA practitioners, the results provide LCA users with suggestions where attention should be paid in selecting suitable and reliable databases.

On the other hand, quality function deployment (QFD) is also a useful tool to gather data from users in order to pursue better product design. For instance, the concept of environmental conscious quality function deployment (Vinodh and Rathod, 2010) was proposed to integrate QFD into the LCA process.

## 5.3 Data Mining Techniques and Sustainability Tools to Handle Environmental Impact Issues

Data mining approaches are effective tools for classification and prediction. Data mining is a process to discover knowledge from large amounts of data. The inventory data of the design concept, namely, input-output of materials and energy, can be analyzed through data mining. In general, data mining consists of Clustering (Lv et al., 2011; Sousa and Wallace, 2006), Association rule generation (Lee et al., 2012) and Neural networks (Cao et al., 2011; Chen and Liau, 2001; Mazhar et al., 2007; Park and Seo, 2003). Clustering is mainly used for classification based on distances (similarities) between different concepts or designs. Association rule generation is employed to find regularities between products in large-scale transaction data. It is possible to cope with both numerical data and textual information and has become an important method to evaluate conceptual designs with large textual information. According to the characteristics of the impact categories, the greenhouse gas emission or environmental impacts are extracted and clustered. Then the relationships between the inventory data and environmental impacts can be further identified. Neural networks consist of interconnected groups of artificial neurons and process information through a connectionist approach to computation. In LCA, a neural network is used to bridge product design with its environmental impacts and to provide a useful approach to untangle the impacts (Ocampo-Duque et al., 2012; Park et al., 2001; Seo et al., 2005; Sucena et al., 2013).

Considering the dimensions of sustainability, the trade-off between the environment, economy and society should be considered (Kloepffer, 2008). These three dimensions encourage the extensions of LCA: Life cycle costing (Gluch and Baumann, 2004), Cost benefit analysis (Johansson, 1996), Total cost accounting (Udo de Haes, 2004), Life cycle social assessment (Gluch and Baumann, 2004) and Environmental risk assessment. There is no doubt that they contribute to a more comprehensive LCA system for achieving sustainability. Moreover, they are indispensable components for environmental management as they are indicators for the communication of LCA results and applications (Lim and Park, 2009). On the other hand, these life cycle approaches provide more paradigms to deal with environmental trade-offs.

## 5.4 Decision Support Tools to Facilitate Decision Making

Multiple objective optimization provides an important approach to find the best solution under multiple constraints (Adisa, 1999). Multi-criteria analysis, with the advantage of incorporating both qualitative and quantitative data into the process, is also a useful strategy to identify the optimal policy (Ness, 2007; Wrisberg et al., 2002). Moreover, the Analytic Hierarchy Process (AHP) is also a systematic decision-making method to organize the whole structure layers and provides a clear knowledge presentation (Li et al., 2006). Case-based reasoning (CBR) is an easy approach to represent knowledge and a kind of expert system that supports decision making (Lee et al., 2006). Rough set theory and fuzzy theory are usually applied in computation with uncertain and fuzzy data (Cao et al., 2011; Güereca et al., 2007; Lv et al., 2011; Zhang and Qu, 2008). These methods help to pursue better computation processes, which contain uncertainties. In addition, Window analysis is a method to assist selection and prediction (Iribarren, 2010), and examines the changes of efficiency of every unit at a chosen time set. According to the analysis, an estimation of the system performance can be obtained, providing evidence for selection and decision making.

Apart from quantitative methods, the Theory of Inventive Problems Solving (TRIZ) is also widely adopted to support the exploration of optimal decision making (Clifford et al., 2010; Raymond et al., 2002; Wang et al., 2010). Clifford et al. (2010) developed a model embedding TRIZ into the impact assessment stage of LCA, and the results showed that a decision with optimal environmental performances can be achieved by this model.

