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Review Article

Methodologies for Measuring Sustainability of Product/Process: A Review

Pezhman Ghadimi, Noordin Mohd Yusof*, Muhamad Zameri Mat Saman and Mahmood Asadi

Department of Manufacturing and Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor, Malaysia

ABSTRACT

Academic and corporate interest in sustainable product and process development has risen considerably in recent years. This can be seen by the number of papers published and in particular by special issued of journals. This paper reports the results of a review of published peer-reviewed literature from 1987 to 2012 to provide an up-to-date picture of sustainability and sustainable assessment. A structured methodology is followed to narrow down the search from around 3500 papers to 111. A variety of different sustainability assessment methodologies are reviewed in two classified research areas: product sustainability assessment and process sustainability assessment. In presenting a detailed taxonomy of product and process sustainability assessment methods, the paper also outlines the advantages and weaknesses of the sustainability assessment methods. The review sheds light on the weak points of current research in this area. The paper also highlights several key issues which have to be taken into account in attempting to develop a product or process sustainability assessment research paradigm for future applications in manufacturing systems.

Keywords: Sustainable product, sustainable manufacturing process,sustainability, sustainable development, measuring sustainability

INTRODUCTION

Life in a fast changing world has led to an ever increasing uncertainty about what is in store in the future. Nowadays,dramatic changes in environment and economy may occur in just a few years and it is difficult for society to adjust themselves to these changes due to

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E-mail addresses:
gpezhman2@live.utm.my (Pezhman Ghadimi),
noordin@fkm.utm.my (Noordin Mohd Yusof),
zameri@fkm.utm.my (Muhamad Zameri Mat Saman),
mahmoodasadi09@yahoo.com (Mahmood Asadi),
*Corresponding Author

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lack of time (Phillis *et al.*, 2009). The human population is always growing but the earth will not be able to support the extraordinarily rapid growth of population due to limited capacity (Tsoulfasand Pappis, 2006). Therefore, a lower level of resource usage should be the order of the dayso that future generations will have an undiminished or even enhanced stock of natural resources and other assets (Munasinghe & Lutz, 1991).The Brundtland Commission in 1987 defined the concept of sustainability as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability is also defined or described by many researchers (Barbier, 1987; Common & Perrings, 1992; Dovers, 1990; Lele, 1991; Opschoor & Van der straaten, 1993; Pearce *et al*., 1989; Ravetz, 2000; Strange & Bayley, 2008).

Sustainability seems to be an attractive proposition because of its meeting points with environmental concerns, manufacturing and product design activities (Rusinko, 2007). As a matter of fact, reducing the total life-cycle cost of products andthe prevention of environmental problems can lead to improving sustainability (Kaebernick *et al.,* 2002). Integrating and transforming environmental requirements into product design and development is becoming an outstanding issue (Brent & Labuschagne, 2004). Environmental requirements increase costs as it generates more design constraints. Consequently, Kaebernick *et al.* (2002) were concerned about current product designs which are focussing on reducing cost and increasing quality and profit. Addressing these concerns, Conteras *et al.* (2009) stated that by integrating all aspects of environmental requirements in every stage of product design and development can lead to possible solutions to these difficulties.

Interest from the manufacturers, decision makers, policy makers and also the public in the impact level of any manufactured product or manufacturing process on society has increased dramatically (van Weenen, 1995). However, to date only a few studies have been reported that concern sustainability assessment, which, in fact, are not focussed on process or product sustainability assessment. Diwekar *et al.* (2011) attempted to describe developments in process design for environmental considerations. Singh *et al.* (2012) provided an overview of various sustainability indices applied which are practically implemented to measure sustainable development. Mayyas *et al.* (2012) focused on current sustainability research within the automotive industry through a comprehensive review of the different studies on the life cycle of vehicles, disposal and end of life analyses and the different sustainability metrics and models used to quantify environmental impact. To our knowledge, there is no review paper addressed in the literature on compiling information specifically on sustainability assessment of a typical product or process. Consequently, it is high time to have an extensive review of the related literature. This paper provides a synthesis of the following issues: sustainability, sustainable development and sustainable product design with emphasis on existing tools and methodologies for measuring the sustainability level of any manufactured product and the manufacturing process. It aims to compare these methods with one another with a focus on their weaknesses and advantages. Finally, some topics for future research are presented.

LITERATURE-REVIEW METHODOLOGY

Our review reports on the academic publications regarding existing tools and methodologies for measuring the sustainability level of any manufactured product and manufacturing process over the 17 years from 1996 to 2012. This review also contains the most cited academic publications regarding sustainability and sustainable development. Consequently, it was important to establish an efficient method to process this amount of literature while, at the same time, capturing the important elements of the overall picture. Fig.1 presents the building blocks of the search methodology employed. In this paper, the articles were identified according to searches done through the Scopus citation database (http://www.scopus.com). Scopus is possibly the largest citation database in which 19,500 peer-reviewed journals from more than 5,000 publishers are indexed (Elsevier, 2011). The Boolean keyword combination "(sustainable product OR process) AND (assessment OR measurement)" was applied to conduct the literature search. Keywords such as "sustainability", "sustainable assessment", "sustainable process", "sustainable product" and "sustainability indicator" were used to search the databases. www.sciencedirect.com, www.springerlink.com, www.scopus.com and the web-based GoogleScholar™ tool (including all the most popular academic search engines) were selected as the main databases to be searched. Around 3,500 papers were generated at the outset. With the help of Scopus searching tools such as "Limit to", this number was narrowed down to 578 papers. Further filtering, based firstly on abstract reviewing and secondly on full-text reading, resulted in a set of 111 relevant papers. Table 1 reports journals including at least two papers. They account for 44 total papers out of 111. The top contributor is the Journal of Cleaner Production. This is not surprising as sustainable product and process development fall in the field of practising cleaner production.

