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LIFE CYCLE AND SUSTAINABLE SUPPLY CHAIN ASSESSMENT BASED ON EXERGY ANALYSIS

Astract

Integration of environmental aspects and taking into account all aspects of sustainable development is one of the new trends in supply chain management (sustainable supply network). In this paper a new method, which is a comprehensive approach to determining the sustainable supply chain from raw material acquisition to the end of life is presented. Applications of the exergy concept in the field of sustainability is shown. The paper presents exergy as useful tool to measure sustainable supply chain. Exergy analysis can be used to identify problem areas in supply chain and inefficient uses of natural resources and design the supply chains for new products in multi-criteria decision making. Several methods taking into account the exergy analysis of any resource of a supply chain for sustainability performance measurement in whole life cycle was proposed.

Key word: Sustainable Supply Chain, Life Cycle Assessment, Exergy Analysis

1. INTRODUCTION

There are many methods taking into account the exergy analysis of any resource of a supply chain for sustainability performance measurement. They include: Extended Exergy Accounting (EEA), Cumulative Exergy Consumption (CExC), Exergetic Life Cycle Analysis (ELCA) and Life Cycle Exergy Assessment (LCEA). The relationship between sustainable development, sustainable supply chain and use of resources, fuel, food, soil, water is very important. The Sustainable Supply Chain extends the supply chain by considering the backward flow (reverse supply chain) and the environmental, economic and social aspects. According to the sustainable development principles non-renewable resource depletion should be minimize. Exergy analysis can be used to assess the depletion of these resources in supply chain.

2. SUSTAINABLE DEVELOPMENT AND ECO-EFFICIENCY ANALYSIS

Sustainability means that processes are considered from the perspective of all the sustainable development factors – environmental, economic and social aspects - in whole life cycle. One of the methods to comprehensive assessment processes, products or technologies at every stage of life is Life Cycle Sustainable Assessment (LCSA). The second method of the effectiveness assessing of taking into account all three components of sustainable development is Socio-Eco-Efficiency Analysis (SEEbalance) [1]. The concept of sustainable development was first described in 1987 by the World Commission on Environment and Development under the leadership of the former Norwegian Prime Minister Brundtland [2].
Eco-efficiency is one of the key factors of sustainable development, which integrates environmental considerations with economic analysis to improve products and technologies in full life cycle. Eco-Efficiency Analysis (EEA) allows to find the most effective solution

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taking into account economic aspects and environmental compatibility of products or technologies [3].
Author proposed in [4] integration of environmental and economic aspects of product or technology in whole life cycle and suggested Eco-Efficiency Analysis (EEA) as a new criterion for production system assessment (instead of productivity). In article [5] was presented the importance of economic and environmental aspects assessment in the logistics process and the essence of eco-efficiency analysis in the production logistics. Eco-efficiency analysis allows to find the most effective solution taking into account economic aspects and environmental compatibility of products or technologies. The concept of eco-efficiency (EE) was first introduced by Schaltegger and Sturm (1990) [6], the concept only became popular after adoption by the World Business Council for Sustainable Development (WBCSD) in 1992. Although, there is as yet no unambiguous and generally accepted definition of eco-efficiency, consensus seems to be growing that an eco-efficiency indicator expresses the ratio between an environmental and a financial variable [7]. The methodology of eco-efficiency calculation is known for almost twenty years. According to WBCSD "Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity". In short, it is concerned with creating more value with less impact [8]. One of the eco-efficiency tool is Life Cycle Assessment (LCA). LCA represents application relating to the environmental dimension of sustainability. According to ISO 14040 LCA is defined as "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" [9,10]

3. GREEN SUPPLY CHAIN, SUSTAINABLE SUPPLY CHAIN AND SUSTAINABLE SUPPLY NETWORKS

The Green Supply Chain extends the supply chain by considering the backward flow and the environment impacts of the Supply Chain activities. The backward flow is known as reverse supply chain. The Green Supply Chain was adapted from Beamon [11] and Cash and Wilkerson [12]. An extensive state-of-the-art review for the green supply chain management is presented by Srivastava [13]. The author classifies the existent works about Green Supply Chain according to the sub-areas of this discipline and the used evaluation technique. Some of the classified sub-areas are: products manufacturing and remanufacturing, Life Cycle Assessment (LCA), reverse logistics, network design and waste management.

The Sustainable Supply Chain extends Green Supply Chain by considering besides the backward flow (reverse supply chain) also all of sustainability aspects: the environmental, economic and social aspects [14].