Moreover, sustainability has aroused the public interest in making the planet a better place to live. Regarding sustainability as the ideal solution, a large numbers of concepts and methods have emerged to improve the adoption of LCA. Especially in manufacturing production, sustainability inspires researchers to develop LCA methodologies and decision tools (Kaebernick et al., 2003), providing practical guidance for businesses and industries, whether in production or in project management (Labuschagne and Brent, 2005; Maxwell and van der Vorst, 2003). Extending LCA from eco-efficiency to global energy distribution and materials recycling helps to achieve global sustainability (Hanssen, 1999). These cases indicate that researchers are attempting to integrate relevant techniques with LCA in order to develop more advanced sustainable design models.

Table 1 summarizes the different types of analytical methods used in LCA, and provides LCA users with a list of optimization tools for reference.

Table 1. Collection of commonly used techniques

| Methods | | | Applications | References |
|---|---|---|---|---|
| **Decision support and statistical techniques** | Decision support techniques | Multiple objective optimization | Process Design<br>Selection<br>Decision | Adisa, 1999 |
| | | Analytic Hierarchy Process (AHP) | Green design<br>Decision | Li et al., 2006 |
| | | Case-based Reasoning (CBR) | Product design<br>Decision | Lee and Lau, 2006 |
| | | Rough set theory | Prediction | Cao et al., 2011;<br>Zhang and Qu, 2008 |
| | | Fuzzy theory | Decision<br>Manufacturing system | Lv et al., 2011;<br>Zhang and Qu, 200;<br>Güereca et al., 2007 |
| | Statistical techniques | Window analysis | Selection<br>Prediction | Iribarren et al., 2010 |
| | | Weibull analysis | Reliability<br>Field failure | Mazhar et al., 2007 |
| | | Regression analysis | Reliability<br>Field failure | Mazhar et al., 2007;<br>Wang et al., 2010 |
| | | Possibility theory | Uncertainty | Raymond et al., 2002 |
| **Data mining and simulation techniques** | Data mining techniques | Clustering | Product classification<br>Conceptual Design | Lv et al., 2011; Sousa and Wallace, 2006 |
| | | Association rule generation | Classification<br>Concept design | Lee et al., 2012 |
| | | Neural network | Concept design<br>Design environment<br>DFX | Cao et al., 2011;<br>Mazhar et al., 2007;<br>Park and Seo, 2003;<br>Chen and Liau, 2001 |
| | Simulation techniques | Monte Carlo Simulation | Data quality analysis<br>Uncertainty<br>Process analysis | Manfred, 2001;<br>Raymond et al., 2002;<br>Maurice et al., 2000;<br>Guido et al., 2003;<br>May and Brennan, 2003 |
| | | Discrete Event Simulation | Manufacturing system analysis<br>Decision making | Löfgren and Tillman, 2011 |
| | | Latin Hypercube Simulation | Uncertainty analysis<br>Rule generation<br>Variability | Huijbregts, 1998 |
| | | Probabilistic Simulation | Uncertainty<br>Rule generation<br>Variability | Huijbregts, 1998 |

## 6. Life Cycle Assessment in Product Development

Multiple steps are involved in the completion of a product (e.g. design, manufacturing, and delivery). Based on a survey conducted by Veshagh and Obagun (2007), LCA is widely accepted among manufacturing industries as the most important way to integrate environmental concerns into product development (Nielsen and Wenzel, 2002; Khan et al., 2002). Before starting Product Design, the concept should be designed first (Fig.3). Concept design is the stage at which ideas are generated and the general frame of the new product is defined. The concepts will then be selected and verified. After comparing all the selected concepts, the final concept will be chosen. At the Part Design stage, each component is selected and examined. At the Process Design stage, processing methods, such as electroplating or grinding, are selected. Finally, designers and project managers have to make an appropriate decision considering all the information they have. Supported by LCA methodology, decision makers can practice sustainable product development in a better way.

