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Environmental constraints in joint product and supply chain design optimization

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ABSTRACT

Environmental concerns are increasingly taken into account by companies, owing to the significant legal and consumer issues being raised today.

This paper considers the environmental constraints inherent in the design of a product family and its supply chain. Mathematical models are proposed for optimizing costs in the face of carbon emissions restrictions and for optimizing carbon emissions, given the need to limit costs in the current economic climate.

A method is provided, along with accompanying graphical illustrations, to enable the analysis of each of the three parts of the cost and carbon emissions issue, that is, production, transportation, and component, on three different academic case studies.

Analysis of the models applied on our case studies illustrates that, while optimizing carbon emissions is extremely costly, reducing them can be achieved efficiently.

1. Introduction

Government regulations and consumer concerns are focusing more and more on the environmental impact of the production and use of manufactured goods. Even though producers are not yet prepared to minimize this impact, some limitations can be imposed that will improve their brand image or increase sales, or both. Part of the environmental impact involves carbon emissions. Brezet and Hemel (1997) analyze the sources of carbon emissions generated by product consumption, and highlight the importance of looking at the product life cycle: each step in the life cycle, from the design phase to the end-of-life phase, has an impact on carbon emissions. A quantitative study has been presented by Tukker and Jansen (2006), in which they describe the environmental impact of product consumption, depending on the line of business and size of the geographical region involved.

In terms of cost reduction, there is clearly a need for joint product and supply chain optimization. This need has been highlighted by Baud-Lavigne, Agard, and Penz (2012), who show that decisions taken in these two manufacturing areas impact one another. However, it is only in the last few years that the issues of product optimization and supply chain optimization have been tackled simultaneously. In their work, Baud-Lavigne et al. (2012) compare sequential design with simultaneous design in a case study, and provide a detailed analysis of the production network concerned. The idea of including an explicit bill of materials (BOM) in a supply chain design model is a recent consideration in this field, and one that has been studied very little to date. A single-period, multi-product, multi-level model was proposed by Paquet, Martel, and Desaulniers (2004), and a multi-period model was presented by Thanh, Bostel, and Peton (2008); however, the BOM in these models is fixed. Among the small number of studies that have investigated the possibility of simultaneously optimizing the product and the supply chain are the following two approaches. One is aimed at defining the product family that best meets market demands, and uses a generic BOM to model the product (Lamothe, Hadj-Hamou, & Aldanondo, 2006; Zhang, Huang, & Rungtusanatham, 2008). In these formulations, BOM are determined so as to respect assembly constraints. The other considers the final product as fixed, but with BOM that are flexible. In this assemble-to-order context, where the final assembly time is constrained, El Hadj Khalaf, Agard, and Penz (2010) consider a functional, modular design in which all conceivable assembly configurations are possible. ElMaraghy and Mahmoudi (2009) define several alternative BOM, one of which is selected for the optimal solution. This approach, which facilitates both formulation and solution, calls for a complete listing of all the configuration options. To our knowledge, the only fully integrated

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models have been proposed by Chen (2010) and Baud-Lavigne, Agard, and Penz (2011a).

A recent subject of study has been the integration of environmental issues into supply chain design. Beamon (1999) describes the issues and key components of environmental integration, and Beamon (2005) focuses on ethical considerations. Some approaches use an environmental objective function with multicriteria optimization (Wang, Lai, & Shi, 2011), or an objective function combined with a global cost function based on the direct cost of the carbon footprint, also taking into account taxes (Chaabane, Ramudhin, & Paquet, 2012).

The aim of this paper is to integrate carbon footprint constraints into the design of a joint product and supply chain model. Section 2 describes the hypothesis underlying the model and the mathematical formulation of the model. Experiments on the impact of environmental constraints on cost and of cost constraints on carbon footprint optimization are described in Section 3. In Section 4, we conclude the paper and offer some perspectives on the topic.

2. Integrating carbon footprints into joint product and supply chain model design

The mathematical model proposed here extends the model of Baud-Lavigne, Agard, and Penz (2011b). Previous modeling focused on cost minimization exclusively, and considered a typical supply chain with suppliers, a production center network, distribution centers and customers, and a product family. In this type of model, a different set of options can be implemented in every production center. Each option corresponds to a technology, and every product assembly operation requires the realization of a number of technologies. A product family is composed of several products, defined by a bill of materials (BOM) consisting of several levels, and every product in a product family contains components and assemblies that are shared. Moreover, some assemblies and components can be substituted for others. The aim of optimization is to define the best product family along with its supply chain, with a view to optimizing production costs.

