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Environmental constraints in joint product and supply chain design optimization

Bertrand Baud-Lavigne [a,b,*], Bruno Agard [b], Bernard Penz [a]

[a] G-SCOP, Université de Grenoble/Grenoble INP/UJF Grenoble 1/CNRS, 46 Avenue Félix Viallet, 38031 Grenoble Cedex 1, France
[b] CIRRELT, Département de Mathématiques et Génie Industriel, École Polytechnique de Montréal, C.P. 6079, succ. Centre-Ville, Montréal, Québec H3C 3A7, Canada

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A B S T R A C T

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

* Corresponding author at: CIRRELT, Département de Mathématiques et Génie Industriel, École Polytechnique de Montréal, C.P. 6079, succ. Centre-Ville, Montréal, Québec, Canada.

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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	$\mathbb{R}$		

$$Min \quad Z$$

$$\begin{aligned} Z = &\sum_{i\in\mathcal{N}}\sum_{p\in\mathcal{P}}(A_i^p\alpha_i^p + B_i^p\beta_i^p) \\ &+ \sum_{i\in\mathcal{N}}\sum_{p\in\mathcal{P}}\sum_{q\in\mathcal{P}^p} S_i^{qp}\sigma_i^{qp} \\ &+ \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}\setminus\{i\}}\sum_{p\in\mathcal{P}}(F_{ij}^p\phi_{ij}^p + T_{ij}^p\tau_{ij}^p) \\ &+ \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}\setminus\{i\}} L_{ij}\lambda_{ij} \\ &+ \sum_{i\in\mathcal{N}}\sum_{o\in\mathcal{O}} O_i^o\omega_i^o \\ &+ \sum_{i\in\mathcal{N}} Z_i\zeta_i \end{aligned} \tag{1}$$

Objective function (2) minimizes the cost of carbon emissions associated with components, option implementation, and transportation.

$$Min \quad C$$

$$\begin{aligned} C = &\sum_{i\in\mathcal{S}}\sum_{p\in\mathcal{R}}(A_i^p c^p) \\ &+ \sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}\setminus\{i\}}\sum_{p\in\mathcal{P}}(F_{ij}^p c_{ij}^p) \\ &+ \sum_{i\in\mathcal{N}}\sum_{o\in\mathcal{O}} O_i^o c^o \\ &+ \sum_{i\in\mathcal{N}} Z_i c_i \end{aligned} \tag{2}$$

Constraints (3) and (4) limit the global cost and carbon emissions cost respectively. When using objective function (1), constraint (4) is added; and when using objective function (2), constraint (3) is added.

$$Z \leqslant z_{max} \tag{3}$$

$$C \leqslant c_{max} \tag{4}$$

Constraints (5)–(9) are flow constraints. The sources are the component flows from the suppliers to the production centers, and the sinks are the final product flows to customers. Constraint (5) considers the flow of each manufactured product assembly in each production center.

$$\begin{aligned} &A_i^p + \sum_{j\in\mathcal{U}\setminus\{i\}} F_{ji}^p + \sum_{q\in\mathcal{P}^p} S_i^{qp} \\ &= \sum_{j\in\mathcal{U}\setminus\{i\}} F_{ij}^p + \sum_{q\in\mathcal{M}\cup\mathcal{F}} g^{qp}A_i^q + \sum_{q/p\in\mathcal{P}^q} S_i^{pq} \\ &\forall i \in \mathcal{U}, \forall p \in \mathcal{M} \end{aligned} \tag{5}$$

Constraint (6) considers the flow of each component in each production center.

$$\begin{aligned} &\sum_{j\in(\mathcal{S}\cup\mathcal{U})\setminus\{i\}} F_{ji}^p + \sum_{q\in\mathcal{P}^p} S_i^{qp} \\ &= \sum_{j\in\mathcal{U}\setminus\{i\}} F_{ij}^p + \sum_{q\in\mathcal{M}\cup\mathcal{F}} g^{qp}A_i^q + \sum_{q/p\in\mathcal{P}^q} S_i^{pq} \\ &\forall i \in \mathcal{U}, \forall p \in \mathcal{R} \end{aligned} \tag{6}$$

Constraint (7) considers the flow of each component from each supplier.

$$A_i^p = \sum_{j\in\mathcal{U}} F_{ij}^p \qquad \forall i \in \mathcal{S}, \forall p \in \mathcal{R} \tag{7}$$

Constraint (8) considers the flow of each final product from each distribution center.