TABLE 1
Journals accounting for at least two papers

Journal	Papers
Journal of Cleaner Production	17
Clean Technologies and Environmental Policy	9
Ecological Economics	4
Journal of Sustainable Product Design	2
Process Safety and Environmental Protection	2
Materials and Design	2
Computers in Chemical Engineering	2
Resources, Conservation and Recycling	2
International Journal of Sustainable Manufacturing	2
Environmental Impact Assessment Review	2

DEFINING SUSTAINABLE DEVELOPMENT

Our Common Future publication (Bruntdl and Commission Report, 1987) report triggered governments, local authorities, businesses and consumers to define and adopt strategies for sustainable development. The Earth Summit which was held in Rio de Janeiro in June

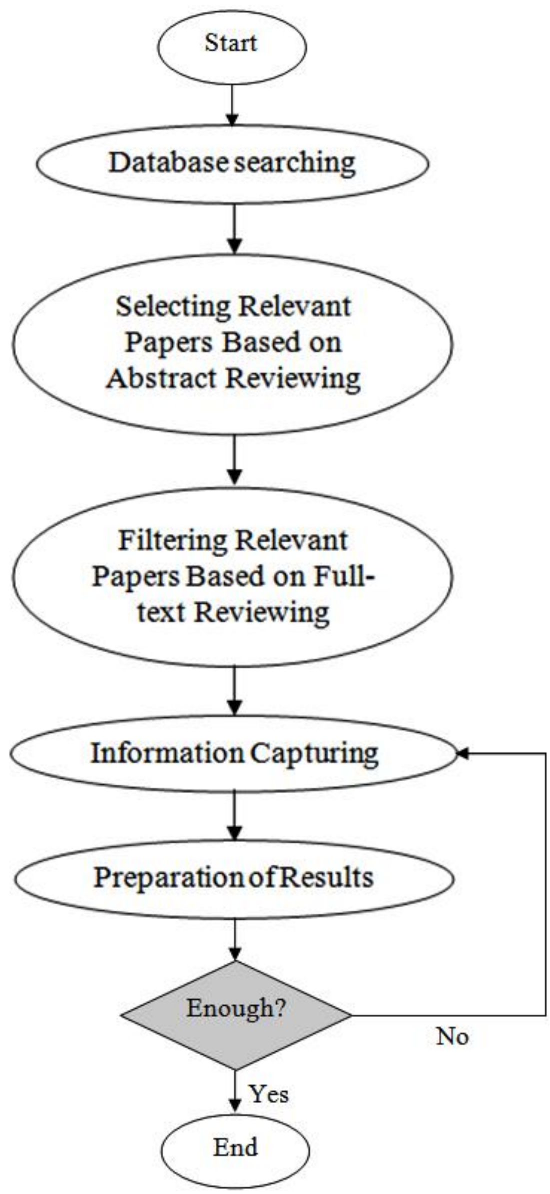

Fig.1: Literature-review methodology

1992 was one of the most noticeable activities that focussed on the concept of sustainable development. Agenda 21 was the outcome of the Summit which is an action plan for pursuing sustainable development (UNCED, 1992). Sachs and Warner (1995) believed that sustainable development would be an outstanding issue in the 21st century. Giudice *et al.* (2006) explained that development process should contain environmental protection as one of its integral parts to achieve sustainable development. In Table 2, some definitions of sustainable development are presented along with their references.

TABLE 2
Definitions of sustainable development

No.	Definition
1	Sustainable development argues for: (1) development subject to a set of constraints which set resource harvest rates at levels not higher than managed natural regeneration rate, and (2) use of the environment as a "waste sink" on the basis that waste disposal rates should not exceed rates of managed or natural assimilative capacity of the ecosystem (Pearce, 1988).
2	Sustainable development means basing developmental and environmental policies on a comparison of costs and benefits and on careful economic analysis that will strengthen environmental protection and lead to rising and sustainable levels of welfare (World Bank, 1995).
3	Sustainable development is about maintenance of essential ecological processes and life support systems, the preservation of genetic diversity, and the sustainable utilization of species and ecosystems (IUCN *et al.,*1991).
4	The term "sustainable development" suggests that the lessons of ecology can, and should be applied to economic processes. It encompasses the ideas in the World Conservation Strategy, providing an environmental rationale through which the claims of development to improve the quality of (all) life can be challenged and tested (Redclift, 1987).
5	Sustainable development involves a process of deep and profound change in the political, social, economic, institutional, and technological order, including redefinition of relations between developing and more developed countries (Strong, 1992).
6	Sustainable development is a balancebetween the available technologies, strategies ofinnovation and the policies of governments (Vollenbroek, 2002).
7	Development that improves the quality of human life while living within the carrying capacity of supporting ecosystems (IUCN, 1980).