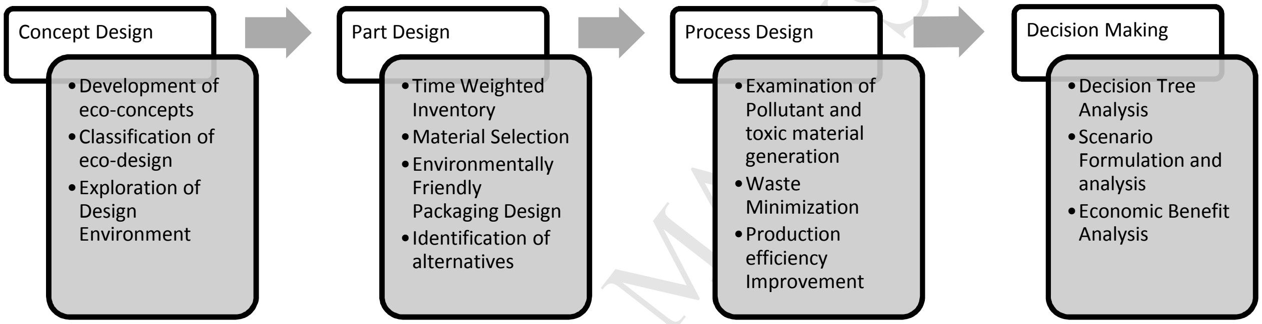

Fig. 3 Life cycle assessment in Product development

### 6.1 LCA for Concept Design

At the concept design stage, the inputs are customer and technological requirements, and the outputs are the prototypes. Because of a lack of sufficient accurate data, this step requires more delicate assumptions and computations. Sometimes, prediction and possibility analysis is needed to figure out as much explicit information as possible. Therefore, mathematical methods are commonly integrated with LCA to facilitate the estimation and evaluation of these concepts.

- **Development of eco-concepts**. At the conceptualization stage, general information about the product is determined such as shape, size, materials, functions and complexity, and constitutes initial data about the product design. Accordingly, a relationship can be established between the design data and the final features (e.g. emissions caused by aluminum). Due to the uncertainty of the conceptual data, the outputs need prediction and possibility analysis to constrain the scope and reveal the uncertainty. Thus, analytical algorithms such as an Artificial Neural Network (ANN) can be integrated in LCA to bridge the gap between the concept data and the final environmental impacts (Chen and Liau, 2001). The results are valuable references for designers to identify these concepts according to environmental consequences (Sousa and Wallace, 2006). Combined with the measurement of life, energy consumption, and environmental effects, concepts can be compared from a more comprehensive viewpoint. Thus, designers can recognize environmentally friendly features for each concept and integrate them in an early design stage leading towards a sustainable product. On the other hand, economic considerations (Economic Efficiency), as another dimension of sustainability, can also be taken into account in the conceptual design stage (Yan et al., 2009). Through balancing environmental issues and cost, the maximum benefit can be sought. In this respect, Byggeth and Hochschorner (2006) conducted a study to analyze the value of 15 eco-design tools from a sustainability perspective.

- **Classification of eco-design** (Sousa and Wallace, 2006). Based on LCA results, all design concepts can be labeled with their environmental influences, providing an effective way to classify and evaluate different concepts (e.g. aluminum cup vs. wooden cup). This can help enterprises to position their products appropriately in the market. However, most existing classification methods are based on functions or customer preferences, so eco-classification brings about a new perspective in improving product appeal. Furthermore, it is a good way to improve the product brand name and build up a strong reputation. To utilize the classification, data mining methods are helpful (e.g. clustering and rule generation) (Olafsson et al., 2008; Renato Coopi, 2002; Romero and Ventura, 2007). Actually, data mining has been successfully used in customer relationship management (Ngai et al., 2009), text mining (Ur-Rahman and Harding, 2011), quality management of distributed manufacturing (Lv et al., 2011) and customer service (Hui and Jha, 2000), and so on. It is also promising in SPD. For instance, hierarchical clustering can assign products into different categories based on certain attributes/features (Sousa and Wallace, 2006). Moreover, learning surrogate LCA was proposed by Sousa et al. (Sousa et al., 2001; Sousa et al., 1999), and is a developmental model, compared with the traditional full LCA. It begins with full LCA data and extracts simplified LCI as training data into ANN. The output of the system is associated through ANN, and the learning surrogate LCA simplifies the inventory processing. Learning surrogate LCA has been applied for product classification and in achieving efficient classification (Sousa and Wallace, 2006).
- **Exploration of design environment** (Park and Seo, 2003). A theoretical model of knowledge-based approximate life cycle assessment was proposed for embedding LCA into the design process. Consequently, a systematic framework on how to integrate environmental considerations into product design process was established. This design process framework can be used to develop more comprehensive theoretical ideas for designers (Heijungs et al., 2010). Such work makes it for more convenient sustainable designs to be built in a contemporary design environment.

