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A hierarchical approach for evaluating energy trade-offs in supply chains

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A R T I C L E I N F O

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A B S T R A C T

Supply chain design and operational decisions may impact the energy needed to keep the products flowing through to the customers. It is a challenge to determine the energy consumption and even more challenging to understand the impact of design and operational decisions on the energy consumption along the supply chain. This paper presents a hierarchical simulation based approach for estimating the energy consumption to keep the products flowing through a supply chain. System dynamics simulation is used at a high abstraction level to understand the major factors that may affect the energy consumption. Discrete event simulation is then used to delve down in detail for evaluating the critical stages in the supply chain. A case study for a closed loop supply chain of forklift brakes is used as an example of application of the approach.

1. Introduction

A number of progressive companies are making conscious efforts for reducing environmental impact of their operations. These companies obtain a competitive advantage towards customers in addition to making a contribution to a more sustainable future. An example from food and service industry is provided by the award winning restaurant in Sweden called MAX. They reported that their efforts for evaluating and improving their product value chain led to a reduction of their CO_2-emmisions by 44% between 2007 and 2008 (MAX, 2008). Market research shows that 13 times more customers relate the MAX brand to environmental friendly products compared to their main competitor. MAX's sustainability manager states that the latter figure is not the result of an increase in traditional marketing, but derives solely from communication of their products' environmental footprint.

Matthews et al. (2008) highlight the importance of determining the carbon footprint across the supply chain and across the life-cycle. They recommend that the firms consider the life-cycle footprints from the outset, and "allow the largest sources of carbon emissions along the supply chain to be targeted first and most cost-effectively." Hertwich and Peters (2009) stress that indirect impacts in the supply chain are more important than the direct impacts in the household in their analysis of carbon footprint of nations. Weber and Matthews (2008) show that about 30% of the carbon footprint of U.S. household consumption is outside the country, that is, the impact is in the international supply chains. These articles stress the importance of consideration of carbon footprint of the entire supply chain, in particular, the importance of including the international parts of supply chain.

A large contributor to the carbon footprint of a supply chain is the energy consumed in manufacturing and logistics. Ngai et al. (2012) identify control and reduction of unnecessary energy and utility consumption as one of the major ways to reduce greenhouse gases. This paper focuses on the energy consumption across a supply chain and presents an approach for evaluating options for reduction efforts and trade-offs related to energy use.

Calculation of energy use and emissions for a product across the supply chain can be challenging since almost all nodes and links across the supply chain serve multiple products. The energy use and emissions from manufacturing and logistics facilities may need to be allocated to determine the amounts for a specific product. Use of engineering models has been recommended to separately estimate the energy use for each product to avoid allocation (WRI/WBCSD, 2011). This paper presents an approach that uses engineering models, specifically simulation models of different paradigms, to calculate energy use for selected products across their supply chain.

The presented approach helps identify the largest consumers of energy along the supply chain at the outset using system dynamics modeling and then explore cost effective strategies for the largest consumers using discrete event simulation. Furthermore following the recommendations in the above mentioned literature, our proposed approach includes consideration of the entire supply chain including international segments if present as part of the configuration alternative.

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The next section provides background information on different simulation paradigms and on hierarchical levels in supply chain. Section 3 briefly reviews related work. The proposed approach is presented in Section 4 followed by a case study in Section 5 for demonstrating the application of the approach. Sections 6 and 7 describe the implementation of key steps of the approach for the case study. Section 8 concludes the paper and includes potential future work.

2. Background

The proposed approach in this paper utilizes models of different simulation paradigms as appropriate for the level of detail in the supply chain hierarchy. The following sub-sections briefly define the simulation paradigms and supply chain hierarchical levels.

2.1. Simulation paradigms

Simulation techniques can be classified using different perspectives. With the perspective of modeling of time, they can be classified as continuous and discrete. From the perspective of representation of the underlying phenomenon, they may be classified in four paradigms that admittedly have some overlaps (McLean et al., 2012, p. 20–29): system dynamics (SD), discrete event simulation (DES), agent-based simulation, and physical-sciences-based simulation. We briefly describe the four paradigms below with a bit more detail for SD and DES as they are used for the case study in later in this paper.

