Integration of Sustainability Issues during Early Design Stages in a Global Supply Chain Context

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Abstract

A method is introduced to incorporate sustainability considerations in the early design stages, while simultaneously accounting for supply chain factors, such as cost and lead time. Overall, this work is our first step in understanding the trade-offs between sustainability metrics and more traditional supply chain performance metrics (i.e., cost and lead time). Based on our understanding of these trade-offs, we intend to help build computational artificial intelligence tools that can exploit these trade-offs for improved customization in products.

Introduction

Sustainability and carbon footprint (CF) concepts are becoming increasingly important for companies to incorporate into their business practices (Matthews et al., 2008). Consumers are more aware of their impact on the environment and are pressuring companies to produce sustainable products (Labuschagne and Brent, 2005). It is anticipated that the government will legislate cap and trade policies for greenhouse gas (GHG) emissions (Matthews et al., 2008). In fact, trial programs have already been enacted globally for assessing and reporting the life cycle GHG emissions of products and services (Finkbeiner, 2009). Denmark has CO_2 taxes in place, which motivates industry to move away from fossil fuels (Herman and Hauschild, 2009). The International Organization for Standardization (ISO) is developing a standard on the carbon footprint of products (Finkbeiner, 2009).

Some companies have initiated efforts to track and reduce GHG emissions, so they are less likely to incur fines from anticipated future legislation and more likely to keep and expand their customer base through a *green* image. Should a carbon price be put in place, understanding emissions from current business practices could aid in appropriate product price adjustments (Matthews et al., 2008). Given that the global carbon footprint of product manufacturing was estimated as 13% of the total carbon footprint in 2001 and, though consumers in wealthier nations purchase more manufactured goods, such purchases in developing nations are increasing, efforts toward producing more sustainable products are critical (Hertwich and Peters, 2008).

Several questions are raised. *How can the goal of sustainability be best achieved across a global supply chain when considered from the product design stage? In what way should sustainability be measured for uniformity across the supply chain?*

Previous top-down and bottom-up approaches to sustainability have not succeeded in reducing CF (Labuschagne and Brent, 2005). Therefore, it is important that design concurrently consider the manufacturing of the product and its supply chain. If the product design aligns with the consumer's taste and is feasible to produce, the likelihood that the product will require redesign is reduced. A poor product design increases costs and slows the product's release. Thus, the design stage should consider product sustainability aspects (economic, environmental, and social) for profitability, capturing the voice of the customer, and improving environmental performance. When such criteria are considered early in design, there is more flexibility and reduced costs of product design modification and supplier selection. In this way, businesses can mitigate emissions across the supply chain, rather than only in their own plant (Matthews et al., 2008).

The objective of the research described herein is to reveal the tradeoffs among cost, lead-time and carbon footprint considerations within the supply chain context as determined by product design. With this purpose, we examine a product that is not complicated in its structure at this initial stage, i.e., a bicycle. We appreciate the increasing complexity of many other products, and thus, consider this work as a preliminary step in our quest to develop and use artificial intelligence tools to appropriately exploit potential cost, lead time and carbon footprint trade-offs to customize products for specific regulations and consumer needs across the globe.

Literature Review

There are a number of sustainability challenges that individuals and companies face today. Increased development typically emits more CO_2, which has been linked to global climate change (IPCC, 2007). Limited natural resources are being rapidly consumed, and as a result of development, biodiversity has been declining. Increases in population and unsustainable agriculture have put a strain on sanitary living spaces and clean water for people (Howarth and Hadfield, 2006).

Sustainability can be a vague concept in terms of consumer products, as neither consumers nor companies have an official, accepted definition. Likewise, there is no specific or universally standardized way of measuring the level of sustainability of a company. It is generally agreed that sustainability includes social, environmental and economic goals or dimensions. The U.S. Environmental Protection Agency (EPA) defines sustainability as calling "for policies and strategies that meet society's present needs without compromising the ability of future generations to meet their own needs" (EPA, 2010), based on the definition of sustainable development from the Brundtland Commission (WECD, 1987).

A definition for sustainability from the International Institute for Sustainable Development (IISD) aimed directly at businesses states: *For the business enterprise, sustainable development means adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today, while protecting, sustaining and enhancing the human and natural resources that will be needed in the future* (Labuschagne, 2005).