ADVANTAGES OF SUSTAINABLE PRODUCTS

A product that has little possible impact on the environment can be classified as a sustainable product (Ljungberg, 2007; Maxwell *et al.,* 2006; Maxwell & van der Vorst, 2003; Vinodh & Rathod, 2010; Huand & Bidanda, 2009; Kaebernick *et al.,* 2003; Hanssen, 1999; Rydberg, 1995). However, the use phase of a product's life cycle can have an outstanding impact on the environment (Jarvi & Paloviita,2007). As shown in Fig.2, Mcauley (2003) pointed out that the use phase of the motor vehicle has the highest percentage (almost 87%) of a vehicle's life cycle energy consumption. Table 3 presents the variety of reasons indicating that sustainable products have the ability to boost both tangible and intangible corporate profits (USA Sustainable Products Corporation, 2002).

Satisfaction experienced by the end customer is an important feature of a good sustainable product. According to the estimations, 90% of all good products cannot find a way to stay in the market (Patrick, 1997). Risk of failure of a newly launched sustainable product in the market is high and, therefore, proper information for customers is needed to make them understand the basis on which the product can be considered as a sustainable one (Ljungberg, 2007).

"Triple bottom line" balance focusses on achieving economic success, environment cleanness and social responsibility all together and is considered as the central concept of sustainability, or sustainable development (Elkington, 1998; Hacking & Guthrie,2008; McDonough & Braungart, 2002; Fairley *et al.,* 2011). Othman *et al.* (2010) stated that "Design for sustainability" is a concept and also a design philosophy. By this, a variety of design methodologies have been developed for improving process design, product design, material design etc. at different points and for different lengths of time .

Product designs that focus on eliminating waste and use of toxic materials and facilitating end-of-life activities will reduce costs and bring benefits to the manufacturer in the long run (Fiksel *et al.*, 1998; Jaafar *et al.,*2007; Afrinaldi *et al.*, 2009; Mat Saman *et al.*, 2010; Zakuan *et al.*, 2011). End-of-life activities should be handled at a dedicated treatment facility in which the consumer of the product will not incur any additional expenses. For instance, Fig.3 shows the recycling and recovery rate of End-of-Life of Vehicles (ELVs) at European Union in 2008. Dinh *et al.* (2009) stated that,"A sustainable product or process is one that constraints resource consumption and waste generation to an acceptable level, makes a positive contribution to the satisfaction of human needs and provides enduring economic value to the business enterprise."

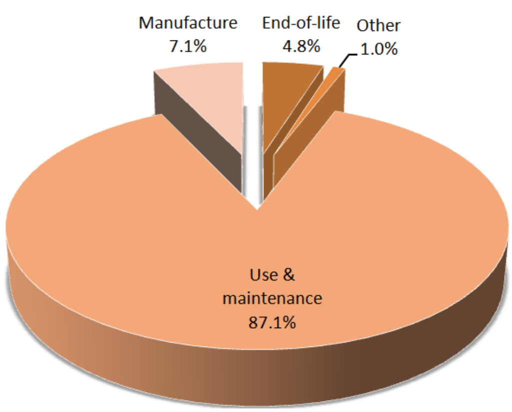

Fig.2: Energy consumption in auto life-cycle (Mcauley, 2003)

SUSTAINABILITY INDICATORS

Measuring environmental, social and economic impacts is important in assessing sustainability. When doing so, it is critical to select vital indicators. In general, sustainability assessment indicators can be divided into two groups, that is, hard and soft.

Quantitative evaluation of a process using formulas is the main feature of hard indicators. Some examples of indicators used by different researchers are net present value (NPV) and rate of return (ROR) (Ulrich, 1984; Baasel, 1990)ineconomic performance assessment; life cycle assessment (LCA) (Harding *et al*., 2007; Kasai, 1999; Guo *et al.*, 2002; Klopffer & Rippen, 1992) and waste reduction (WAR) algorithm (Young & Cabezas, 1999; Heikkila,1999; Cabezas *et al.,* 1999) in environmental performance assessment; and fault tree assessment (FTA) (Volkanovski *et al.,* 2009) and chemical exposure index (AIChE, 1998) in safety-related