$$\sum_{j\in\mathcal{U}\cup\mathcal{D}\setminus\{i\}} F_{ji}^p = \sum_{j\in\mathcal{D}\cup\mathcal{C}\setminus\{i\}} F_{ij}^p \qquad \forall i \in \mathcal{D}, \forall p \in \mathcal{F} \tag{8}$$

Constraint (9) considers the flow of each final product on each production center.

$$A_i^p + \sum_{j\in\mathcal{U}} F_{ji}^p = \sum_{j\in\mathcal{D}\cup\mathcal{C}\setminus\{i\}} F_{ij}^p \qquad \forall i \in \mathcal{U}, \forall p \in \mathcal{F} \tag{9}$$

Constraint (10) ensures that the customer's demands are satisfied.

$$\sum_{j\in\mathcal{D}} F_{ij}^p + \sum_{q\in\mathcal{P}^p} S_i^{qp} = \sum_{q/p\in\mathcal{P}^q} S_i^{pq} + d_i^p \qquad \forall i \in \mathcal{C}, \forall p \in \mathcal{F} \tag{10}$$

Constraint (11) ensures that B_i^p is set to 1 if a production of p occurs. It also ensures that fixed costs are paid when a component is provided by a supplier or when an assembly is manufactured in a production center. A_{max}^p is the upper bound of $A_i^p \quad \forall i \in U$.

$$A_i^p \leqslant B_i^p A_{max}^p \qquad \forall i \in \mathcal{S}\cup\mathcal{U}\cup\mathcal{D}, \forall p \in \mathcal{P} \tag{11}$$

Constraint (12) ensures that Z_i is set to 1 if plant i is used.

$$B_i^p \leqslant Z_i \qquad \forall i \in \mathcal{S}\cup\mathcal{U}\cup\mathcal{D}, \forall p \in \mathcal{P} \tag{12}$$

Constraint (13) defines the capacity of each technology needed in a production center.

$$\sum_{p/u\in\mathcal{P}^p} l^{pt}A_i^p \leqslant \sum_{o\in\mathcal{O}^t} O_i^o c^o \qquad \forall i \in \mathcal{U}, \forall t \in \mathcal{T} \tag{13}$$

Constraint (14) ensures that T_{ij}^p is set to 1 if the arc from i to j is used by at least one product p.

$$F_{ij}^p \leqslant T_{ij}^p A_{max}^p \qquad \forall i \in \mathcal{N}, \forall j \in \mathcal{N}\setminus\{i\}, \forall p \in \mathcal{P} \tag{14}$$

Constraint (15) ensures that L_{ij} is set to one if at least one product uses the arc from i to j.

$$T_{ij}^p \leqslant L_{ij} \qquad \forall i \in \mathcal{N}, \forall j \in \mathcal{N}\setminus\{i\}, \forall p \in \mathcal{P} \tag{15}$$

Constraint (16) limits the number of substituted products to be used in the plant in which they were created.

$$\sum_{q\in\mathcal{P}^p} S_i^{qp} \leqslant \sum_{q\in\mathcal{M}\setminus p} g^{qp}A_i^q + \sum_{j\in\mathcal{C}} F_{ij}^p \qquad \forall i \in \mathcal{U}, \forall p \in \mathcal{P} \tag{16}$$

We define Problem 1 as the MILP using objective function (1) with constraint (4), Problem 2 as the MILP using objective function (2) with constraint (3), $Z(c_{max})$ as the optimal solution of Problem 1, and $C(z_{max})$ as the optimal solution of Problem 2. The differences between this model and that of Baud-Lavigne et al. (2011b) are in the addition of constraint (4) in Problem 1 and the study of Problem 2.

3. Experiments

3.1. Experiment design

The supply chain used in this academic case study is illustrated in Fig. 1.

Two areas are considered: Area 1 and Area 2. Two production centers are available in each area, with a pay rate of $\$30_{/h}$ and $\$25_{/h}$ respectively (Area 1), and $\$6_{/h}$ and $\$5_{/h}$ respectively (Area 2). In Area 1, the unit carbon emissions are lower because of stricter regulations, but the labor cost is higher. The markets are also different: in Area 1, demand is high for high quality products with many functionalities, whereas in Area 2, the demand is for simpler products. Suppliers, distribution centers, and customers are set randomly.

Table 2 shows the parameters used in this case study.

Transportation cost is computed based on the part volume, the distance between the units, and the logistical cost. As the model considers a mono period, all the fixed costs apply to this period.