A comprehensive and standardized way to measure and account for the environmental impacts of a product is needed. Without reliable and accepted measures, consumers will not trust the information that companies advertise. Some companies that advertise products as being "green" do not even have an environmental policy or report (Howarth and Hadfield, 2006). This absence of reliable product assessment is due to the lack of information and data communicated within departments in companies, the supply chains, and the distribution channels (Waage, 2006). Higher levels of transparency in companies can help to build a better reputation and stakeholder trust if the company performs responsibly (Carter and Rogers, 2008). With today's increasing technology and capability for data storage, sorting, and retrieval, transparency is becoming easier to achieve – that is, for example, if they so choose, companies can collect data and report their key sustainability metrics through web-based technologies.

Consumers, environmental activists, and social responsibility policies, among other drivers, are all pressuring companies to become more sustainable. Finding best practices and building applicable models can help companies achieve this goal. The aim is to determine what activities will help companies achieve the triple bottom line, which positively affects environmental, social and economic performance for long-term economic benefit (Carter and Rogers, 2008). This requires creativity and strategic company vision. Carter and Rogers (2008) proposed that companies focused on improving all three aspects will reach higher economic performance than companies trying to achieve only one or two of the three. Easy initial steps can be taken, such as replacing outdated, inefficient equipment with new energy efficient equipment, which will save money in the long-term through energy costs.

Sustainability in the Design Stage

It is important that sustainability considerations are included in the design stage. It is posited that as much as 70% of product development, manufacturing, and other life cycle costs are established by decisions made during design (Waage, 2006). The issues of sustainability are often neglected in design or expected to be someone else's responsibility (Howarth and Hadfield, 2006). This mindset is especially prevalent when considering the product end-of-life options, e.g., disposal or recyclability. Changes can be made during design that affect the materials chosen, energy used for processing, and wastes generated (Waage, 2006; Howarth and Hadfield, 2006). Much literature has investigated design for sustainability, but supplier selection is rarely taken into account concurrent to sustainable design activities. Various suppliers will have different levels of sustainability for manufacturing the same product, depending on their location and manufacturing practices.

Supplier selection can be facilitated by knowledge of which product architecture is best for the supply chain. Product architectures can be categorized as having modular or integrated components. Modular components are designed to be interchangeable and standardized and, thus, can have a widely dispersed supply chain. Integrated components are customized for the product and generally have a smaller supply chain, as they are unlikely to be interchangeable (Chiu, 2010).

Parts that are recovered from consumers can be used in new products if designed correctly. This cuts down on raw material usage and energy consumption of manufacturing (Kimura et al., 2007). Kwak and Kim (2010) evaluate the end-of-life recovery of products while considering both the product and recovery network design. They maximize the recovery potential in terms of cost, time, and materials recovered. Their study emphasizes the importance of incorporating the end-of-life possibilities into the design stages, but does not include the supply chain in the optimization.

Sustainable Supply Chains

Sustainable Supply Chain Management (SSCM) is defined by Carter and Rogers (2008) as *the strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its supply chains*.

Benjaafar et al. (2010) stated that there is a need for model-based research that includes minimizing cost and includes consideration of carbon footprint. Their work aimed to draw attention to the connection between carbon footprint and supply chain operations. They proposed a few potential models that could be applied to a product and supply chain assuming different governmental restrictions regarding carbon emissions. These restrictions included situations with strict carbon caps, a carbon tax, carbon cap and trade, and carbon offsets. Overall, their work pointed to the modification and extension of the existing operations management models to include sustainability metrics.

Life Cycle Analysis

Life cycle analysis/assessment (LCA) or input-output analysis is a common technique used for estimating the environmental impacts of a product. There is an international initiative to move toward a standard LCA and environmental management standards (EMS, ISO) by the International Standards Organization (ISO, 2004). It would be useful to consumer decision-making to have a comprehensive assessment of the product carbon footprint, thus LCA with the inclusion of the supply chain impacts would be most fitting (Matthews et al., 2008). Depending upon the predetermined boundaries, an LCA study can encompass some or all stages of the product life cycle including raw materials extraction, manufacturing, product use, recycling and final disposal. In general, LCA impact assessment methods account for environmental impacts including global warming, acidification, energy use, non-renewable resource consumption, eutrophication, conventional pollutant emissions, and toxic releases to the environment (Joshi, 2000).