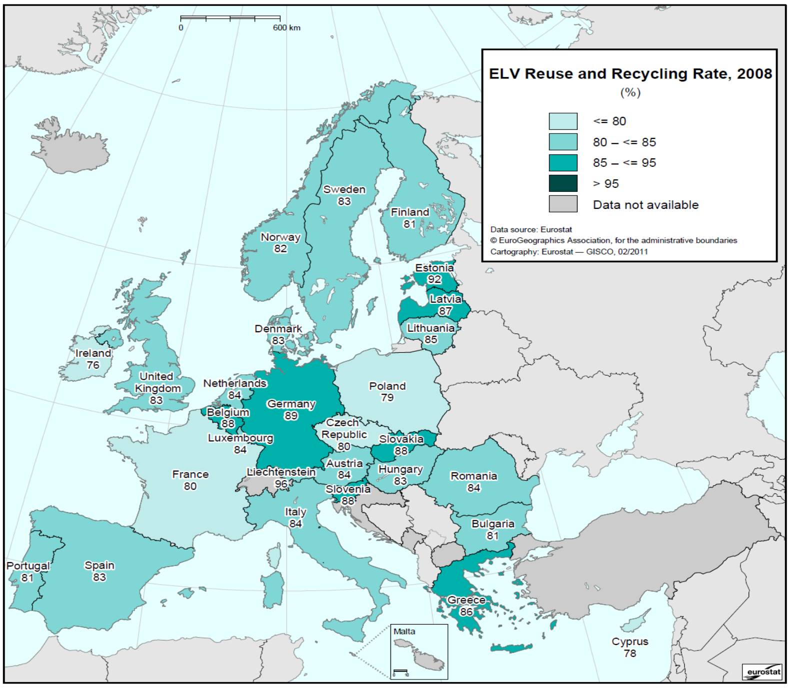

Fig.3: The recycling and recovery rate of ELVs at European Union in 2008 (Eurostat, 2010)

TABLE 3
Advantages of sustainable products

No.	Advantages of sustainable products	Explanations
1	Faster product time to market	Sustainable products will overcome the competitiveness existing in the market.
2	Fewer regulatory constraints	Sustainable products will satisfy all environmental laws and regulation existed in any country.
3	High demand	Costumers will be satisfied by using sustainable products instead of conventional products.
4	Improved employee health and safety	Incorporating social sustainability into the assessment is involved with increasing the employees health and safety
5	Reduced costs for raw materials and manufacturing	Competition among suppliers and manufacturers will ensure that material and manufacturing resources are provided at a cheaper rate than for conventional products.
6	Delivery of value-added products to consumer	Sustainable products are more value-added than conventional products due to their reduced costs of raw material and manufacturing and also improved manufacturing processes.

social responsibility assessment.

On the contrary, soft indicators depend solely on the designer and expert's knowledge and experiences. This would be categorised as qualitative evaluation due to different levels of understanding; these can be very subjective but at the same time are still very important. Soft indicators can be scaled numerically using proper ranking and scaling techniques (Othman *et al.,* 2010). Several types of sustainability indicators have been used for different types of studies (Krajnc & Glavic, 2003; Azapagic & Perdan, 2000; Yan *et al.,* 2009; Lems *et al.,* 2003; Petrie *et al.,* 2007; Pop-Jordanov, 2003; Tokos *et al.,* 2011; Okkonen, 2008; Korhonen *et al.,* 2004; Block *et al.,* 2007; Jain, 2005). However, most product indicator frameworks focus exclusively on economic or environmental performance; very few address societal concerns (James, 1997).

EXISTING TOOLS AND METHODOLOGIES FOR MEASURING SUSTAINABILITY LEVELS

Several tools and methods can be applied in measuring the sustainability level of a product or process. Basically, each of these tools has some advantages and limitations. In this review, an attempt was made to list down all the published methodologies in the field of sustainable product and process assessment. The existing tools for measuring sustainability are described in the following sections. For the purpose of space limitations, main points of each methodology and their applications are described in each section. More detailed information is available in the related original articles.

Weighted fuzzy assessment method (WFAM)

WFAM is a product assessment methodology recently introduced by Ghadimi *et al.* (2012) which tries to incorporate expert knowledge in its assessment process. This effort was done with emphasis on weighing the assessment elements and sub-elements based on the expert opinions of any industry in whichthey are intended to be applied. This methodology was proposed for use as a road map for manufacturers to move towards manufacturing more sustainable products, and a the possibility of a simple improvement to product sustainability that could lead to sustainable manufacturing was illustrated. A case study of the automotive industry showed the efficiency of the proposed method. One of the challenging issues stemming from this method is dealing with the cradle-to-grave boundary that only covers the raw material extraction point and manufacturing stages of the lifecycle. The authors claimed that WFAM can be extended to embrace the whole lifecycle stages and be utilised as a fully functional assessment method, which can be considered as an advantage; this has not yet been done. Other than that, all three aspects of sustainability have been considered in this assessment methodology.

Sustainable process index (SPI)

The sustainable process index (SPI) was introduced by Krotscheck and Narodoslawsky (1996) for evaluating industrial process based on mass and energy balances and measures total environmental impact. The advantages of SPI are the use of natural concentrations of substances in the atmosphere, ground water and soil as a reference, which makes SPI independent of varying legal norms. The disadvantage of SPI is that it evaluates only sustainability in its environmental dimension. The general idea of SPI is to compare mass and energy flows induced by human activities with natural mass flows on a global as well as local scale. The boundary of analysis for SPI is considered as "cradle-to-grave", which covers all four life-cycle stages from raw material extraction point and manufacturing until use and recycle stages. Sandholzer and Narodoslawsky (2007) refined this methodology into an easy applicable form to facilitate the process of calculation. SPI was used by other researchers for measuring environmental impact of processes (Ku-Pineda & Tan, 2006; Narodoslawsky & Krotscheck, 2004; Narodoslawsky & Krotscheck, 2000).