Three product families are tested (Table 3).

Instance 1 is a medium-sized product family, in which each component has between 1 and 4 alternatives. Instance 2 has the

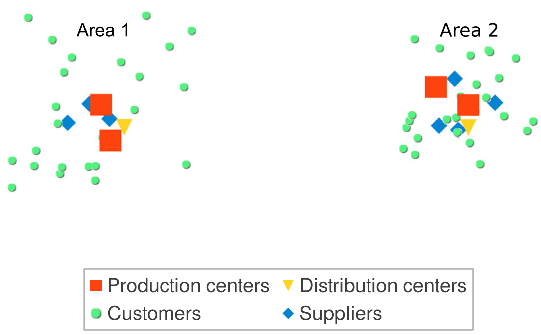

Fig. 1. Supply chain in our case study.

Table 2
Case study characteristics.

Type	Parameter	Value
Network node	Logistical cost	100 $\$_{/m^3/km}$
	Logistical carbon emissions	100 $t_{/km}$
Customers	Quantity	50
	Prob demand	.3
	Max demand per product	1000
Fixed costs	Per (axe, product)	$200
	Per (component, supplier)	$1000
	Per (product, plant)	$50,000
	Per suppliers	$5000
	Per plants	$200,000
	Per DC	$10,000
Product parts	Max carbon emission	10
	Max procurement cost	$20
	Max physical volume	1 m^3

same characteristics as Instance 1, but without any alternatives. Instance 3 is a small product family with many alternatives. One part can substitute for another when it has more or better components.

The aim of the experiments initially is to analyze how the optimal cost allocation is impacted by carbon emissions constraints, using Problem 1. The global carbon emissions, C are bounded by c_{max}, which varies between c_{min} and αc_{min} ; c_{min} are the optimal global carbon emissions when only carbon emissions minimization is addressed and no cost constraints are imposed. A similar methodology is followed to analyze how the optimal carbon emissions allocation is impacted by cost constraints, using Problem 2, in the subsequent aim of the experiments.

The results are assessed based on four criteria: cost level; cost allocation to production, transportation, and components; carbon emissions allocation to production, transportation, and components; and the commonality index of the manufactured product. Many commonality indices have been described in the literature (Thevenot & Simpson, 2006). In this paper, we propose the Extra Commonality Index (ECI) to measure the commonality brought about by substitution decisions. The ECI is computed as follows:

Table 3
Instance parameters.

	Inst. 1	Inst. 2	Inst. 3
BOM height	2	2	1
Components	12	6	11
Sub-assemblies	23	12	3
Products	15	15	20
Max. quality levels	4	1	10

$$\mathrm{ECI} = 1 - \frac{\#\ \text{parts used} - \#\ \text{parts min}}{\#\ \text{parts max} - \#\ \text{parts min}}$$

Parts contain components, high-level assemblies, and make up final products. The minimum number of parts (# parts min) refers to the solution with a unique final product, all the components of which are of high quality. It can be substituted for any other product. The maximum number of parts (# parts max) refers to the number of parts in the initial BOM, *i. e.* there is no reason to produce any other type of part. The ECI is between 0 (no extra commonality) and 1 (total commonality), and can differ because of the substitution possibilities: additional components can be added to the subassemblies to increase standardization, and components can be substituted for lower carbon emissions impact or higher quality – either to achieve a lower carbon emissions impact or to increase standardization. Initial commonality does not affect the ECI. Experiments are conducted by solving the MILP presented in Section 2 with ILOG CPLEX 12 Java libraries on a server under 64 bits OS with a 2.27 GHz Intel Xeon CPU with 8 cores and 8 GB of memory.

3.2. Cost function minimization with a carbon emissions constraint

A carbon emissions constraint (constraint (4)) is added to analyze the cost structure that must be found which respects a global carbon emissions limit. This limit $C_{max} = \alpha C_{min}$ is tested for $\alpha \in [1, 3.5]$. When $\alpha = 1$, resolving Problem 1 is the same as resolving Problem 2 without a cost constraint. When $\alpha C_{min} \geqslant C(Z(\infty))$, the carbon emissions constraint is relaxed.

Fig. 2 presents the ECI according to C_{max} variation. In the three examples tested, the ECI increases with alpha. When the carbon emissions constraint is tight, commonality is lower when more carbon emissions are authorized. Fig. 3 presents the cost allocation on the three examples according to C_{max} variation. The allocation of carbon emissions is not relevant, as it has not been optimized.

