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An Overview on Life Cycle Inventory Leads to Green Manufacturing: Methods and Modifications

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Green manufacturing requires methods to measure and compare the environmental impacts of products throughout its entire life cycle. Life cycle inventory (LCI) is a tool for green manufacturing which deals with the compilation and quantification of the inputs (i.e. raw materials) and outputs (emissions) for a given product throughout its life cycle. The three main classifications of LCI are: Process oriented modeling, Input output analysis and Hybrid method. In this paper, literatures on methodological evolution of LCI methods are reviewed and the advantages and limitations and applicability of these methods are also presented. Finally, conclusions are drawn, combined with development scope of these inventory compiling methods in green manufacturing.

1. Introduction

The inventory results found from LCI is utilized to assess the environmental impacts which are linked to the opportunity of green manufacturing practice. A clear need therefore exists to calculate this inventory with a method that provides greater accuracy and reliability. However, availability of data, time, resource and methodological complexity etc. are important factors to be considered for this computation. Some LCI methods offer greater accuracy but they lack system boundary completeness; some offer boundary completeness but lack in temporal differentiation and face data uncertainty; some offer greater accuracy and boundary completeness but face with data double counting and mathematical complexity. The three principal methods of LCI are: Process Oriented Modelling, Economic Input Output Analysis (IOA) and Hybrid method. Process Oriented Modelling consist**s** of two other classifications namely: Process Flow Diagram (PFD) and Matrix Inversion (MI). Hybrid method has three classifications. They are: Tiered hybrid, Input Output (IO) based hybrid and Integrated hybrid. The aim of this paper is to provide an overview on the developments in LCI methods towards sustainable green manufacturing practice, their strengths and limitations and applicability of LCI into different methods currently in practice under green manufacturing.

2. Evolution of LCI methods

The practice on LCI begins with a product level improvement in green manufacturing which is cumulative energy requirements in a production process (Smith, 1969) via Process Flow Diagram (PFD). However, in reality the production system can include multi input/multi output or there may be internal looping. By considering all these issues, Consoli (1993) introduces iterative methods. However, the time and cost for this method is still higher specially when a rapid decision is required in green practice i.e.: Design for Environment (DfE) process, make/buy decision in green bill of material etc. Therefore, practitioners start to search for methods to make it faster and easier. Heijungs (1994) come up with Matrix Inversion (MI) method which can perform large number of equation simultaneously. Nevertheless, the method is still too complicated and huge amount of data is required. In contrast, lack of data from the upstream and downstream processes hamper the LCI result. Therefore, Leontief's (1936) economic Input Output Analysis (IOA) method is followed. After that, six models for IOA is revealed by Joshi (1999) which solve all

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the difficulties on boundary incompleteness and inflexibility in LCI calculation. The resolution of LCI result in green manufacturing practice increases more when the Missing Inventory Estimation Tool (MIET) is introduced by Suh and Huppes (2002). MIET takes the dollar value of a product as input and reports green performance (environmental flows) as an output throughout the economy. This method is quite faster but suffers from coarsely modelling commodities in terms of unit processes in a product life cycle. Attempts to overcome these disadvantages, hybrid approaches are introduced since early 70's (Bullard et al., 1978). Greening of a product life cycle doesn't end with manufacturing rather the system boundary should be increased to include the consumer usage and end-of-life. With a view to increasing the system boundary, Moriguchi et al. (1993) added the use phase and end-of-life phase emissions to the previous LCI results. In this case, most of the process data are obtained from IO table and processes not covered by the IO table obtained from POM. However, this method suffers from double counting for overlapping data. Therefore, Treloar (1997) introduced IO-based hybrid which solves the double counting problem by extracting the particular paths from IO matrix. However, this method suffers from the same uncertainty problem suffered by IOA based LCI. Therefore, Suh and Huppes (2000) introduced integrated hybrid for reducing uncertainty in IO-based hybrid by interconnecting IO table at upstream and downstream cut-offs.
Since these evolution phases, modification on the LCI techniques are still under practice to avail this tool more suitable for green product development. Some recent contributions of the practitioners' are given in Table 1:

Table 1: Recent contribution of LCI methods

Reference	Contribution	Comments
Munksgaard et al. (2005)	Multi-Region Input–Output (MRIO) accounts	Environmental impact in case of trading in different countries
Crawford (2008)	Assessed the completeness of the IO-based hybrid approach	Including capital inputs in LCI increase inventory result by 22 %
Tan et al. (2008)	Fuzzy linear programming model for multiple environmental impact categories.	A framework to get fuzzy targets from experts interview is necessary to implement this model for practical implications
Tan et al. (2012)	Fuzzy input–output optimization model	Reducing uncertainty in MRIO LCI
Cellura et al. (2012)	Various recent practices on process flow diagram method	Identifying which stages of process should be improved to avail green practice
Cruze et al. (2014)	Least square technique for allocation	Helps to correctly allocate the environmental burden among the co-products in a multi output production system.
Vinodh and Rathod (2014)	Application of life cycle assessment and Monte Carlo simulation for enabling green product design	Monte Carlo simulation for reducing uncertainty in green product design
Jiang et al.(2014)	IO based hybrid inventory analysis for a diesel engine	Uncertainty of process based LCI is lower than that of IO based hybrid in determining the green value of a product
Pinsonnault et al. (2014)	Reasons for adding temporal effects in LCI calculation	The lack of a temporal aspect in current inventory analysis creates large uncertainties and may result in misleading conclusions in green manufacturing practices, especially on those long-lived products.
Bellon-Maurel et al. (2015)	Considered temporal differentiation in LCI computation	Decision making in green manufacturing.
De Marco et al. (2015)	Gate-to-gate and gate-to-grave approach	LCI is utilized to determine environmental key performance indicators (KPIs)

3. Advantages and limitations of various LCI methods

Different methods of LCI have different advantages and limitations. Depending on the objective of green manufacturing, the goal and scope definition of LCI result is selected. These actually determines which particular LCI method should be chosen. The advantages and disadvantages of different LCI methods are presented in Table 2.

