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Mutual impacts of product standardization and supply chain design

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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

This paper deals with two major issues for industries; the product design and the supply chain design. These problems are usually solved separately, but in recent years, approaches were proposed to tackle these two problems together. In this paper, we investigate more precisely the links between the standardization of products or components, and the design of the supply chain. First, we show on a little example that there is a great interest to consider simultaneously these two decisions, and that solving these interdependent problems separately could result in a suboptimal, or even a bad, decision. Then, on a simplified problem issued from an industrial case study, we outline the impact of standardization choices on the structure of the supply chain and the gain that can be obtained from solving the problem as a unique compound optimization model. To illustrate the solutions of the problem, we propose graphics in order to visualize, in function of quantities and/or transportation costs, the best decision for the product standardization and for the supply chain design. Graphics also permit to anticipate the impacts of a variation of either quantities or transportation costs, from a specific situation. Such graphics they could be used in a decision aid tool to help companies in their choices. Finally, we show that costs and supply chain structure are highly impacted.

1. Introduction

In a highly competitive business environment, companies must diversify their offers to meet customer's demands. Managing diversity is a central issue: how to offer a wide variety of products that meet customer's needs, while controlling production, inventory and logistical costs? The answers usually involve many separate disciplines, mainly product design, production and logistics. Interdisciplinary, however, appears as a key in managing diversity (Riopel et al., 1998).

Integrating product and supply chain optimization is facing two important barriers. The first issue is to prove that the simultaneous design of the product and the supply chain is relevant. In fact, cost from the product itself should be much higher than logistical and production costs. Appelqvist et al. (2004) explain this in a recent survey:

> Why is there then a lack of research into modelling of supply chains in the product design phase? Perhaps, in the final analysis, it is not important. Material costs typically stand for the majority of the product costs, and are determined in the product design phase. If these, in turn, are determined by the desired product functionality, there is little that supply chain modelling can achieve.

However, this limitation is slowly taking down with the increase of transportation costs mainly due to oil price and carbon taxes. Also, simultaneous optimization of criteria is relevant if and only if there exist linked impacts between these criteria. Otherwise, sequential optimization can be used. It is well established that product design has a great impact on manufacturing and logistics (Dowlatshahi, 1996). However, the opposite link has to be highlighted. This paper focuses on this first issue.

The second issue concerns the solution of such a combined problem. The integrated supply chain design is already a complex problem. Adding new decisions, such as product standardization, increases the difficulty to model the problem and to solve it efficiently.

When considering mass customization, it may be sub-optimal to first design the product, and then the supply chain. A review of the current literature shows that attention is mainly given on separated approaches, while very few studies consider joint design. Nevertheless, joint design of product standardization and supply chain offers new perspectives. Standardization is the possibility of replacing a component or a sub-assembly by another one with either more function or including components with higher quality in order to decrease the number of parts. In terms of product costs, the standardization is not advantageous. However, standardization can reduce the number of parts that have to be managed. This reduction permits to save fixed costs. Furthermore, the demand for each part increases economies of

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scale for transportation and permits a better use of production capacity (Fixson, 2007). This can provide economies of scale to allow cheaper relocation. To highlight this, a little case study is proposed to show the optimality of the joint design on sequential design under some restrictive hypotheses. Then, the analysis of more realistic cases shows various impacts of the standardization on the supply chain design. To illustrate the solutions of the problem, we propose graphics in order to visualize, in function of quantities and/or transportation costs, the best decision for the product standardization and for the supply chain design. Graphics also permit to anticipate the impacts of a variation of either quantities or transportation costs, from a specific situation. Such graphics could be used in a decision aid tool to help companies in their choices. Finally, we show that costs and supply chain structure are highly impacted.

The paper is organized as follows. In Section 2, a literature review is given. Section 3, presents the problem of supply chain design considering product standardization. A small example shows that, in certain circumstances, product standardization and product allocation must be taken into account simultaneously. To better understand the links between product standardization and the supply chain, numerical experiments are led using MILP exact solution (Section 4). These results show that the impacts are important for both costs and structure of the solutions. Section 5 concludes the paper and proposes ways to investigate this difficult problem.