Figs. 3 present the cost allocation on the three instances according to C_{max} variation. Carbon emission allocation is not relevant, as it has not been optimized.

For instance 1, the carbon emissions constraint has little impact on cost. The optimal cost is reached when alpha is above 1.35. Under 1.35, gain is obtained mainly through transportation cost reduction and some product cost variation. Instance 2 is impacted more by this constraint. When relaxing the constraint by 50%, cost can decrease by 30%. When alpha is under 1.7, the gain is generated by transportation and production. Above 1.7, transportation cost continues to decrease, while the component costs increase a little. Cost is optimal when alpha is above 2.9. For instance 3, three stages are visible. When alpha is under 1.1, the global cost is high because of the component costs, which decrease by 30%, while transportation and production costs remain stable. Between 1.1 and 1.9, the optimal cost gradually decreases, mainly through component cost reduction. Above 1.9, the solution is stable.

3.3. Carbon emission function minimization with maximal cost constraint

A maximal cost constraint (constraint (3)) is added to analyze the carbon emissions structure that must be found which respects a global cost limit. This limit, $Z_{max} = \alpha Z_{min}$ is tested for $\alpha \in [1, 3.5]$. When $\alpha = 1$, resolving Problem 2 is the same as resolving Problem 1 without a carbon emissions constraint. When $\alpha Z_{min} \geqslant Z(C(\infty))$, the cost constraint is relaxed.

Fig. 4 presents the ECI according to the variation in Z_{max}. In the three examples tested, the ECI decreases with alpha. When the carbon emissions constraint is tight, commonality is greater when more carbon emissions are authorized, with a large plateau between the extreme values.

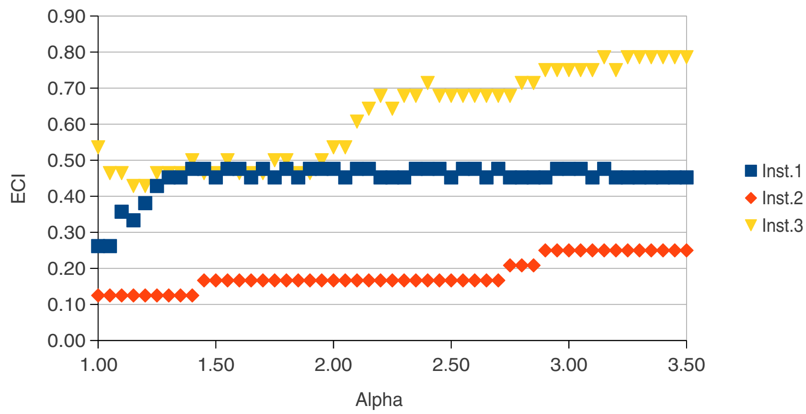

Fig. 2. Extra Commonality Index (ECI) with C_{max} variation ($C_{max} = \alpha C_{min}$).