Product sustainability index (PSI)

A new comprehensive evaluation methodology was developed by Jawahir *et al.* (2007) to assess the sustainability content of any given manufactured product, as displayed in Fig.4. This new method considers all three components of sustainability (economy, environment and society), over total lifecycle (pre-manufacturing, manufacturing, use and post-use). This system will assist product developers and manufacturers in achieving sustainability targets. This methodology requires joint effort and commitment from legislators, product developers, manufacturers, researchers etc. to standardise the scoring system and to sub-group the influencing factors that affect product sustainability. Other researchers have used PSI for assessing the product sustainability level (Ungureanu *et al.,* 2007; de Silva *et al.,* 2009; Jayal *et al.*, 2010).

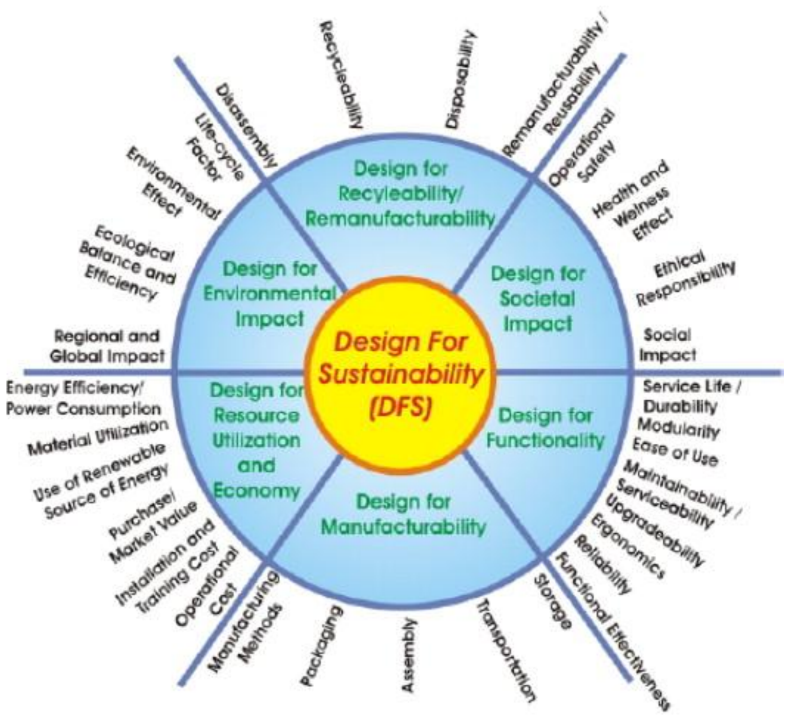

Fig.4: Major elements contributing to design for sustainability (Jawahir *et al.*, 2007)

Fuzzy method for sustainability evaluation

This method helps designers and decision makers to develop sustainable products and process with consideration for environmental, economic and social concerns. This method can focus on the cradle-to-grave boundary of analysis. One of the important advantages of this methodology is the ability to handle severe uncertainty; another is its ability to evaluate qualitative and quantitative data simultaneously due to its integration with the fuzzy logic approach (Hemdi *et al.,* 2011). Also, Phillis and Andriantiatsaholiniaina (2001) developed a model based on fuzzy logic which provides a mechanism for measuring development sustainability (Phillis & Kouikoglou, 2009; Andriantiatsaholiniaina *et al.*, 2004). Ghadimi *et al.* (2011) developed a Graphical User Interface (GUI) that simplifies the use of Hemdi*et al.* (2011) methodology. The efficiency of the developed GUI was illustrated by a case study on an automotive component.

AHP (analytic hierarchy process) with fluctuant weight analysis

Integrated analysis of environmental and economic aspects of sustainability by expanding the domain of LCA is believed to be valuable by many researchers. The structure of the AHP model for the integrated assessment of environmental and economic performances of chemical products was developed by Qian *et al.* (2007).This method covers two dimensions of sustainability which are environmental and economic sustainability. In the AHP model, the top level of the hierarchy specifies the goal, and the intermediate levels specify the criteria and sub-criteria, which reflect successive categorisations of environmental performance and economic performance. The lowest level corresponds to the input associated with chemical product alternatives. One advantage of this method isthat some initial guidelines for judging the feasibility of using a certain product can be perceived based on the obtained results. AHP algorithm has also been used by other researchers in the area of product and process sustainability assessment (Choi *et al.*, 2008; Perez-Vega *et al.,* 2011; Pineda-Henson *et al.*, 2002).

Methodology for process design for sustainability (PDfS)

The methodology for integrating sustainability considerations into process design as described here follows the usual stages in process design i.e.

- Project initiation
- Preliminary design
- Detailed design and
- Final design

It covers the three roots of sustainability. In this method, identifying the sustainability criteria seems to be the starting point. Cradle-to-grave boundary is applied in PDfS which can respond to the need fora systems approach based on life-cycle thinking. Azapagic *et al.* (2006) stated that at this initial stage of designing the sustainable process, there is a need for a complete amount of data and information. Stages of PDfS are shown pictorially in Fig.5. Identification of relevant sustainability criteria and indicators, comparison of alternatives, sustainability assessment of the overall design and identification of hot spots in the life-cycle of the system are enabled by the proposed methodology. Consequently, the most sustainable performance of the plant and product over their whole lifecycles would be ensured by designing the processes according to this proposed method.