2. Literature review on product and supply chain design

In product design, high diversity at low cost can be obtained through mass customization, concept well defined by Pine (1993). Mass customization seeks to offer a wide variety of finished product with the advantages of mass production, i.e. low production, storage and logistic costs. Mass customization involves a set of concepts that can be used at the product design stage: modular design, scalability and commonality. Modular design (Kusiak and Huang, 1996) consists to assemble the product from functional modules. Scalability allows easy changes to the product, while, commonality (Fixson, 2007) reuses components or sub-assemblies of other existing products. During the industrialization phase, delayed differentiation (Su et al., 2005) has permitted to personalize products in the manufacturing process (Fournier and Agard, 2007). These developments offered new opportunities for optimization. Authors then worked on either optimization of product families to meet customer needs precisely and at lowest cost (Briant and Naddef, 2004; Barajas and Agard, 2009) or module optimization (da Cunha et al., 2007; Agard and Penz, 2009).

Once the product is designed, the goal is then to reduce logistic costs by the design of a supply chain, taking into account both strategical and tactical decisions. The strategic level includes decisions impacting the long term of the company. For example the choice of production facilities, their load/manufacturing capacities and technologies used may be viewed as strategic. The tactical level includes mid-term decisions, such as the choice of suppliers, the allocation of products to production facilities, and the flow of each product and sub-assembly in the network (Cordeau et al., 2006). The parameters considered in the supply chain design problem are related to the manufacturing (cost structure, workforce, capacity, etc.) and to the logistics induced by a dispersion of production sites. Many studies have focused on the supply chain design problem, an overview is proposed by Shapiro (2001) who provided models for a wide variety of issues related to supply chain. See also Melo et al. (2009) for the most recent review for deterministic models and Peidro et al. (2009) for the stochastic models. A comprehensive study on the logistical decisions is also proposed by Riopel et al. (2005) who presented a framework which highlights all the links between the product and supply chain design.

Joint product and supply chain design opens new perspectives in the issue of high diversity of products. Most approaches developed to solve this combined problem are crossed approaches. The first type of approach consists to incorporate product constraints in the supply chain design, by taking into account, for example, the assembly constraints. Integrated supply chain models considering bill-of-materials are recent and still little studied. Several single-period, multi-product and multi-level models have been proposed by Paquet et al. (2004, 2008), and Cordeau et al. (2006) and a multi-period model was presented by Thanh et al. (2008). Some studies analyzed the impact of the product design on the supply chain. For example, Salvador et al. (2004) investigated the consequences of the level of mass-customization on the supply chain by an empirical research and showed that the degree of customization has a significant impact on the supply chain configuration. Montreuil and Poulin (2005) proposed a supply chain design suited to personalized manufacturing.

The second type of crossed approach is to integrate logistic constraints in the product design. Benefits of "design for logistics" (DFL) have been highlighted by Dowlatshahi (1996). These approaches promote the use of concepts such as modular design, delayed differentiation and other qualitative rules. Such as reducing the number of components or references used, and integrating of upstream suppliers of design projects to allow lower costs associated with storage and transportation products.

Integrated approaches, which involve complex models, are poorly investigated yet. The simultaneous optimization of product and supply chain design is a difficult problem. Authors have looked at partial models, simpler to solve and to implement. Gupta and Krishnan (1999) presented a mixed integer programming formulation to integrate component standardization and supplier selection decisions. Fixed and variable costs are associated to each different component. The optimal solution is found with the proper level of standardization, which allows fixed cost economies, while increasing variable costs. In order to develop more comprehensive models, the product design is limited to a choice among pre-defined bill-of-materials (BOM), which are more-or-less fixed earlier in the design phase. Two approaches are listed in the literature. The first approach seeks to define the best product family which meets the market needs, by using generic BOM to model the product part of the problem (Lamothe et al., 2006; Zhang et al., 2008). In these formulations, BOM are determined so as to respect assembly constraints. The second approach considers the final products as fixed, but the BOM are more-or-less flexible. To model this in an assembly-to-order context, El Hadj Khalaf et al. (2009) considered function and modular design, in which all the assemblies are possible. The background of their study is the automobile industry, in a mass-customization context. El Hadj Khalaf et al. (2009) proposed a model to choose simultaneously the modules to produce and their suppliers, with a constraint on the final assembly time. ElMaraghy and Mahmoudi (2009) defined several alternative BOM, one being selected in the optimal solution. This approach needs a complete enumeration of all product configurations. In return, both formulation and solution are facilitated.