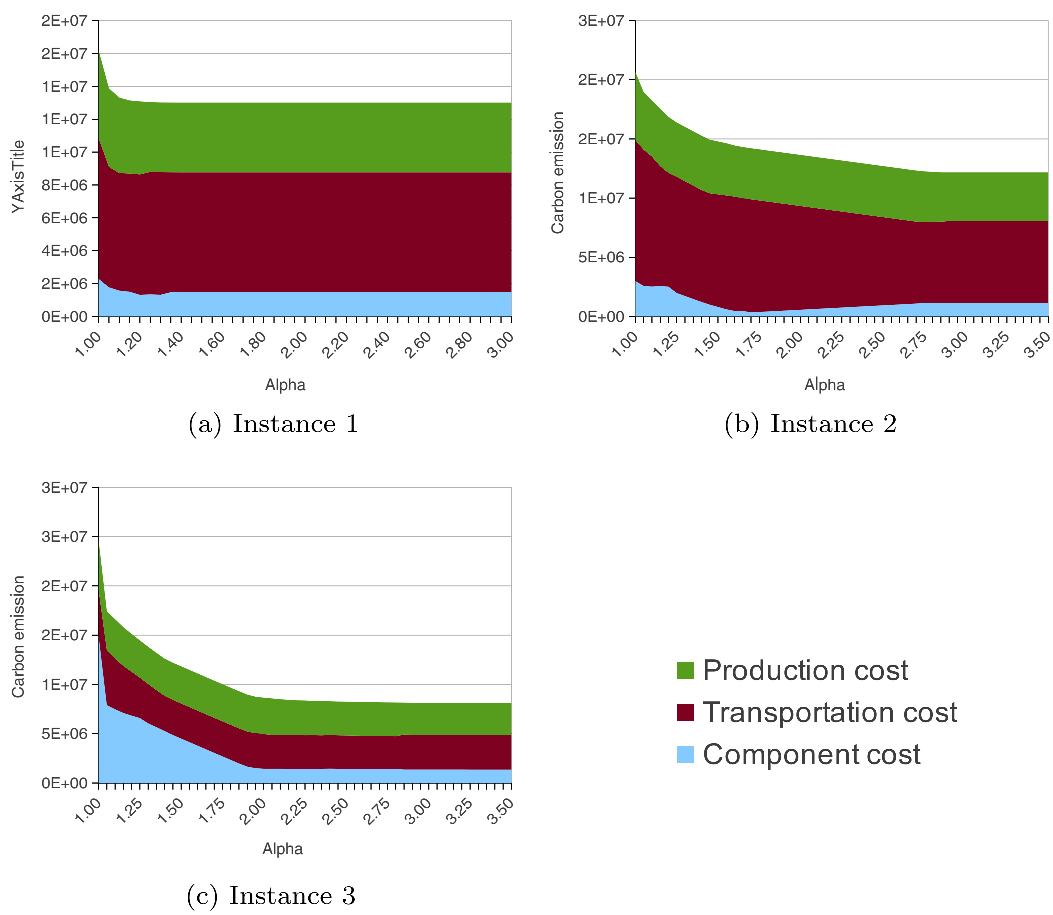

Fig. 3. Cost optimization under the carbon emission constraint variation.

Figs. 5 presents the allocation of carbon emissions to the three examples according to the variation in Z_{max}. Cost allocation is not relevant, as it has not been optimized.

For instance 1, the solution is little impacted by the cost constraint. Global carbon emissions significantly decrease, by 25% while alpha is under 1.1, mainly through component reduction. Between 1.1 and 1.25, the global carbon emissions are stable, with a transfer from component source to transportation. For instance 2, the carbon emissions component decreases dramatically, by 90% when alpha moves from 1 to 1.6 while carbon footprints generated by transportation increase slightly. The solution is stable above 1.5. For instance 3, three stages are visible. When alpha is under 1.1, global carbon emissions decrease sharply, by 40%, thanks to a reduction in the carbon emissions generated by the components. Between 1.1 and 2.2, these carbon emissions gradually decrease, while those generated by transportation increase slightly. Above 2.2, the phenomena are inverted, as component carbon emissions increase slightly, while transportation carbon emissions decrease.

3.4. Global analysis

There is greater commonality when cost is the main issue (when the cost constraint is tight, as in Problem 2, or when the carbon emissions constraint is relaxed, as in Problem 2). In contrast,

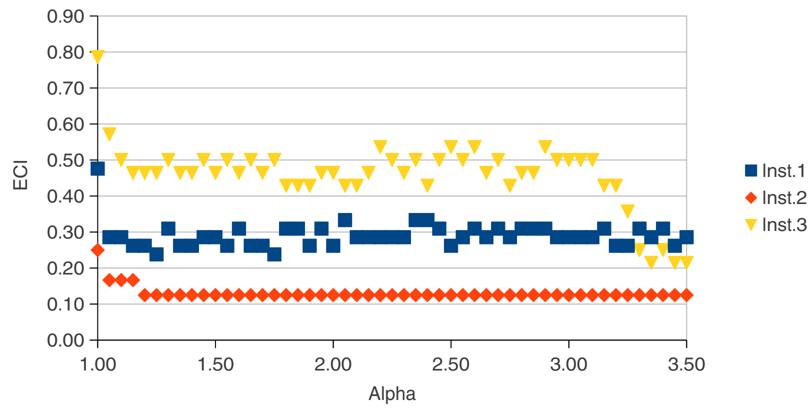

Fig. 4. Extra Commonality Index (ECI) according to the variation in Z_{max} ($Z_{max} = \alpha Z_{min}$).