In the supply chain are developed primarily informatics models, for example the hybrid intelligent decision support system [15]. One of the new trends in supply chain management is Sustainable Supply Network. A Sustainable Supply Network is comprised of raw materials as they flow from source to product to disposal/reuse. It encompasses people, environmental and human rights activities, information flow and resource consumption. Every organization is involved in multiple supply networks as a manufacturer and/or consumer.

There are presented nine categories of a Sustainable Supply Network [16]:

1. Social Accountability
2. Climate Change / Carbon and Environmental Management
3. Energy Efficiency
4. Waste Management
5. Air Emissions
6. Water Management
7. Chemical Management
8. Raw Material Extraction
9. Transportation

Wal-Mart is example of company that is leveraging its buying power to increase sustainability throughout its supply chains. Wal-Mart has launched a number of sustainable supply chain programs, including its Sustainability Value Network which directly involves its suppliers in a number of green initiatives. Wal-Mart also implemented a supplier packaging scorecard, that formally rates suppliers on their progress toward developing sustainable packaging, as well as their ability to help Wal-Mart reach the company's sustainability goals to reduce waste, use renewable energy and sell sustainable products [17].

Raw materials constitute one of the important elements of each supply network. Each material has an environmental and social implication. Raw material extraction assessment is very important. For this can be used exergy analysis and concept of the Thermo-Ecological Cost (TEC) [18].

4. LIFE CYCLE ASSESSMENT, SUSTAINABILITY AND EXERGY ANALYSIS

The Life Cycle Assessment (LCA) is an environmental assessment method for evaluation of impacts that a product, process or technology has on the environment over the entire period of its life – from the extraction of the raw material through the manufacturing, packaging and marketing processes, the use, re-use and maintenance of the product or technology, to its eventual recycling or disposal as waste at the end of its useful life. LCA is a method of the evaluation of environmental aspects and potential impacts associated with all stages of the life of product, process and technology. LCA can assist companies in the environmental management [27]. LCA of a product includes all the production processes and services associated with the product through its life cycle. Such a complete life cycle is also often named " cradle-to-grave". Transportation, storage, retail, and other activities between the life cycle stages are included where relevant. This life cycle of a product is hence identical to the complete supply-chain of the product plus its use and end-of-life treatment [28]. The LCA method consists of four phases (Fig.1) [9,10]. Comparative analysis of supply chain approach, life cycle and exergy analysis (Thermo-Ecological Cost TEC) was conducted (Fig.2). The exergy analysis can be employed to measure and compare the use of different energy sources in technologies and processes [19]. This kind of analysis aims at comparing the energetic efficiency and destruction considering the Second Law of Thermodynamics [20]. Some efforts have also been made with the objective of combine exergy and LCA. There are several proposals that consider the exergy analysis for measuring sustainability performance. Extended Exergy Account (EEA) [29], Cumulative Exergy Consumption (CEC) [30], Life Cycle Exergy Analysis (LCEA) [23], Exergetic Life Cycle Assessment (ELCA) [22,31] are some of these approaches, which usually measure the amount of exergy consumed, or destroyed, in a process. Thus, the less exergy a process consumes, or destroys, the most sustainable it is. The Life Cycle Exergy Analysis (LCEA) aims at measuring the total input and output exergy in the product life cycle, also differing renewable and non-renewable resources. It divides a system in three stages: construction, operation, and clean up [23]. These methods have been employed in different areas like electricity production [24], supply chains [25] and IT companies [26].

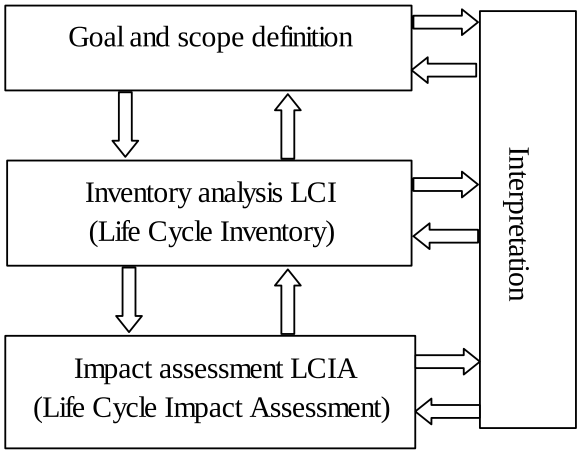

Fig. 1. LCA phases
Source: modified according to [9,10]

