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Hybrid modeling and simulation for complementing Lifecycle Assessment

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ABSTRACT

This paper presents a new complementary lifecycle assessment (LCA) approach to address several limitations of the standard LCA methodology. An integrated approach of agent-based modeling, system dynamics and discrete event simulation was adopted to complement the standard LCA methodology. A hybrid simulation model was developed as a proof-of-concept system, then it was validated using a case study of bottled water and alternative drink products. The model was based on the assumption that parameters and relationships were constant regardless of local uniqueness. The research demonstrates that the hybrid modeling and simulation method can address several limitations of the standard LCA. Also, it is also proven that the method has a potential to address social and economic aspects.

1. Introduction

As energy consumption and pollution become critical issues worldwide, people are more and more concerned with sustainability issues through various attempts ranging from creating environmental-friendly products to changing habits to reduce waste. Governments and corporations also make numerous efforts such as managing energy usage, waste, emission, etc. While such initiatives deserve commendations, there is a danger of focusing on local improvement only thus unintentionally worsening the situation unless a holistic systems thinking guides those executions. One of the useful tools in evaluating overall environmental impacts throughout a product's entire life is lifecycle assessment (LCA). LCA is the "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle" (ISO 14040, 1997). In a LCA study, many aspects throughout a product's lifecycle can be considered including production, transportation, distribution, usage and end-of-life activities. LCA has been used to identify potential opportunities for improvement such as in better design, better manufacturing processes and better management in order to minimize negative sustainability impacts (Brezet & Hemel, 1997).

LCA is a unique tool that comprehensively examines the environmental impacts of a product or service throughout its life cycle. It is an ISO standardized method and proved to be a useful aid in decision-making for designers, managers, government and consumers (Brezet, Stevels, & Rombouts, 1999; Rahimifard & Clegg, 2007). However, the standard LCA method has a number of limitations and some of these problems can be critical (Reap et al., 2008). One of them is that the LCA method takes a static viewpoint that its parameters and internal relations among entities remain constant. Also, the social and economic impact, local environmental uniqueness, effects of dynamic environment, and temporal perspectives cannot be easily considered in the LCA. In other words, the standard LCA is useful as a high level tool, but not necessarily for dealing with dynamics and uncertainties.

This research aims to demonstrate that a hybrid simulation model can address these limitations of the standard LCA approach. All the steps in LCA – goal and scope definition, inventory analysis, and impact assessment, including interpretation – are considered in our research. However, the focus is placed on the third step of the LCA, that is, impact assessment. A hybrid simulation model combining agent-based modeling, system dynamics and discrete-event simulation methods was developed as a proof-of-concept system. The validity of the developed approach was done on comparing bottled water alternatives such as tap water and vitamin water along with different bottle options.

The paper is organized as follows. First, limitations of traditional LCA approach will be addressed, followed by explanation of an integrated hybrid modeling and simulation approach. Drinking water and beverages are chosen to illustrate how the framework is developed and modeled. Impact analysis based on the simulation

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results is explained to show the value and potential of the new complementary LCA approach. Conclusion and future work is provided at the end.

2. Limitations of standard Lifecycle Assessment (LCA)

The standard LCA method has been adopted to address the needs of research and practical analyses for a long time (Azapagic, 1999; Guinée et al., 1993; Van den Heede & De Belie, 2012). It is useful because it constructs a grounded structure and procedure to analyze an overall environmental impact that a product can make during its whole life cycle. However, its advantages through adopting a systematic viewpoint (Forrester, 1968) became its limitations because many systems of interest are never static, but evolving.

Stasinopoulos et al. (2012) points out one kernel limitation of standard LCA method is that its life cycle inventory studies assume that parameters used are always constant or fixed functions of time which prevents taking temporal effects and dynamic response of the system into consideration. The report that the simplified assumption made in estimating energy benefits is not reasonable later. In comprehensive discussion of unresolved problems in LCA, Reap et al. (2008) explains the reason and progress made to overcome numerous disadvantages, and classifies those critical problems and difficulties into several categories. Categories are also rated for severity and adequacy of traditional LCA solutions.