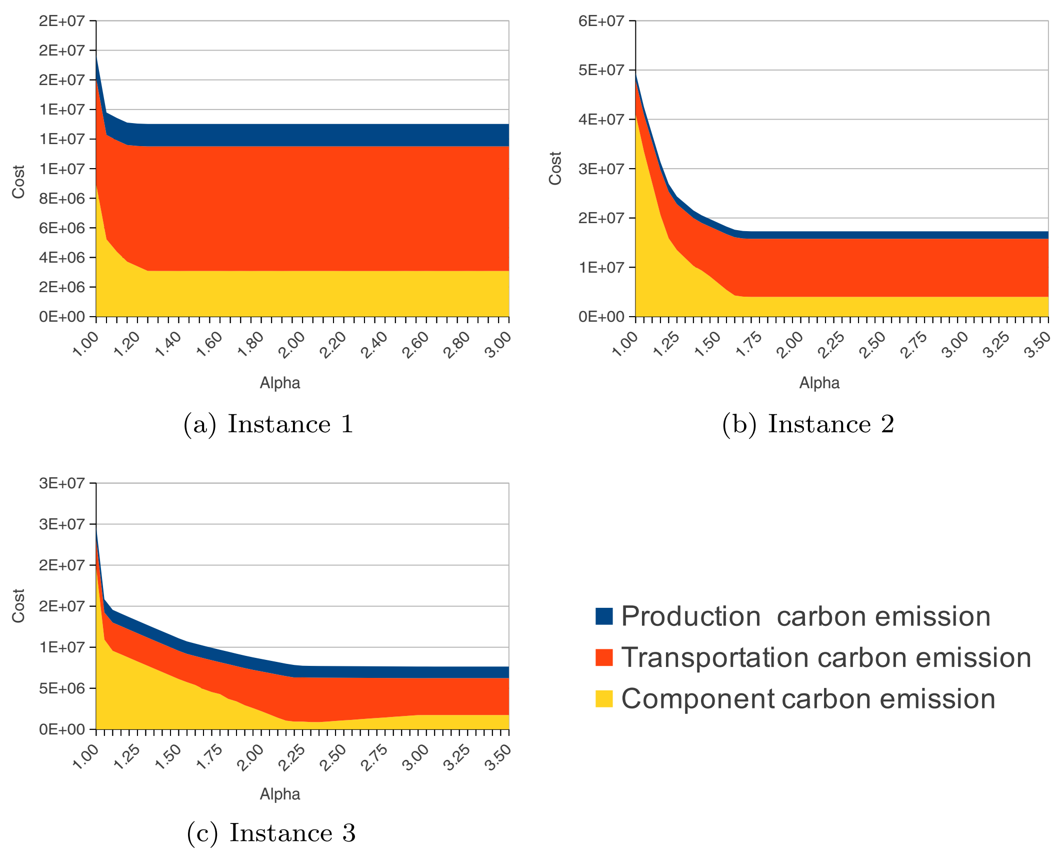

Fig. 5. Carbon emissions optimization with variations in the cost constraint.

there is little commonality when carbon emissions are the priority. These effects on commonality operate in all the examples, even in the second one, where there are no alternatives to consider. However, the impact on commonality is even greater in Example 3, where there are many alternatives to choose from. So, standardization involving a small number of component is impacted more than standardization involving a large number of component.

Concerning cost and carbon emissions allocation, when a balance is found between components and transportation, production is not much impacted by the constraints. In instance 1 with Problem 1 and 2 Figs. 3a and 5(a), the solution is stable when the constraint is not too tight (+10%). In terms of cost optimization, the more flexibility there is, the less transportation is required, as production can occur close to where the customers are located (Fig. 3b). When carbon emissions are optimized, it can be an advantage to increase transportation distances, so that component costs can be reduced (Fig. 5c).

4. Conclusion

In this paper, we have proposed a way to deal with environmental issues through carbon footprint optimization and by considering carbon footprints as a constraint. Our analysis of the impact of cost constraints on carbon emissions optimization shows that the optimal solution involves tight constraints on cost, but that this is an extremely costly option. It also shows that acceptable solutions exist when the cost constraint is loosened. Our analysis of the impact of carbon emissions constraints on cost optimization shows a slight peak where the impact of a tight carbon emissions constraint on cost is really high, after which this has a small impact on cost. To ensure an appropriate carbon emissions (cost) limit, a balance must be found between the component cost and the transportation cost (carbon emissions).

Our perspective in this work is to address a wider range of sustainable development issues by covering its three principal areas: economic, ecological, and social. In terms of ecological issues, a methodology to accurately assess carbon emissions is needed to apply our proposal in an industrial case study. A widespread social challenge today is to maintain employment levels in some areas. The integration of minimum production level constraints in production centers in these areas could be an efficient way to implement optimized solutions that are *i.e.* keeping with the political decisions that must be taken.

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