Our study differs from the literature by addressing the specific problem of the product standardization. The aim of the paper is to analyze the impact and benefits of product or component standardization on optimizing the supply chain.

3. Supply chain design and standardization possibilities

3.1. Problem description

In this study, the integrated supply chain design is to define both the supply chain structure and the product bill-of-materials. The supply chain is limited to production units, which can exchange sub-assemblies with each others. The distribution is not considered in the model, and demands are allocated to a determined production unit. Each unit is described by its labour cost and the transportation costs to other units. Products are represented through their bill-of-materials, *i.e.* their sub-assemblies. By definition, all assemblies can be produced and transported from a unit to another.

When considering products build up with only one assembly, this problem reduces to a classical facility location problem. However, constraints between assemblies through the bill-of-materials change the issue, and the problem becomes more difficult to solve. In the literature, some authors used the term "facility location" to define this kind of problem, as Thanh et al. (2008). However, the model presented in the paper does not include implantation unit costs. Only product allocation is considered.

In the small example presented in Fig. 1, two products are considered: P and P'. Each product is composed of two sub-assemblies. P is composed of sub-assemblies A and B, while P' contains A' and B'. Sub-assembly B is composed of two components D and E, and B' contains only E.

Each sub-assembly is described by its processing time (which determines the production costs) and by its physical volume (which determines the transportation costs).

Standardization possibilities can be express through explicit equivalences between assemblies. In Fig. 1, B' contains E. Also, B contains D and E. We observe that $B' \subset B$. We assume then that B has more functionalities than B' and that B' can possibly be replaced by B. Then B can be used to standardize B'.

The aim of the optimization is to decide what sub-assemblies have to be standardized, and where the different assemblies have to be produced. Fig. 2 shows an example of the result that is expected. In this solution, B replaced B'. Also P, P', A and A' are affected to site 1, B and D to site 2, and E to site 3.

3.2. Mathematical formulation to design the supply chain

The model presented in this section product allocates products to facilities, while satisfying production and logistic constraints. An integrated supply chain design can be easily obtained by adding component and supplier constraints. Standardization possibilities are not included in the model. The goal of the paper is to analyze the impacts of the standardization on the supply chain on various examples. The integration of standardization leads to a more complicated model, discussed later in the perspectives.

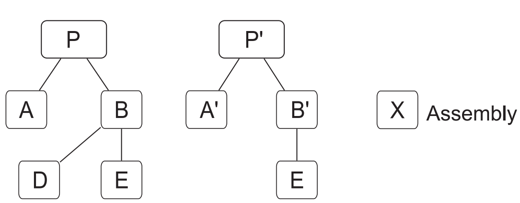

Fig. 1. Bill-of-materials for the products P and P'.

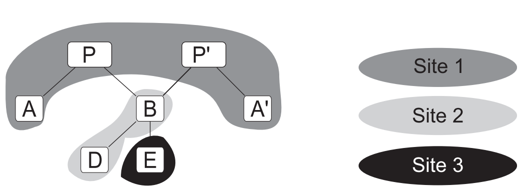

Fig. 2. Solution pattern of the problem.

Experiments presented in Section 4 are made by solving the model presented in this section for all standardization alternatives.

The initial model is a simplified version of the model developed by Paquet et al. (2004). The simplified model allows to concentrate the analysis on the impact of the standardization. The problem is formulated with the following notations:

Sets:

- P: products; index: $p,q \in P$,
- U: production center; index: $i,j \in U$.

Parameters:

- G_{ij}: bill-of-materials. $G_{ij}=1$ if P_i is composed of P_j. P_i is a finished product if column i is zero, a raw material if raw i is zero, else a manufactured product,
- D_{pi}: demand for product p on center i,
- t_p: processing time for product p,
- v_p: volume of product p.

Costs:

- C_i: mean hourly cost of manpower in production center i,
- Cf_{pi}: fixed cost if center i produces product p,
- Ct_{ij}: transportation cost by unit of volume of a product between centers i and j.

Decision variables:

- X_{pi}: quantity of product p manufactured in center i,
- Y_{pi}: 1 if center i produces product p, else 0,
- F_{pij}: flow of product p from center i to center j.