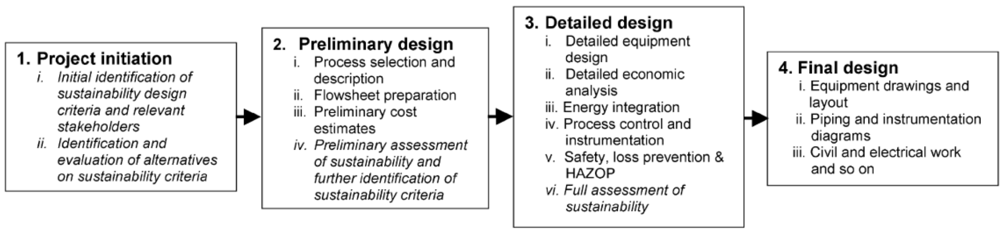

Fig.5: Stages in process design for sustainability (adapted from Azapagic *et al.,* 2004)

A modular-based sustainability assessment and selection (m-SAS)

Othman *et al.* (2010) presented m-SAS which covers all three roots of sustainability in its process evaluation for systematic assessment and selection of sustainable process design alternatives.Analytical process hierarchy (AHP) was applied to assist designers in alternative design selection. Fig.6 shows an overview of the framework. It includes four modules that are commonly part of the design stages and are systematically integrated to assist case model development, data acquisition and analysis, team contribution assessment and decision support process. Two biodiesel processes were investigated to show the efficiency of the proposed method. Considering both soft and hard indicators enables m-SAS that not only offers a quantitative evaluation but also imparts a knowledge-based solution, thereby providing the decision makers with important and holistic information for achieving sustainable design.

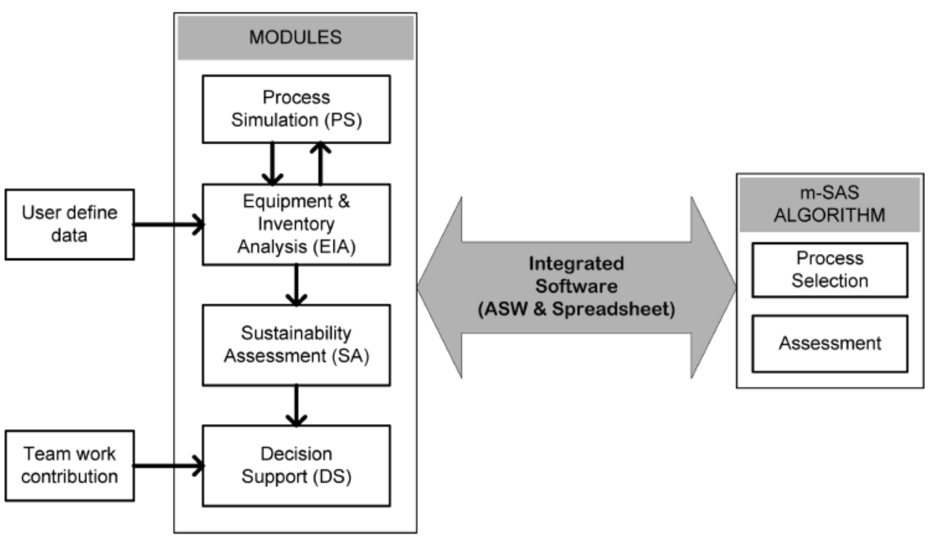

Fig.6: Overview of the modular-based sustainability assessment (m-SAS) framework (Azapagic *et al.,* 2006)

Life cycle index (LInX)

LInX has been proposed by Khan *et al.* (2004); it takes the advantages of LCA to select and make decisions for designing product/process. However, Bailey *et al.* (2010) used this methodology in a different field instead of in large industrial systems. This systematic indexing system contains five aspects which are the environment, health and safety (EHS), technology, cost and socio-political considerations. Each of these aspects has some parameters. For instance, technology has four parameters. Computing weights for each basic parameter and sub-indices are done by an analytical hierarchy process. One of the important limitations of this method is related to its boundary of analysis, which is “cradle-to-grave”,which covers just the first two life cycle stages (raw material extraction and manufacturing) while the two other stages are excluded. Therefore, the use and end of life activities are not covered in this methodology.

Green Pro

A systematic methodology for cleaner and greener process design was proposed by Khan *et al.* (2001) such as Green Pro. The objective of this method is to design processes with minimum impact on the environment through utilising life cycle analysis principles and optimisation framework. One outstanding advantage of this method is that it considers environmental objectives together with technology and economics at the design stage so as to determine cost efficient solutions, right at the early design stage.Cradle-to-grave boundary of analysis is taken into account in this methodology instead of conventional process boundary in order for a more precise evaluation.The basic algorithm of Green Pro is presented in Fig.7.