2.1.1. System dynamics (SD)

SD modeling and simulation, by design, is aimed at modeling systems at high level of abstraction for supporting high level decision making. It has been applied to study a wide range of systems including industrial, social, environmental, financial, and socio-political systems, and their combinations. While generally used to model large systems at high abstraction levels, the strength of modeling feedback loops also allows the technique's applications for control policies of small electro-mechanical systems.

Originally developed by Forrester (1958) to analyze manufacturing supply chains systems (then called industrial production systems), SD simulation is suited for studying behavior of large systems. It focuses on modeling causal relationships between key aspects of the system operating under governing policies, especially feedback loops that form beneficial or vicious cycles and determine the overall system behavior. It uses the continuous paradigm for representing time.

The technique utilizes causal loops for conceptual modeling that are enhanced into stock-and-flow diagrams for setting up the framework. The computer implementation then converts the causal and stock-and-flow relationships into differential equations that are used to calculate the change in system parameters over the simulated time horizon. The changes in key parameters of interest define the system performance over time. Sterman (2000) provides a detailed description of system dynamics simulation and guidance for its use for many applications.

2.1.2. Discrete event simulation (DES)

DES is suitable for modeling system operations to evaluate system configurations and resource allocations in order to achieve desired system performance or to investigate causes of less than desired performance. It is generally used to model systems at medium to low levels of abstraction. DES models are generally used for planning purposes, however, there are increasing instances of their use in near real-time decision support systems, particularly in manufacturing.

In DES, the operation of a system is represented as a chronological series of events. As the name indicates, it uses discrete event paradigm for representing time – the simulated clock time jumps from one event of interest to the next event of interest without going through successive unit increments.

Discrete-event simulation models may be developed using one of two major views: process view or event view. Process view essentially uses flow charts of process of interests and models them using corresponding simulation software features. The process view is also referred to as entity view or transaction view as it models the process that entities (or transactions) of interest go through in the system. The event view model uses the actions that happen following an event. Consider for example a part being processed through a machine shop. The process view may model the flow of the part going from one machine to the next and the processing that happens at successive machine until its completion. The event view may model events such as arrival of the part at a machine that triggers the start of its processing and schedules the processing completion event. The processing completion event in turn initiates the part's transfer to the next machine. Schriber et al. (2012) explain the inner workings of DES and the implementations in a few commercial DES software packages.

2.1.3. Agent-based simulation (ABS)

ABS is suitable for modeling systems where the behavior is determined by the interactions of a large number of independent entities. Example applications include modeling the behavior of a crowd of people affected by an incident, and modeling the spread of a pandemic flu based on the behavior of individuals in the population in the affected area. ABS utilizes a decentralized representation of systems and allows the system behavior to be determined based on defined behaviors of a number of modeled agents. ABS may follow the discrete event paradigm or the continuous paradigm for time representation or they may utilize the hybrid form, i.e., using a combination of discrete and continuous representations. A good overview of agent based simulation is provided by Macal and North (2011).

ABS has been used for modeling supply chains with each of the nodes represented as a separate agent. Such representations with only a few agents may be hard to differentiate from a DES representation of the system being modeled.

2.1.4. Physical-science-based

Physical-science-based simulations utilize scientific knowledge, e.g., the laws of physics or mathematical models of observed phenomena to study, understand, or predict the behavior of physical systems. Physical systems can range from modeling a single entity, e.g., in the study of motion of a bullet, to modeling a complex set, e.g., the behavior of multiple organisms, crowds, or global climate.

Physical-science-based models may use mathematical equations and schematic diagrams as conceptual models. These models typically utilize differential equations based on laws of physics that model such factors as mechanical dynamics and statics, material behavior under stress and impact, and fluid dynamics. They are generally used for modeling at detailed level, that is, at low abstraction level, such as, equipment and equipment component behavior, and behavior of built structures when subjected to explosions in close proximity. A number of examples of physical-science-based simulation are provided in Engquist et al. (2009).

2.2. Supply chain hierarchical levels

We propose to analyze the supply chain impact on environment in a top–down manner along the supply chain hierarchy. While a number of metrics may be used for measuring impact on