Then, the supply chain design problem can be formulated as a mixed integer linear program as follows:

$$Z = \min \sum_{i \in U}\sum_{p \in P}(X_{pi}C_i t_p + Y_{pi}Cf_{pi}) + \sum_{i \in U}\sum_{j \in U \setminus i}\sum_{p \in P} F_{pij}Ct_{ij}v_p \qquad (1)$$

s.t.

$$X_{pi} + \sum_{j \in U \setminus i} F_{pji} = \sum_{j \in U \setminus i} F_{pij} + \sum_{q \in P \setminus p} G_{qp}X_{qi} + D_{pi} \quad \forall i \in U, \quad \forall p \in P \qquad (2)$$

$$X_{pi} \le Y_{pi}D_p \quad \forall i \in U, \ \forall p \in P \qquad (3)$$

$$X_{pi} \in \mathbb{Z}^+ \quad \forall i \in U, \ \forall p \in P \qquad (4)$$

$$Y_{pi} \in \{0,1\} \quad \forall i \in U, \ \forall p \in P \qquad (5)$$

$$F_{pij} \in \mathbb{Z}^+ \quad \forall i,j \in U, \ \forall p \in P \qquad (6)$$

The objective function (1) minimizes production and transportation costs. Constraints (2) are the flow constraints, described in Fig. 3. For each product p on a center i, entering flows represent products transported from every other centers to i, and production of p on i (the source), while outgoing flows represent products p transported from i to every other centers, products in the bills-of-materials of other assemblies produced in i and the demand (the

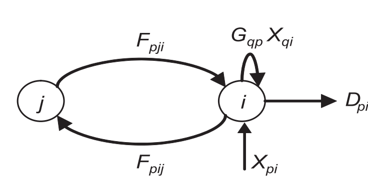

Fig. 3. Flow of assembly p on site i.

sink). Constraints (3) assure that fixed costs are paid when a product is manufactured on a unit. When $X_{pi} > 0$, $Y_{pi} = 1$. To verify this inequality, D_p must be a constant greater that X_{pi}. So, D_p is the total demand associated with assembly p in the whole supply chain. Constraints (4), (5) and (6) define decision variables as positive integers for X and F, and as boolean for Y.

3.3. Relevance of joint standardization and supply chain optimization

The following example is a small case built to show that standardization and supply chain design should be tackled simultaneously. In this small case, we look for a situation in which the standardization and the allocation of production to different sites are not advantageous if they are considered independently, but advantageous if the two decisions are taken into account simultaneously. Then, we propose a simple Linear Program in order to find a case where the sequential approach gives bad results, and the integrated approach gives good results.

Let us consider the following situation. Two products p and q, and two production centers i and j are considered. Product q can be standardized, and then replaced by product p. The demand occurs only in site i.

The model considers the following parameters:

- two production units i and j,
- $Cf_i = Cf_{pi} = Cf_{qi}$ and $Cf_j = Cf_{pj} = Cf_{qj}$ are the fixed production cost for products p and q where $Cf_i \leq Cf_j$,
- $Cf_a = Cf_j - Cf_i$ is the additional production fixed cost for an assembly in production center j instead of production center i,
- $t_p = t_q = t$, the processing time is the same for the two products,
- C_i and C_j are the hourly production costs in centers i and j, and $C_i \geq C_j$,
- $CV = t(C_i - C_j)$ is the variable production saving when manufacturing a product in j instead of i,
- CS is standardization cost, *i.e.* additional cost per product when product q is replaced by product p,
- T is the unit transportation cost from centers i to j and conversely, assuming $v_p = v_q$ and $Ct_{ij} = Ct_{ji}$,
- $D = D_{pi} = D_{qi}$ are the demands of each final product.

Table 1 presents the four possible alternatives. The initial solution is to produce both products p and q in production center i. The initial solution cost (noted ISC) can be calculated as $ISC = 2Cf_i + 2tDC_i$. Three other alternatives are possible. Alternative A consists in producing products p and q in production center j and transporting them from centers j to i. In alternative B, product q is replaced by product p and the production is made in site i. In alternative C, product q is replaced by p and the production is made in site j. Due to the parameters chosen in this example, it is easy to see that solutions where the production is split on plants i and j are dominated. In Table 1, the impact on cost of these alternatives is compared to the initial solution.