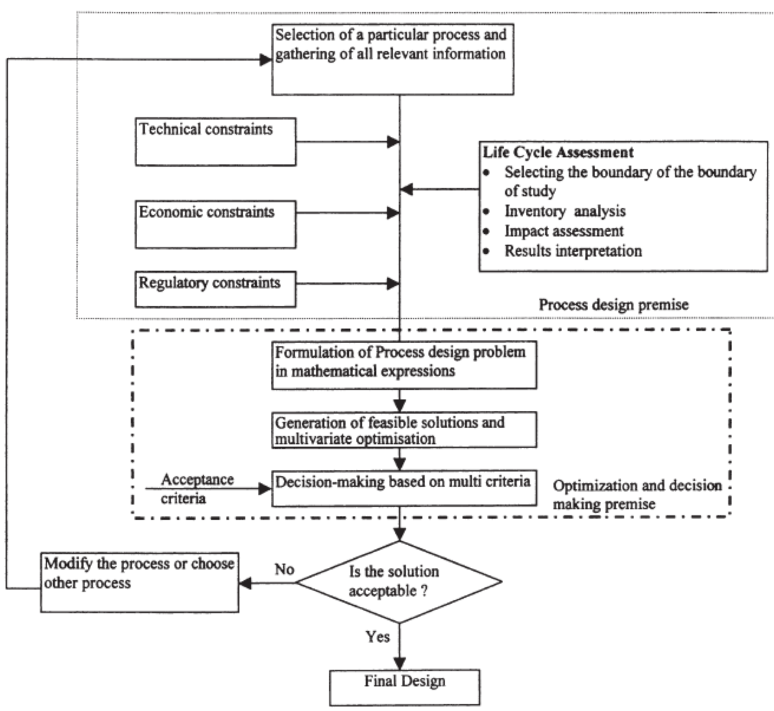

Fig.7: The basic algorithm of Green Pro (Khan *et al.,* 2001)

Green Pro I

Khan *et al*. (2002) modified Green Pro methodology using a holistic and integrated methodology, Green Pro I, for process/product design which employs the Multi Criteria Decision Making (MCDM) approach of fuzzy composite programming (FCP). Advantages of this methodology can be summarised as being more robust against uncertainty in the data andbeing simple and applicable at the early design stage of any process which makes it more efficient than the previous version. Although it seems that Green Pro-I could be applicable for designing processes, the social aspect of sustainability is missing, which can be considered as a weakness. This method was also used by Sadiq *et al.* (2005) for green and clean process selection and design.

Eco Indicator 95

The Eco Indicator 95 is a quantitative distance-target based on LCA methodology (Goedkoop *et al.,*1996). A displayed in Fig.8, by setting a target level for a particular environmental effect, the gap between the environmental impact and the target level will be measured. The more serious impact is the one that obtains the higher weight according to the measured gap. Not covering the economic aspect such as cost, resource depletion and technology can be considered as this methodology's weakness. However, it is an applicable tool for evaluating any type of product and is also understandable by any product designer who does not have a deep knowledge of environmental issues. Other researchers have used Eco Indicator 95 methodology in their research activities (Zabaniotou & Kassidi, 2003).

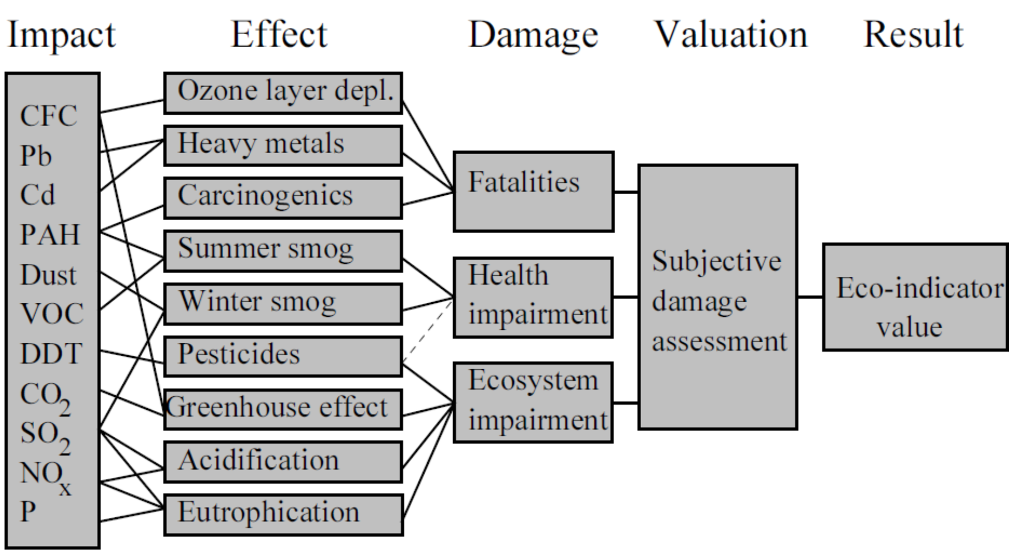

Fig.8: General framework for Eco Indicator 95 (Goedkoop *et al.,* 1996)

Eco Indicator 99

Goedkoop and Spriensma(2001) developed Eco indicator 99 based on the damage-oriented method for life-cycle assessment which is a modification of Eco Indicator 95. Human health, ecosystems and mineral resources are the main three damage categories. Eco Indicator 99 has the advantage of being a generalised tool to evaluate any product and is also well documented as an international standard (Li & Zhang, 2008). However, economic index of sustainability is not encompassed in this methodology. There are also several works in the literature related to assessing environmental sustainability using Eco Indicator as their assessment methodology (Dehghanian & Mansour, 2009; Bovea & Vidal,2004; Gernuks *et al*., 2007).