Matthews et al. (2008) and Herrmann and Hauschild (2009) use input-output analysis stemming from Leontief's production equation (Leontief, 1986) using matrices of process interactions. The model described by Matthews et al. (2008) is flexible to incorporate different numbers of supply chain tiers desired as well as the type of environmental burden, such as GHG. The model from Herrmann and Hauschild (2009) incorporates relative purchasing power parity. This model can account for the emissions embedded in an imported product, or show the emissions avoided by importing from a different country. This approach would be relevant for studying a supply chain for parts manufactured in China, where there are fewer restrictions and then shipped to the United States for final assembly.

Broader Methods for Sustainable Design

Much research has reported general frameworks for the design and manufacture of sustainable products; Ramani et al. (2010) provide a review of these. In general, these works point out many different considerations that could be incorporated into the vision of achieving more sustainable production and supply chains. Howarth and Hadfield (2006) acknowledge the views and concerns of all the stakeholders included in design. These include the client, customer, energy and water supplier, planning officer, community, waste contractors, trade associations, environmental agency, material supplier, professional institutions, employers, local council, manufacturers and users. Howarth and Hadfield (2006) declare a few items that should be included in a sustainable product development assessment:

- Life cycle impacts due to raw materials, manufacture, distribution, use and final disposal,
- The Annual Report, Corporate Social Responsibility, Environmental, Ethical and Sustainable Reports for the company,
- The site selected for manufacturing and how it impacts the local community and wildlife surrounding it.

The assessment of the product, company, and site should have a specific list of issues along with the importance and the risk or benefit of the issue.

There are two elements necessary to ensure that sustainability is viewed from a broad perspective. The company first should have a sustainability vision and then develop or adopt appropriate strategies and tools to achieve this vision. These broad viewpoints comprise many aspects at the same time, some of which are design, material selection, supply chain and manufacturing technique. However, there are no specific models integrating the relationships of these aspects since the scope of topics is generally large. Feng et al. (2010) stated that companies can achieve sustainable manufacturing by working to eliminate waste, improve energy efficiency, design products for reuse or recycle, conserve natural habitats and move toward zero consumption of non-renewable resources.

Measurement and Assessment of Environmental Impact

The environmental impact of a product can be measured as the sum of many different aspects. The carbon footprint consists of all the GHG emissions from producing a product. It is important that measures for evaluating sustainability are relevant, comprehensive, meaningful, reliable, cost effective, timely and quantitatively measurable (Feng et al., 2010).

Sustainability performance indices exist for the company, local, national and international levels (Shelton, 2010). Sustainability performance is generally measured by a set of metrics or indicators, e.g., rate of injury, dollars of net revenue, or kilograms of emissions, which encompass the three aspects of sustainability. Among the most widely used software tools for assessing the environmental impacts of a product are SimaPro LCA software and the ecoinvent life cycle inventory (LCI) database. SimaPro has the ability to interface with ecoinvent and other databases as well as allowing the user to input energy and materials required by processes, e.g., material production, manufacturing, and transportation, across the life cycle to calculate different environmental impacts of producing the product. A commonly used impact measure is carbon footprint in kilograms of carbon dioxide equivalent (kg CO2 eq.). The energy costs and recyclability fractions for common materials also can be obtained from databases such as those in the Cambridge Engineering Selector (CES) materials selection software (Giudice et al., 2004).

Method

The research described herein is an extension of the work by Chiu (2010) where a graph-theory based optimization approach was proposed for simultaneous optimization of product and supply chain design. Chiu used design for assembly (DfA) criteria to initially rank 64 different bicycle concepts from easiest to hardest to assemble. The best scoring concept was selected, and a model created with an objective function to minimize the total cost of processing, transportation, and inventory for the finished concept. Also included are the product architecture and modularity options for many different suppliers. The model allows selection of the supplier used for each bicycle component. While this approach is useful for cost and lead-time considerations, it neglects potential environmental aspects.

Research described herein extends prior work to include considerations of cradle to gate processes to improve sustainability. The product life cycle is considered from manufacturing parts through full assembly of the finished product before it is shipped to a warehouse, store, or consumer.