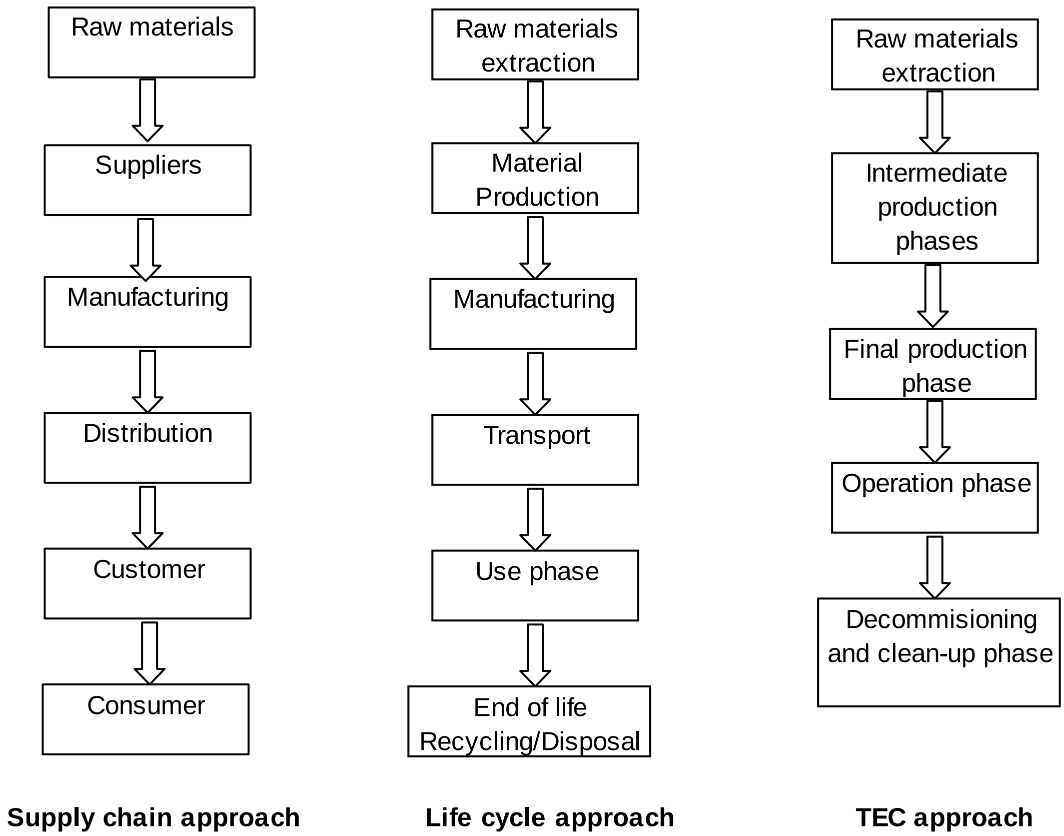

Fig. 2. Comparison of supply chain, life cycle and thermo-ecological cost (TEC) approach
Source: own analysis

LCA and exergy are similar methods, but there are among them also important differences. LCA and exergy analysis methods take on a life-cycle perspective from “cradle to grave". Exergy analysis can be part of an LCA, representing a method for the life-cycle impact assessment (LCIA) of resource consumption (for assessing the quality and quantity of a resource). In Fig.3 is showed life cycle approach in whole supply chain.