For concept design, LCA gives us an approach to test our concepts from the environmental impact viewpoint. Feedback needs to be considered so as to formulate design strategies which can provide help in achieving more environmentally friendly products.

## 6.2 LCA for Part Design

At this stage, the mechanism for every module is figured out and validated. Designers are more likely to be able to find a sustainable design if they possess environmental impact measures.

- **Time weighted inventory** (Chung and Wee, 2008). Due to increasing competitive pressure, shorter life cycles and efficient production are demanded urgently. A time-weighted inventory (TWI) was proposed to incorporate time efficiency into life cycle analysis. Pre-assessed and labeled parts make the selection process easier, because designers only need to select a more environment-friendly part for assembly. Through the combination of LCA with the responsive product development, TWI makes agile production possible. Effective and efficient assembly and delivery are achieved to improve the product life cycle management.

- **Material selection** (Hanssen, 1998; Heijungs et al., 2010; Menoufi et al., 2012; Tu, 1998). Firstly, LCA provides an approach to measure different materials, such as raw materials and recycled materials. Afterwards, these materials are evaluated and compared according to the results obtained. Secondly, companies pay great attention to the environmental impacts of the material use for the finished product, as LCA is a popular tool for doing relevant material analysis (Maruschke and Rosemann, 2005; Seager et al., 2008). Particularly in the automotive industries, firms pay high costs in analyzing the materials they use in their products. Examples include: BMW studies the environmental impact of all materials used; some electric vehicle manufacturers are very careful about the effects caused by the batteries they use. Moreover, the analysis of material/substance flow is an important method to discover the environmental impacts of the product and enables effective measurement of sustainability (Ness et al., 2007). In this regard, an approach to substance flow analysis was proposed to identify the environmental impact source, and how the environmental burden can be reduced (Antikainen et al., 2004).
- **Environmentally friendly packaging design** (Hanssen, 1998; Simon et al., 2001). Packaging design is one crucial design process which can cause major impacts on the environment. As mentioned in Section 1, LCA was initialized because of concerns about beverage containers. Through decades of development, LCA has been a precise way to estimate packaging and improve packaging systems. Generally, it promotes packaging techniques towards recyclable and greener directions.
- **Identification of alternatives**. The alternatives can be different types of parts or different candidates within the same type. Identification of alternatives is often mentioned in electronic products (Mazhar et al., 2007). As is known, electronic products consist of huge numbers of parts. For example, a printed circuit board (PCB) is built with hundreds of chips. An efficient and environment friendly assembly method is needed. LCA is able to identify environmental impacts of each component. Thus, the environmentally hazardous components can be detected and replaced by environmentally friendly ones. The identification of alternatives is a helpful way for designers to make quick decisions for final assembly.

## 6.3 LCA for Process design

Process design relates to the selection of a process (e.g. turning or grinding) and arrangements for the processing sequence (e.g. turning first or milling first). From the LCA viewpoint, the process can be decomposed into material and energy flows. The majority of environmental impacts are produced when resources are consumed.

- **Examination of pollutant and toxic material generation** (Adisa, 1999; Azapagic et al., 2006; Culaba and Purvis, 1999; Manfred, 2001). For the chemical and electronic industries, the impacts of every chemical element/substance and every reaction should be strictly controlled, since the outputs and emissions often cause pollution and are even toxic to human beings. It is necessary to evaluate the overall effects with LCA in order to keep the impacts within an acceptable range. According to the latest research efforts, LCA has gained more and more attention and has turned out to be a good assisting tool for industries in planning their production efficiently and effectively.