For alternative A, as the production is relocated in site j, we have to pay two times the additional production fixed cost (Cf_a) and the transportation cost for the two products (DT), but we gain two times the variable production saving. In alternative B, we must pay the additional cost per product when product q is replaced by product p, but we gain a fixed production cost Cf_i. Finally, for alternative C, we pay the cost of the standardization ($D.CS$), two times the additional production fixed cost (Cf_a) and the transportation cost for the standardized products ($2DT$), and we gain a fixed production cost Cf_i and the variable production saving ($2D.CV$).

As we now show that the standardization (resp. the move of the production to site j) is not profitable, and that taking both decisions simultaneously is interesting, the following model is written. The production does not provide any benefit when only standardizing (7) or only relocating (8), whereas both combined is profitable (9):

$$D.CS - Cf_i \geq 0 \quad (7)$$

$$2Cf_a + 2D.T - 2D.CV \geq 0 \quad (8)$$

$$D.CS + Cf_a + 2D.T - Cf_i - 2D.CV \leq 0 \quad (9)$$

Many configurations respect these constraints. Two of them are presented in Table 2.

With the first set of parameters (Data 1), benefits are resulting neither from relocation only (alternative A) nor form standardization only (alternative B), but both alternative combined provide a benefit of 10 000. Note that the initial value of the solution for alternatives A and B have the same total cost. For the second set of parameters (Data 2), both options (alternatives A and B) result in losses, while the combined alternative (alternative C) gives a benefit of 5000. In both cases, sequential design would lead to keep the initial solution, which is suboptimal. This result can be generalized on more realistic studies. Indeed, when increasing complexity of products, *i.e.* levels of sub-assembly, other effects are added which can increase this phenomena. However, this has to be tested on more realistic case studies. This is the goal of the following experiments which use MILP optimization.

4. Experiments with standardization and relocation

4.1. Design of experiments

Experiments are based on two academic case studies. The first case study represents identical manufacturing units, *i.e.* units with same labour costs, and demand. The problem is to decide the degree of specialization of each unit, between producing all assemblies to meet their own demand, and producing assemblies for both demands. The second case study illustrates the issue of relocation, with a unit with high labour costs which meets the whole demand, and another unit with lower costs but far away from the first one, incurring transportation costs. In this second case, the problem is to decide which parts of the product have to be transferred to the distant unit.

In both cases, the products considered are illustrated in Fig. 4 and their characteristics are given in Table 3. Sub-assembly A is

Table 2
Results for two datasets.

	Cf_i	Cf_a	CV	CS	T	D	Alt. A	Alt. B	Alt. C
Data 1	20 000	10 000	4	2	3	10 000	0	0	−10 000
Data 2	30 000	25 000	5	4	3	10 000	+10 000	+10 000	−5000

Table 1
Differences in cost of the production alternatives.

	Local production		Distant production	
Specific BOM	Initial solution (ISC)		Alt. A	$ISC+2Cf_a+2\,D.T - 2D.CV$
Standardized BOM	Alt. B	$ISC+D.CS - Cf_i$	Alt. C	$ISC+D.CS+2Cf_a+2D.T - Cf_i - 2D.CV$

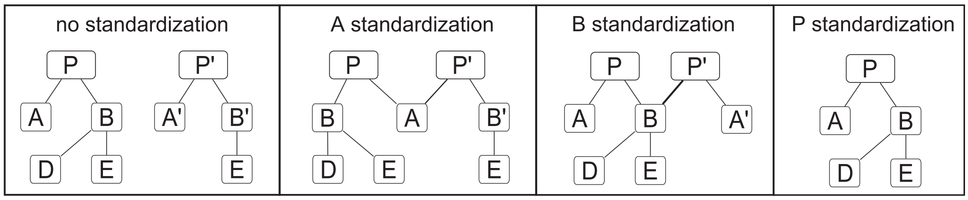

Fig. 4. Standardization possibilities.

Table 3
Product characteristics.

	Sub-assemblies							
	P	*P′*	*A*	*A′*	*B*	*B′*	*D*	*E*
Volume (in m^3)	0.6	0.5	0.5	0.3	0.05	0.05	0.005	0.02
Processing time (in h)	1.7	1.5	0.5	0.45	0.4	0.3	0.2	0.2

Table 4
Variation of parameters.