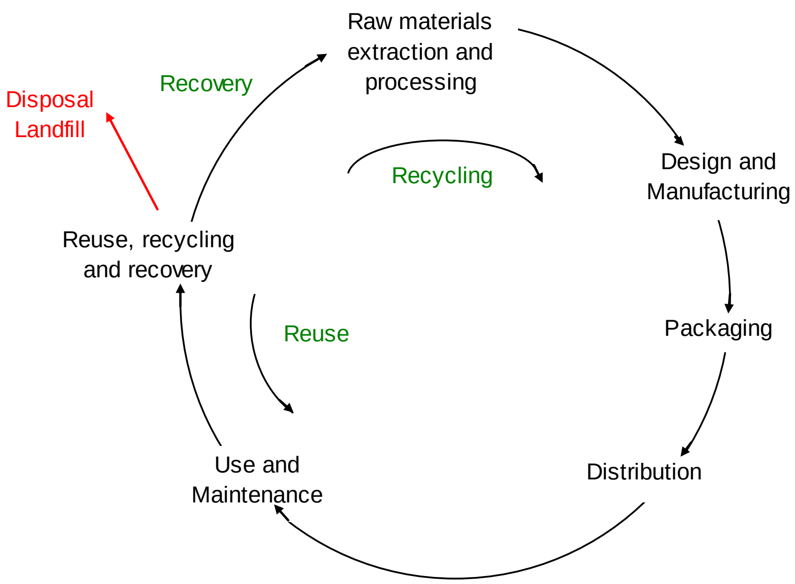

Fig. 3. Full life-cycle approach in whole supply chain.
Source: own analysis

If technology strives for sustainability, it has to consider the resources it requires, the efficiency of the conversion of resources into products and the generated emissions of the selected processes [32]. The quantitative assessment of the sustainability of different technological options is not straightforward [33]. A widely used approach here is the life cycle assessment LCA. Once the inventory of all material streams over a life cycle has been made, the main obstacle in this approach is the weighting of different effects. This is basically due to the lack of an objective scale with the same unit applicable for all kind of effects. In view of this shortcoming for quantifying the sustainability of technology, the exergy concept offers possibilities, as shown by the exergetic life cycle approach of Cornelissen [21] and the sustainability coefficient of Dewulf et al. [32].

Sustainable improvement processes or activities are achieved through the reduction of irreversibility, Gong M. and G.Wall [23] had a clear distinction between renewable and non-renewable resources to assess the sustainability of a process or activity. This method began in 1977 with the work presented by Wall. This type of analysis applied to productive sectors may lead to understanding of how to improve the sustainability of the activities through the reduction of exergy consumption. The methodology of ELCA is relatively the same of LCA, the difference is that the Inventory Analysis is more extensive, the mass and energy balances should be closed and the black boxes must be more simplified for inputs and outputs of production processes considered within the inventory.

5. SUMMARY

One of the main goal of LCA is to reduce resource use and emissions to the environment throughout product or technology life cycle. This enables better links between the economic, social and environmental dimensions throughout entire supply chain. A whole life cycle of product or technology begins with extracting raw materials from natural resources in the ground and generating energy, production, packaging, distribution, use, maintenance, recycling, reuse, recovery or final disposal. One of the method combining life cycle approach and exergy analysis is the Exergetic Life Cycle Analysis (ELCA).
Exergy Analysis is a good measure to get a sustainable development. It is then, a very useful tool, which can be successfully used in performance evaluation and identify problem areas in supply chains and aids in identifying losses and inefficient uses of natural resources. Exergy losses provides not only a measure of both, the energy availability and resource depletion but it is also the most suitable criterion to improve the technological efficiency of the industrial production system. In this way, the Exergy analysis, associated with the energy and mass balances, represents an important advancement in the multi-criteria analysis of products.

Exergy analysis is a thermodynamic approach, which can be used for:

- analyzing and improving the efficiency of chemical and thermal processes
- life cycle assessment of industrial products and processes.
- sustainability evaluation of industrial products and processes.
- improving process efficiency
- environmental assessment
- sustainable supply chain assessment

Exergy analysis is also useful while designing the supply chains for new products. However, in such cases, exergy analysis needs to be extended to include Eco-Efficiency Analysis.

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OCENA CYKLU ŻYCIA I ZRÓWNOWAŻONEGO ŁAŃCUCHA DOSTAW W OPARCIU O ANALIZĘ EGZERGETYCZNĄ

Streszczenie

Uwzględnianie aspektów środowiskowych w powiązaniu z pozostałymi aspektami zrównoważonego rozwoju jest jednym z nowych trendów w zarządzaniu łańcuchem dostaw (zrównoważona siec dostaw). W artykule przedstawiono nową metodę, która umożliwia kompleksowe podejście do oceny zrównoważonego łańcucha dostaw, od nabycia surowca do końca życia. Przedstawiono zastosowanie koncepcji analizy egzergetycznej w obszarze zrównoważonego rozwoju. W pracy przedstawiono egzergię jako użyteczne narzędzie do analizy zrównoważonego łańcucha dostaw. Analiza egzergetyczna może być zastosowana do zidentyfikowania obszarów problemowych w łańcuchu dostaw i nieefektywnego zużycia zasobów naturalnych. Przedstawiono kilka metod uwzględniających analizę egzergetyczną w pełnym cyklu życia.

Słowa kluczowe: Zrównoważony Łańcuch Dostaw, Środowiskowa Ocena Cyklu Życia, Analiza Egzergetyczna