- **Waste minimization** (Adisa, 1999; Culaba and Purvis, 1999; Lu and Realff, 2012; Grossmann, 2004). Waste management has been recognized by the manufacturing industries as the most popular sustainable product design strategy (Veshagh and Obagun, 2007). LCA results provide references for designers to adjust their process details and to optimize their design to minimize waste. Particularly for the chemical industries, changes of chemical agents lead changes of reactions, which result in different types and amounts of emission and waste. Additionally, for process design, waste minimization and production efficiency improvement are two targets to reduce environmental effects and to achieve a win-win situation for the economy and the environment.
- **Production efficiency improvement.** LCA is also applied to develop theoretical models for efficient production. For example, LCA is useful for project initiation, preliminary design, detailed design, or final design when building a sustainable and efficient design environment (Azapagic et al., 2006). Moreover, LCA is applied to detect errors of inventory-based input and output (Manfred, 2001). As a quantitative method, LCA has the ability and potential to combine with analytical algorithms which can verify process errors and improve efficiencies.

Most often, LCA is combined with a knowledge base and database to analyze process design. The inventory tree is an important approach for building systematic and clear storage of a large amount of raw materials and waste data. For product designers, LCA provides a broad platform to introduce analytical algorithms for solving problems.

## 6.4 LCA for Decision Making

Decision-making is always challenging for designers and project managers. It directly determines the final performance and the success of the product. For LCA, it has the advantages of covering performances over the whole product life and therefore can provide the most comprehensive evaluation.

- **Decision tree analysis** (Keoleian, 1993; Miettinen and Hämäläinen, 1997; Tillman, 2000; Udo de Haes, 1993; Waage, 2007). Through the assessment of environmental impacts (e.g. pollution load), designers can get a basic understanding of the environmental performance of a product and thereby identify whether the product is environmentally friendly or not. Additionally, some work shifts the LCA focus from 'product' to 'manufacturing system' in order to get a more general estimate (Löfgren et al., 2011). LCA is also integrated with other methods and theories to enhance decision-making. Discrete-event simulation is used for conceptual evaluation of the manufacturing system. This method is embedded in LCA to make a better arrangement of the manufacturing system (Löfgren and Tillman, 2011). Fuzzy theory embedded in LCA permits construction of a preferred order amongst a series of alternatives (Güereca et al., 2007). In addition, TRIZ is successfully integrated to optimize LCA and helps to reach optimal decisions (Clifford et al., 2010). Because of all kinds of eco-rules and standards, LCA seems essential at the decision stage for optimal decision making, to avoid conflicts with environmental organizations and to meet customers' eco-consciousness.
- **Scenario formulation and analysis**. This means the further potential of joint implementation of LCA and data analysis (Iribarren et al., 2010). Three analysis methods (i.e. super-efficiency analysis, inter-and-intra assessments, and window analysis) are illustrated, and future

development can be predicted. It is beneficial for future product idea generation and enables continuous improvements.

- **Economic benefit analysis** (Westkamper and Osten-Sacken, 1998; William, 2002). The economic benefit is always a priority for industry. Thus, profit is a fundamental concern in decision making. Kloepffer (2003) argued that all the costs, especially hidden costs (e.g. costs in the use of product, waste removal or recycling), should be taken into account in assessing the environmental impact or sustainability of a product. Therefore, Life Cycle Costing Assessment (LCCA) was proposed, affecting the decision together with LCA. It pursues a compromise between environmental impact and economic profit. To some extent, it is a multi-objective optimization process. For example, achieving more sustainable products means a higher cost for clean energy and renewable materials. Through setting sustainability as one constraint and business strategy as another, the best balance, with relatively good sustainability and good profit, is expected to be found.