	Beginning	End	Step
Demand	100	10000	100
Transportation costs	0	200	2
Labour cost	0	25	1
Fixed costs (in percentage of initial costs)	0.1	10	0.1

large, so costly in transportation, while *B* is small, but using more processing time.

The standardization possibilities for product *P′* are to substitute module *A′* by *A*, or *B′* by *B*, or the whole product *P′* by *P*. Additional costs of standardization are induced mainly by volume increase for *A*, and processing time increase for *B*. When standardizing *B*, *D* has to be produced for *P′*, which adds processing time. Consequently, *A* standardization is sensitive to transportation cost variation, while *B′* standardization is sensitive to labour cost, and *P* to both. Transportation costs are paid only when sub-assemblies are moved from a unit to another. For a local production, *A* standardization has nearly no negative effect, while *B* and *P* standardizations generate extra labour cost.

These case studies have been tested with the four standardization options, *i.e.* standardization of *A*, *B*, *P*, or no standardization at all. Variations of parameters are presented in Table 4. For this case study, four models were solved. For a more general problem, this number depends on the number of all possible standardization options and on the compatibilities between them (this could be considered as different scenarios). In the worst case, if we have to consider all standardization options between all components, an exponential number of problems will have to be solved. So, this approach is better adapted for small size problems or to evaluate a limited number of scenarios. Labour cost variations are relevant only in the second case study. Impacts on the first case study are negligible as the two units have the same labour cost. Fixed costs fluctuate depending on the initial fixed costs.

Experiments are led by solving the MILP presented in Section 3.2 with ILOG CPLEX 10.2. Java libraries on a laptop with a Intel Core2Duo CPU at 2.26 GHz and 2 GB RAM. Resolution is launched four times – one per standardization choice as seen in Fig. 4 – for each parameter set. For example, Fig. 12 required solving 39 600 MILP problems.

To analyze the results, we give comprehensive figures that could be used by managers in the decision process. In the first type of figures (Figs. 5–11), we show the evolution of the gain given by the standardization (left *Y*-axis). The reference value is the optimal solution without standardization but with an optimized supply chain. The gain is expressed as a percentage of the optimal solution. The second *Y*-axis (on the right side) shows the level of standardization in the optimal solution. These results are given in function of the evolution of a selected parameters (*X*-axis). The studied parameters are the fixed costs, the transportation cost and the demand for the case with same facilities; for the relocation case, the parameters are: the labour cost, the fixed costs, the transportation cost and the demand. Moreover, the standardized components are given at the top of the graphics. The letter *X* means that the components *X′* is standardized by *X* in the optimal solution. The second type of figures (Figs. 12 and 13) is a three-dimensional graphic which shows the optimal standardization strategy when two parameters vary. This graphic first identifies, for each couple of data, the best solution in terms of standardization, and then draws zone showing the best strategy. The same principal is used to show the relocated sub-assembly percentage. The analyzes are made for demand and fixed costs, and for demand and transportation cost, for the case of differentiated facilities.

Table 5
Case study 1—demand characteristics.

	P demand	*P′* demand
Each unit	1500	1500

4.2. Case study 1: same facilities

This case study considers two manufacturing units with identical characteristics. Each unit faces the same demand for *P* and *P′*. Parameters are presented in Tables 5 and 6.

The impact of the following parameters has been tested separately: demand, transportation cost, labour cost and fixed cost. For each data value, three results are given: (1) the modules that have to be standardized, (2) the structure of the supply chain: an indicator is used, which represents the percentage of sub-assembly made in only one unit. When this indicator is at 100%, each unit makes distinctive parts for the products and then shares the assemblies—when 0%, each unit produces the whole products and therefore the units are independent, *i.e.* no assembly is shipped. (3) The gain/loss of standardization against basic product. In all cases, optimized supply chain is considered. When there is no other information, parameters are fixed as presented in Tables 3 and 5.

4.2.1. Variation of the fixed cost

The variations of fixed cost is the same in the two production units, from 0.1 to 10 times initial values (Table 5). The results are presented in Fig. 5.

First, when the fixed costs grow, more components or products are standardized. Obviously standardization permits to save fixed costs, and when these costs are large, the gain becomes interesting. Between 0.1 and 1, only *A′* is standardized by *A*. From 1 to 10, *P′* is standardized by *P*. The supply chain function increases with the

Table 6
Case study 1—production unit characteristics.