Carbon footprints can be integrated at any of three levels: production, transportation, and component. All three levels are considered in the optimization process.

Component choice can impact the carbon footprint in several ways. First, different materials can require different amounts of energy for extraction or preparation for the same functionality. Second, the ease and efficiency with which the materials can be recycled may differ substantially. Finally, there can be differences in the amount of energy a component requires during use, when energy consumption is not a key functionality;

Production creates carbon footprints based on production center characteristics (Is water recycled? Is the insulation efficient?) and workstation implementation;

Transportation results in carbon emissions, which vary with the distance that the products and components travel.

We model the problem with both flow and fixed cost constraints, and substitution options are included at each level of the BOM (component, subassembly, and product). The supply chain and the product family are optimized simultaneously, in accordance with either a cost or a carbon emissions minimization target. First, we define the following sets and indices:

- $\mathcal{P}$: products; $p, q \in \mathcal{P}$
  - $\mathcal{R} \subset \mathcal{P}$: raw materials or supplied components
  - $\mathcal{M} \subset \mathcal{P}$: manufactured products/sub-assemblies
  - $\mathcal{F} \subset \mathcal{P}$: finished products
  - $\mathcal{P}^p \subset \mathcal{P}$: products, sub-assemblies and components that can substitute for p
- $\mathcal{N}$: network nodes; $i, j \in \mathcal{N}$
  - $\mathcal{S} \subset \mathcal{N}$: suppliers
  - $\mathcal{U} \subset \mathcal{N}$: production plants
  - $\mathcal{D} \subset \mathcal{N}$: distribution centers
  - $\mathcal{C} \subset \mathcal{N}$: customers
- $\mathcal{T}$: technologies; $t \in \mathcal{T}$
- $\mathcal{T}^p \subset \mathcal{T}$: technologies needed by product $p, p \in \mathcal{M} \cup \mathcal{F}$
- $\mathcal{O}$: capacity options; $o \in \mathcal{O}$
- $\mathcal{O}^t \subset \mathcal{O}$: capacity options for technology t

General parameters:

- g^{pq}: quantity of q in p. q can be a component or a sub-assembly. g represents the bill-of-materials, $p \in \mathcal{M} \cup \mathcal{F}, q \in \mathcal{R} \cup \mathcal{M}$,
- d_i^p: demand for product p by customer $i, p \in \mathcal{F}, i \in \mathcal{C}$
- l^{pt}: processing time for product p on technology $t, p \in \mathcal{M} \cup \mathcal{F}, t \in \mathcal{T}$
- z_{max}: maximal global cost allowed

Environmental parameters:

- c_i: carbon emissions generated by unit i
- c^o: carbon emissions generated by option o implantation
- c^p: carbon emissions generated by component or part p
- c_{ij}^p: carbon emissions generated by transport part p from site i to site j
- c_{max}: maximal carbon emissions allowed

The decision variables are as follows: A_i^p is the quantity of p manufactured in production center i. B_i^p is a binary variable that is equal to 1 if production center i is used for product p, zero otherwise. S_i^{pq} is the quantity of p that substitutes for q in production center i. F_{ij}^p defines the flow of p between i to j. T_{ij}^p and L_{ij} are binary variables. The first one is equal to 1 when the flow of p from i to j is strictly positive, and the second one is equal to 1 when at least one p uses the arc from i to j, zero otherwise. Each variable is associated with its proper cost. For the binary variables, the cost is the fixed cost paid only if the variable is set to 1. For continuous variables, the cost is a unit cost. The decision variables and the costs are presented in Table 1.

The mathematical model is as follows. Objective function (1) minimizes the fixed and variable procurement, production, and transportation costs.

Table 1
Decision variables (DV) and their associated costs and carbon emissions.

	DV	Domain	Cost	Carbon emission
Quantity of p produced on i	A_i^p	$\mathbb{R}$	α_i^p	c^p
Production of p on i	B_i^p	$\{0,1\}$	β_i^p	
Quantity of p that substitute for q on i	S_i^{pq}	$\mathbb{R}$	σ_i^{pq}	
Flow of p between i and j	F_{ij}^p	$\mathbb{R}$	ϕ_{ij}^p	c_{ij}^p
Use of flow of p between i and j	T_{ij}^p	$\{0,1\}$	τ_{ij}^p	
Use of axis between i and j	L_{ij}	$\{0,1\}$	λ_{ij}	
Number of options o on i	O_i^l	$\mathbb{N}$	ω_i^l	c^o
Use of node i	Z_i	$\{0,1\}$	ζ_i	c_i
Global costs	Z	$\mathbb{R}$		
Global carbon emission	C	$\mathbb{R}$		