DISCUSSIONS AND KEY ISSUES

At the present time, developing sustainable products and designing sustainable processes are gaining attention due to the rising awareness of environmental changes, resource and energy prices. Both manufacturers and consumers look forward to manufacture and use more sustainable products. Lack of a broad literature review in the area of sustainability assessment methodologies seem to be missing in the existing literature. This paper tries to fill this gap in the literature. Table 4 presents a summary which covers all the 12 methods discussed in this paper together with their sustainable elements, boundary of analysis and method of analysis.

Based on the discussion ofthe 12 methodologies, it can be perceived that each of these methodologies has some advantages and weaknesses that can be considered for future work. There are some key issues that can be mentioned as follows:

Weaknesses:

1. Many of these methods are not able to assess the sustainability of products or processes regarding the three dimensions of sustainability. For instance, SPI mainly quantifies the environmental impact of the processes. This methodology, however, does not deal with other sustainability aspects such as social impact and economic impact.
2. Most of these methods are not able to analyse qualitative data, which can be considered as a great defect. It is the same for many of the discussed methods such as Eco Indicator 99, LiNX and PSI. This defect is due to the fact that large tracts of related data are expressed as opinions and ideas, which cannot be analysed using quantitative methods.
3. WFAM, m-SAS, Green Pro and Eco Indicator 95 are contained in a group of methodologies where the boundary of analysis is cradle-to-grave, which can only cover raw material extraction and manufacturing stages of process/product lifecycle. This review paper provides useful gathered information which can be applied in extending each of these methodologies with respect to their discussed weaknesses.

Advantages:

WFAM was noticed to be the only methodology that considered expert opinion in its assessment, which was undertaken by weighting their assessment elements and sub-elements. Using Multi Criteria Decision Making (MCDM), experts' knowledge was incorporated into the assessment

TABLE 4
Summary of existing sustainability assessment methodologies

Name of methodology	Sustainable elements	Boundary of analysis	Method of analysis
Weighted fuzzy assessment methodology (WFAM)	Environment, economic and social	Cradle to gate	Quantitative and Qualitative
Sustainable process index (SPI)	Environment	Cradle to grave	Quantitative
Product Sustainability Index (PSI)	Environment, economic and social	Cradle to grave	Quantitative
Fuzzy method for sustainability evaluation	Environment, economic and social	Cradle to grave and Cradle to gate	Quantitative and Qualitative
AHP with fluctuant weight analysis	Environment and economic	Cradle to grave	Quantitative
Process design for sustainability (PDfS)	Environment, economic and social	Cradle to grave	Quantitative and Qualitative
Modular-based sustainability assessment and selection (m-SAS)	Environment, economic and social	Cradle to gate	Quantitative and Qualitative
Life Cycle Index (LiNX)	Environment, economic and social	Cradle to gate	Quantitative
Green Pro	Environment and economic	Cradle to gate	Quantitative
Green Pro I	Environment and economic	Cradle to gate	Quantitative
Eco Indicator 95	Environment and social	Cradle to gate	Quantitative
Eco Indicator 99	Environment and social	Cradle to grave	Quantitative

process. Fuzzy method for sustainability evaluation was used to assess both qualitative and quantitative data simultaneously. This ability was incorporated into this methodology by integrating fuzzy logic in its assessment procedure. Eco Indicator 99 and 95 proved to be promising tools in quantifying the environmental impact of each product. SPI provides reliable measures in evaluating industrial processes and can be applied to rate technologies from the viewpoint of sustainable development. LInX may be useful for government and researchers to be considered as sustainable tools in measuring smaller systems.

Unavailability of relevant data:

Besides the advantages of the introduced methodologies, one of the main concerns in this area could be addressed as unavailability of appropriate information. All of these methodologies are data driven methods, which means that they can be fully operative if all the needed data are provided. This prospective allows the assessment of products and processes to be limited to the available provided data. To solve this issue, full cooperation and coordination of all practitioners of sustainability assessment such as company managers, CEOs and government authorities would be most constructive.

Integrated assessment methodology:

From this review of 12 assessment methodologies it can be perceived that there is an absence of a hybrid methodology which can integrate the assessment procedure of both manufacturing process and its manufactured product simultaneouslywhile considering the manufacturing line's entire supply chain and the optimisation of the manufacturing line in order to achieve continuous improvements.

CONCLUDING REMARKS

A broad literature review has been produced to give the reader a comprehensive discussion ofthe main topics related to different sustainability assessment methodologies in the field of manufacturing processes and manufactured products. A discussion of sustainable development was provided in this paper. Also, some challenges associated with advantages of sustainable products were highlighted such as end-of-life activities and use phase of product life-cycle. Moreover, various sustainability indicators have been presented with their application in different fields of research. The rest of the paper discussed the 12 existing methodologies developed for sustainability assessment of products and processes. In conclusion, it can be said that this review may be found to be useful by both practitioners in companies and academics as it outlines major lines of research in the field. Furthermore, it discusses specific features of sustainable products or process design assessment as well as the limitations of existing research; this should stimulate ideas for further research.

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