For decision-making, environmental issues cannot be ignored, especially under the huge pressure from eco-organizations and social responsibility. LCA is acknowledged as a feasible routine for firms to meet the social expectation on environmental protection. For example, HP built a laboratory to study LCA and successfully achieved green products (Löfgren et al., 2011; Löfgren and Tillman, 2011). However, the investment in terms of economies and technology is considerable for most small and medium-size enterprises (Hauschild et al., 2005).

In general, LCA is applied more often by practitioners to achieve environmental-friendly concepts at the conceptual design stage. However, it is more challenging to ensure inventory data quality and LCA results as data at design conceptual stage is incomplete. In addition, there is the necessity of integrating various data analysis techniques (e.g. statistical methods, artificial intelligence) to cope with different data sources. In this regard, more specific data at the product and process design stage can provide practitioners with more opportunities to apply LCA for SPD.

## 7. Discussion and Outlook

A large amount of LCA research has been constantly emerging in recent years. Almost every level of LCA research, from algorithms to applications, is being studied. Nevertheless, there are still areas to be further explored.

On the one hand, at the concept design stage, intangible product features, such as emotional design and user experience (e.g. visual, tactile, and auditory) which are crucial aspects of product design and development, lack deep considerations over the whole product life. Therefore, the associated environmental impacts have not been taken into account in LCA. Based on the analysis of related research, the intangible aspects appear to be more and more important in facilitating product design, but the related environmental impacts caused by these features are often neglected. However, it is difficult to apply LCA to tackle intangible features, since intangible factors are always in a qualitative format and are difficult to be quantified and measured exactly. Moreover, corresponding data collection, processing, and validation methods also need to be further developed. Therefore, new studies need to be done to explore how LCA should cope with intangible features.

On the other hand, fierce market competition requires industries to shrink the lead time and the time to market. Product development activities are not isolated. Actually, information on every single stage is not only necessary input to the following stage but also a referential reflection of the previous stage. Therefore, product development procedures can be performed in parallel and provide interactive feedback with each other so as to reduce the elapsed time. For example, production information (e.g. processing complexity, environmental impacts) can help to improve the design phase to achieve better products with less manufacturing complexity and reduced environmental influences. However, the most sustainable design methods developed in the past have failed to address the interdependencies among the different stages in a product's life cycle (Chiu and Chu, 2012).

As shown in Fig.4, product development activities are interactive, and the information flows between different stages are two-way, giving rise to more complex and interactive materials and energy flows. To some extent, the application of LCA in DFX deals with a similar situation, as it concerns the impacts from the later stages. However, they focus on simple superposition of influences caused by post-treatment, but neglect the interactive and concurrent product development activities that make the inventory data dynamic and flexible. LCA should consider all the relevant influences, instead of only focusing on the volume change in material and energy. Unfortunately, existing LCA methods were mostly developed based on a (a series of) steady system (Hospido et al., 2010), and there is a lack of concern in exploring the improvement of LCA methodology in such an agile product development environment. In order to reflect actual practice, LCA needs to consider the feedback from all the other parts. It requires life inventory data with the flexibility to be updated frequently and modified iteratively.