Powell criticizes the laggard traditional inventory analysis and local environmental uniqueness with impacts that could potentially lead to a faulty decision-making process (Powell, 2000). Mayyas et al. (2012) points out the disadvantages of static point of view, not only on the system's boundary selection and inventory, but also on the data and time horizons. He further uses an example on how to make a sustainable lightweight body-in-white design with improved quick solutions to the standard LCA approach. The uncertainties such as in data and function are also overlooked in the traditional LCA study. However, these uncertainties can play important roles in affecting outputs and estimated environmental impact severity and thus impact decision making for enterprises and governments.

While these are all valid critiques and points for improvement for the standard LCA method to be addressed eventually, we address only a few of these problems in our research, that is, social and economic impacts, alternative scenario considerations, local environmental uniqueness and dynamics and time horizons. Table 1 highlights what this research addresses in the list of problems that Reap and his colleagues pointed out (Reap et al., 2008).

3. Integrated hybrid modeling and simulation method

Three commonly used systems modeling and simulation methods are Discrete Event Modeling and Simulation (DEMS), System Dynamics Modeling and Simulation (SDMS) and Agent-based Modeling and Simulation (ABMS). These are integrated to simulate the life cycle process and study short-term and long-term performance under various scenarios. The new approach has potential for building a unique model that can combine each model's uniqueness and advantages into one model and take their differences into consideration.

Discrete Event Modeling and Simulation (DEMS) can simulate multiple events in a time sequence (Zeigler, Kim, & Praehofer, 2000). They are built in the form of entities, flowcharts and resources. DEMS is a natural choice when linear processes in a complex environment is modeled and an entity's action is triggered by other entities or a certain time. Many service facilities, production systems, maintenance and recycling facilities, and transportation and material handling systems are best described and simulated via DEMS.

System Dynamics Modeling and Simulation (SDMS) is a methodology used to model and simulate a system from a higher system-level viewpoint (Doebelin, 1998; Sterman, 2001). It comprises stocks, flows and unique feedback loops. The state of the whole system could be observed from various stocks at a given time. Aggregates are linked through aggregated mechanisms implemented as flows in SDMS. Stock and flow are natural choice for modeling beverage inventory and production flow. Feedback loops link each module of the system with defined relations and influence.

Agent-based modeling and simulation (ABMS) is a methodology used to model and simulate individual actions and interactions of agents in a complex adaptive system, focusing on their effects on the system as a whole (North & Macal, 2007). ABMS are also called individual based models, due to their bottom-up individual-level modeling approach. They are constructed in the form of active objects, individual behavior rules, and direct or indirect interaction within a dynamic environment. All of these elements can be used to represent agents and their interactive operations in an environment such as a competitive beverage sale market. Therefore, it can be used to bridge marketing and engineering activities. It also suits complex and flexible situations that need to be modeled, especially when taking customers, retailers and competitors into consideration.

These three methodologies can be combined into an integrated hybrid modeling and simulation method to complement each methodology's respective strengths. The most promising part of the integrated modeling approach is its flexibility that can handle dynamic and evolving requirements of a system. SDMS can deal with aggregates at the highest abstraction level while DEMS can be used at middle levels of abstraction and possibly at lower levels as well. ABMS can be used across all levels of abstraction. In our research, we utilized the flexibility of the integrated hybrid modeling and simulation and developed a proof-of-concept system that can complement the standard LCA method.

4. Lifecycle Assessment of Drinking Water and Beverages

Tap water is still one of the major drinking sources in daily life. However, the bottled water market in developed countries such as the United States and Japan has grown rapidly. A report from the Beverage Marketing Corporation (THE 2006 STATS) reveals that there was a 50% growth in America's bottled water consumption between 2002 and 2007. For health, quality and convenience, bottled water has become a popular choice in the drinking water and beverage market. The rise in popularity of bottled water has created a burden on its sustainability (Gleick, 2010), however. For example, bottled water produces waste by product in production, transportation, distribution, refrigeration and recycling. Also, many other drinking alternatives (for example, vitamin water) have become available in the market recently. So the basic questions are:

(i) Which one of the available options (e.g. tap water, bottled water, and other drinking alternatives) is the most sustainable?
(ii) Will consumers' choice make a difference?

From the related important aspect of packaging, Lee and Xu (2005) addressed sustainable packaging issues in general. Büsser and Jungbluth (2009) studied the role of flexible packaging in the lifecycle of coffee. Vellini and Savioli (2009) focused particularly on glass containers from production to recycling. All of these reveal that the packaging issue is a significant one in evaluating