The following criteria are added to Chiu's model: (1) the material from which the product is made, (2) the way in which the product is processed, and (3) the transportation type and distance required to ship the product to its destination. This method focuses specifically on the carbon footprint of the supply chain and manufacturing. Each of these criteria is measured in terms of the amount of CO_2 equivalent gases emitted (kg CO_2 eq.), which is accounted for during supply chain optimization. The model used in this work is an altered and expanded version of that described by Chiu (2010). It is a non-linear programming model that is solved using Extended LINGO Release 9.0.

The transportation carbon footprint is found using the distance that each component, module, or assembly must be shipped. The carbon footprint of the transportation is separated into land and sea transportation. The CO_2 for each mile traveled by land or sea is calculated by SimaPro using a truck specified by *Transport, lorry >28t, fleet average/CH S* and a sea barge specified by *Transport, ocean freighter, average fuel mix/US*. These lorry and barge types were chosen because they have a carbon footprint that is average among all the lorry and barge options. The distance traveled between supplier locations is measured by the Euclidean distance on land or sea. The land distance is measured using the distance of shipping supplier to the closest port, added to the distance of the receiving supplier to its closest port. The sea distance is measured by the water distance between ports.

The impact of material choice is based on the method and energy required to procure the component. The impact of processing is based on the energy it takes to fully process the material along with any chemicals that may be used in the process. SimaPro is used to calculate these measures, primarily using the *ecoinvent* database, which contains inventory values for more than 2,700 processes. Specifically in this study, SimaPro yields the values of CO_2 equivalent for material choices and processing. There are various methods that can be used to calculate the impact of a component. The impact assessment method used for the results in this paper is *IPCC 2007 GWP 20a V1.02*. This method contains the climate change factors of the Intergovernmental Panel on Climate Change (IPCC) with a timeframe of 20 years.

Results

The cost and lead time for each component or module for each supplier and process is provided by Chiu's model. The modified mathematical model (Appendix) was run for each of three optimization objectives, i.e., cost, lead time, and carbon footprint. There were thirteen different suppliers located in Pennsylvania, Illinois, California, Holland, Taiwan and Japan. Table 1 summarizes the results, and shows optimization for different objective functions produce scenarios that are less than optimal for the other criteria, i.e., when optimizing for cost, lead time and CF are sub-optimal. This demonstrates that unavoidable trade-off situations may result when selecting product designs that must meet multiple objectives.

Table 1. Single Objective Optimization Results (shading indicates optimal value)

Optimizing (Minimizing)	Cost Result (US Dollars)	Lead Time Result (Days)	Carbon Footprint Result (kg CO_2 eq.)
Cost	83.74	54.20	60.48
Lead Time	109.30	38.80	65.85
Carbon Footprint	99.94	172.80	44.18

Table 2. Resulting Supply Chain for Cost Minimization

Part	Type	Supplier	Location	Assembly of Parts (Module)	Sub-assembly Supplier
(A) Saddle	1	ATOMLAB	CA,USA	ABCDEF	X-Bike
(B) Frame	1	2-Hip	CA, USA	AB	2-Hip
(C) Fork	2	X-Bike	PA, USA	CD	SRAM
(D) Brake	1	SRAM	IL, USA	EF	BBB
(E) Wheel	2	BBB	Leiden, Holland		
(F) Transmission	1	BBB	Leiden, Holland		

Table 2 shows the representative supply chain for cost minimization. Supply chain results for lead-time and carbon footprint minimization can be found in the Appendix. The result from optimizing a single objective should be used if the decision-maker holds one objective of significantly greater importance than the other objectives. The results for the single optimization are verified by calculating the minimum values of cost, lead-time and CF, manually.

Discussion

These single objective optimizations show the absolute minimum value for each singular objective of cost, lead-time or carbon footprint without consideration of the other objectives. The result from optimizing a single objective should be used if the decision-maker holds one objective infinitely higher than the other objectives. The minimum cost is $83.74, lead-time is 38.8 days and carbon footprint is 44.17 kg CO_2 equivalent.

Based on the optimization results, patterns can be evaluated and conclusions drawn from the observed trends. The supplier information and chosen parts for the minimum cost, minimum lead time and minimum carbon footprint are shown in Tables 2, 3 and 4, respectively. Overall, the minimization results showed an interesting pattern in the locations of all the components. All components and modules came from suppliers in California, Illinois, Pennsylvania and Holland, except for one component and module in the lead-time optimization model which came from Japan. Although there were five suppliers from Taiwan, none were chosen in the optimized solutions.