Table 2: Advantages and limitations of various LCI methods

LCI methods		Advantages	Limitations
Process oriented modeling	Process Flow Diagram(PFD)	• Provides necessary level of detail of the process under study • Gives best result for single product system • Easier to understand	• Dealing with larger system with multiple input/output becomes very complicated and time consuming • Loop among the process needs iterations to be solved
	Matrix Inversion(MI)	• Works effectively with multiple input/output system • Works simultaneously with lager number of equations • Provides necessary level of detail of the process under study	• A lot of upstream and downstream process data are required which makes the method complicated. • Truncation error for underestimating higher order process data. • Mathematical expertise required
Economic Input-Output Analysis		• Calculate upstream or indirect environmental impacts • Reduce truncation error • Reduce time and complexity. • Does not require unit process data. • Easily calculate the amount of environmental impact in goods traded between nations	• Input-output tables themselves do not cover the entire life cycle; • Lack in necessary level of detail • National IO tables have separate entries for import and export, and hence tend to exclude interventions from production abroad • The data found from IO table is quite coarse, so data uncertainty occurs • Data is not always updated
Hybrid method	Tiered Hybrid	• Simplest hybrid method • Relatively complete upstream boundary than process based modelling • Eradicates the error of uncertainty of inventory data.	• Double counting due to overlapping between IO and process based database. • Truncation problem may occur • Interaction between process based and IO based cannot be assessed in systematic way. • The lack of dynamic representations
	Input-Output based Hybrid	• Considers the capital inputs • Shows a significant increase in the total values over the tiered hybrid analysis due to the use of I–O data • No double counting incident	• The disaggregating of IO table is complex. • Uncertainty of LCI results is higher due to not updated IO data (Jiang et al., 2014) • Recurring flows between the main system and use and end-of-life phase (externally added to the main system) are not properly described • Yield misleading results if the national economy relies heavily upon imports
	Integrated Hybrid	• The consistent mathematical framework for the entire life cycle • In comparison with other methods hybrid analysis results accurate environmental impact	• Complexity of use • High data requirement • Time consuming • Double counting may occur

4. Applicability of LCI

LCI has evolved significantly over the past three decades to become more systematic and robust tool for identifying and quantifying potential environmental burdens and impacts of a product. Its integration and connection with other concepts and methods strengthen LCI as a tool and eventually increase its usefulness in the area of green manufacturing. Some methods under green manufacturing where LCI is utilized are given in Table 3.

Table 3: Recent contribution of LCI methods

Method	Function in green manufacturing
Environmental Impact Assessment (Hauschild et al., 2013)	to ensure environmental impacts are considered explicitly both during the design of a new development
Strategic Environmental Assessment (Björklund A., 2012)	helping policy development
Environmental Key performance index (De Marco et al., 2015)	determining green value of a product
Multi-Criteria Decision Analysis (Prado-Lopez et al., 2014)	Supporting comparison of different options
Design for Environment (Vargas Hernandez et al., 2012)	product design phase
Material Flow Analysis (Rochat et al., 2013)	systematic accounting of the flows and stocks of a material within an economic system
Energy Analysis (Bribián et al., 2011)	Focusing on energy flows
Risk Assessment (Linkov and Seager, 2011)	in assessing the environmental, health and safety related risks posed by chemicals, harmful substances, industrial plants, etc
Life Cycle Costing (Swarr et al., 2011)	total costs of a product, process or an activity over its life span

5. Conclusion

In this work, a review has been presented which depicts how the evolution of LCI increases it's usefulness in the area of green manufacturing. The advantages and disadvantages of various LCI methods reflect that various methods are suitable for various phases of green manufacturing. MI method is superior to the PFD method particularly for the most simplified systems. Pure IO-based LCI can be most suitable for first proxy. However, when PFD is compared with the integrated hybrid analysis, the latter provides system completeness in LCI results. With information on the monetary value only for cut-off flows and with improved availability of environmentally extended IO data, integrated hybrid method becomes the best choice though the method is quite expensive. Therefore, with time and money available, integrated hybrid is the best option. On the other hand, the tiered hybrid analysis has the appeal of easy extension on existing PFD and IOA systems in filling the gaps. However, the connection between the two inventory subsystems is made externally which may cause double counting. In contrast, the IO-based hybrid analysis shows higher resolution for the IO-based system and does not have problems of overlap. For a faster rough green manufacturing decision i.e. DfE, IOA is suitable. For long term decision like Policy development, new product development, environmental impact assessment etc. process analysis or tiered hybrid is appropriate. On the contrary, with time and money available, the choice for any green attempt should clearly be integrated hybrid.

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