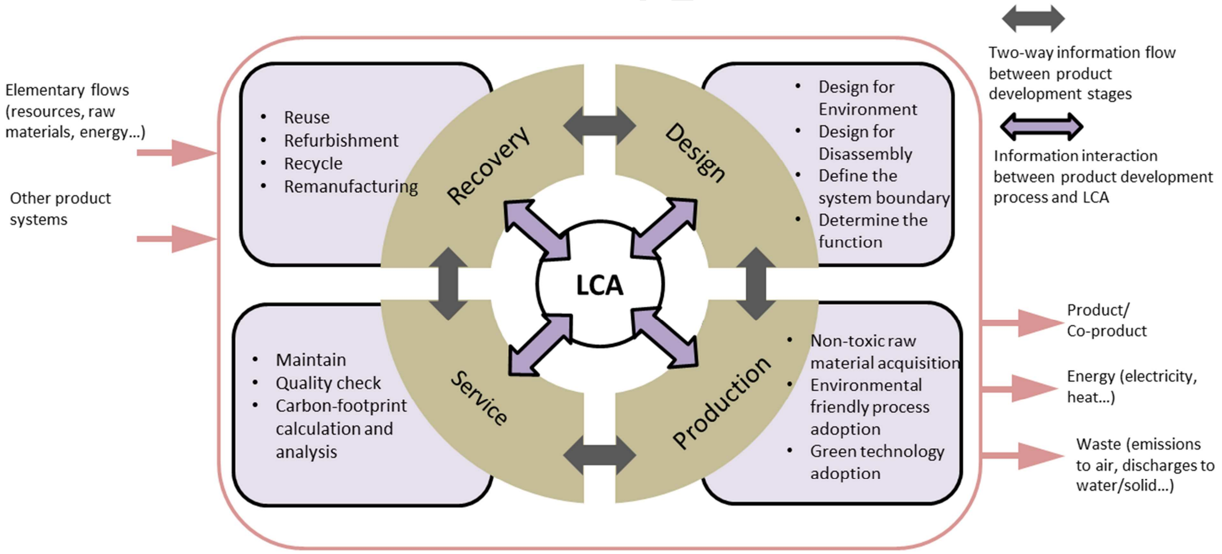

Fig. 4 Interrelated strands of product development for the LCA

## 8. Conclusions

Based on review of more than one hundred papers, an introduction of LCA towards SPD is presented. This paper sheds light on the prevailing problems in LCA research and presents related analytical and theoretical solutions. Four categories of problem are revealed, including vague definitions, uncertain inventory data, fuzzy environmental impacts and trade-offs, and inaccurate interpretations. Relevant principles, methods and models, which provide solutions for the problems revealed, are collected and analyzed. In addition, a table of commonly used LCA tools is organized, and LCA users can look for their preferred tools in this paper. Therefore, the main contributions of this work include 1) a systematic review of more than one hundred LCA research papers; 2) a new perspective for studying the previous excellent LCA research work in product development; 3) a critical summary of commonly used LCA tools; and 4) insights for LCA researchers and practitioners on the challenges and opportunities in adopting LCA for SPD.

Regarding the limitations of this work, to focus on the LCA practices in product development and ensure an appropriate paper length, numerical analysis of the previous publications is not presented, and LCA research is not analyzed chronologically, but is based on the LCA category. Nevertheless, researchers can consider future exploration of the progressive development of LCA through numerical analysis. Moreover, the limitations and the outlook of LCA applied in product development are investigated. The lack of consideration in regard to intangible product features and an agile product development environment is emphasized, and a promising direction for future LCA study is indicated. It is suggested that 1) the environmental impacts of intangible product design should be taken into account in LCA, and 2) developing LCA along with the pace of production technology advancement is necessary. However, LCA adds complexity to the product development process. To work effectively, LCA requires the interactions between the different stages of product development, and it is expected to further extend the capability of LCA to enable flexible data storage and interactive computation.

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# Appendix A

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|---|---|---|
| AHP | .............. | Analytic Hierarchy Process |
| ANN | .............. | Artificial Neural Network |
| CBR | .............. | Case-based Reasoning |
| DFA | .............. | Design for Assembly |
| DFD | .............. | Design for Disassembly |
| DFE | .............. | Design for Environment |
| DFR | .............. | Design for Recycling |
| DFX | .............. | Design for X |
| EIA | .............. | Environmental Impact Assessment |
| ISO | .............. | International Standard Organization |
| LCA | .............. | Life Cycle Assessment |
| LCCA | .............. | Life Cycle Costing Assessment |
| LCI | .............. | Life Cycle Inventory |
| LCIA | .............. | Life Cycle Impact Assessment |
| MC | .............. | Monte Carlo |
| PDD | .............. | Product Design and Development |
| QFD | .............. | Quality Function Deployment |
| SETAC | .............. | Society of Environmental Toxicology and Chemistry |
| SPD | .............. | Sustainable Product Development |
| TRIZ | .............. | Theory of Inventive of Problems Solving |
| TWI | .............. | Time-weighted Inventory |