The minimized cost result uses five different suppliers, X-Bike, 2-Hip, SRAM, BBB and ATOM LAB, from four different locations in Pennsylvania, California, Illinois, and Holland. Each two component module is made up of components originating close to each other. For example, Module AB is assembled in California, where both of its individual components are made. The minimized lead time solution contains six suppliers from five locations: X-Bike (PA), ATOM LAB (CA), Shimano (Japan), Axxis (CA), SRAM (IL) and BBB (Holland). The minimized carbon footprint result contains components from the four different suppliers X-Bike, BBB, SRAM and ATOM LAB and the four locations of Pennsylvania, Holland, Illinois and California.

Perhaps what is more significant to notice is that in addition to the suppliers, and hence the values of performance measures, the selected product architectures are also different across all three solutions. For example, while for all other conditions (cost minimization, etc.) three module architectures are selected, for the CF minimization condition a two-module architecture is selected. As provided in Table 4, module ABC will be sourced from X-Bike, and module DEF will be purchased from BBB. These differences indeed point to the importance of carefully customizing products to better meet the consumer needs in difference parts of the world.

Because the presented case study is built on a real life case study developed with Cannondale Inc., a bicycle manufacturer, the findings should help practitioners and researchers devise methods for simultaneously considering and reducing supply chain cost, lead time, and environmental performance early in the design process. More importantly, however, we would like to direct attention to fact that while we have included a product with a relatively simple architecture and a small component count, we appreciate the complexity in today's products. Accordingly, we consider our work as a first step in understanding the trade-offs between sustainability metrics and more traditional supply chain performance metrics (cost and lead time). Based on our understanding of these trade-offs, we intend to help build computational artificial intelligence tools that can exploit these trade-offs for improved customization in products.

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Appendix

Additions to the Original Mathematical Model

Min {Transportation impact (Tran) + Material choice and Processing method impact (MP)}

Tran = Distance by land * CF per distance * Component + Distance by sea * CF per distance * Component

MP = Material and processing CF * Component

Decision Variables

MPCF – CF for component manufacturing and processing
TCF – CF for component, module, and assembly transport

Parameters

MPX_{pi} – CF for process p and supplier i
TLD_{pi} – Distance on land for process p and supplier i
TSD_{pi} – Distance by sea for process p and supplier i
TLDI – CF per ton-mile traveled on land
TSDI – CF per ton-mile traveled by sea
CW_{pi} – The fraction of a ton for each component or module from process p and supplier i

Objective Function

$$\mathrm{Tran} = \sum_i \sum_p A + B$$

$$A = TLD_{pi} * X_{pi} * Y_p * TLDI * CW_{pi}$$
$$B = TSD_{pi} * X_{ip} * Y_p * TSDI * CW_{pi}$$

$$\mathrm{MP} = \sum_i \sum_p MPX_{pi} * X_{pi}$$

The variables X_{pi} and Y_p are binary, representing if component X was selected with process p and supplier i, and whether process p is performed.

Lead-Time and Carbon Footprint Optimization Results

Table 3. Resulting Supply Chain for Lead-Time Minimization

Lead-Time	Supplier	Type	Location
ABCDEF	X-Bike		PA, USA
ACB	X-Bike		PA, USA
DEF	ATOM LAB		CA, USA
EF	Shimano		Osaka, Japan
(A) Saddle	ATOM LAB	1	CA, USA
(B) Frame	Axxis	1	CA, USA
(C) Fork	X-Bike	2	PA, USA
(D) Brake	SRAM	1	IL, USA
(E) Wheel	Shimano	2	Osaka, Japan
(F) Transmission	BBB	1	Leiden, Holland

Table 4. Resulting Supply Chain for Carbon Footprint Minimization

Part or Module	Supplier	Type	Location
ABCDEF	X-Bike		PA, USA
ABC	X-Bike		PA, USA
DEF	BBB		Leiden, Holland
(A) Saddle	BBB	2	Leiden, Holland
(B) Frame	X-Bike	2	PA, USA
(C) Fork	SRAM	1	IL, USA
(D) Brake	BBB	2	Leiden, Holland
(E) Wheel	ATOM LAB	1	CA, USA
(F) Transmission	BBB	1	Leiden, Holland

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