	Transportation cost	Fixed cost for *P*, *P′*, *A*, *A′*, *B* and *B′*	Fixed cost for *D* and *E*	Labour cost
Each unit	30 €/m³	10 000 €	3000 €	25 €/h

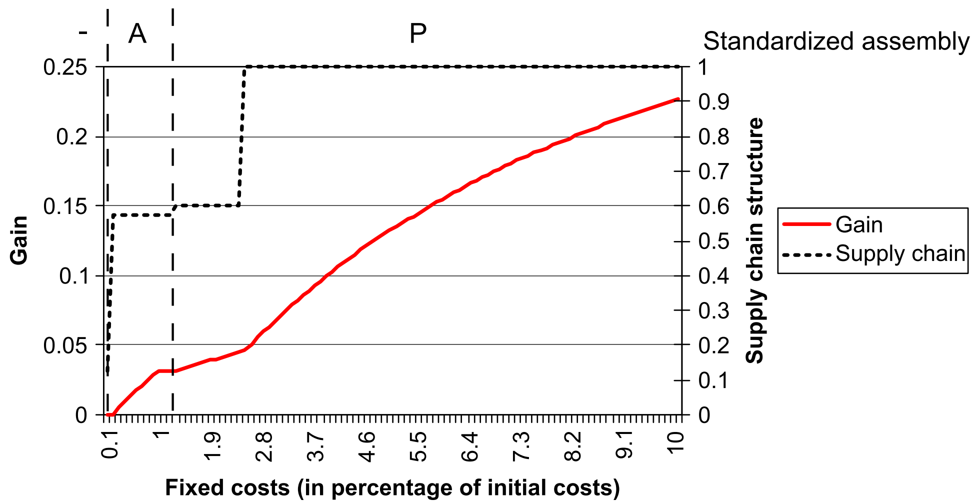

Fig. 5. Gain of standardization and supply chain configuration—fixed cost variation.

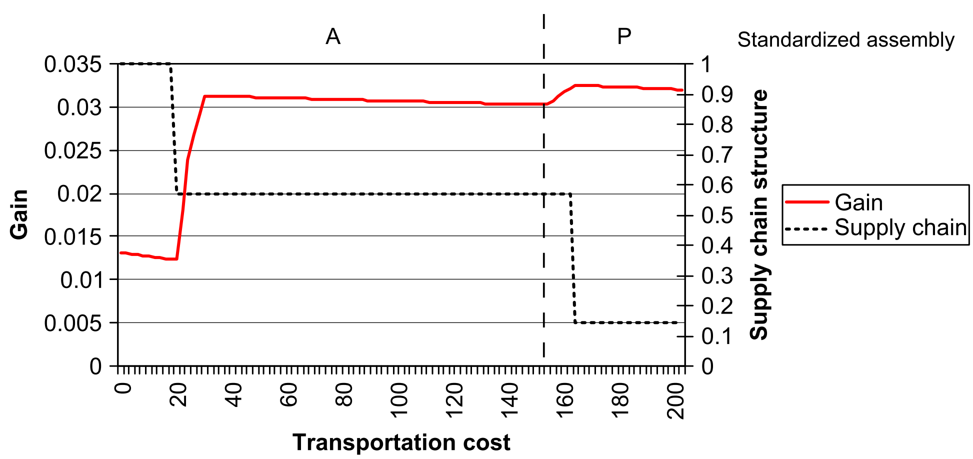

Fig. 6. Gain of standardization and supply chain configuration—transportation variation.

fixed costs by step, either when there is a change in the product (at 0.1 or 1.3) or with fixed cost variations (at 2.5). The gain function also increases with the fixed costs, and its slope depends on the standardization option, the supply chain structure and the fixed cost level.

4.2.2. *Variation of the transportation cost*

The variations of transportation is now studied. Results are presented in Fig. 6. The transportation cost varies from 0 to 200.

Predictable behaviours are highlighted. Shipped quantities decrease in two steps with the increase of transportation costs. Below a transportation cost of 20, units are completely specialized and *A′* is standardized. Then, the product is the same but the supply chain design changes: 40% of sub-assemblies are made in the two units. The gain increases rapidly from 1.25% to more than 3%. At 150, *P′* is standardized without any changes on the supply chain design, but the gain increases of 0.25%. At 160, units become nearly independent, *i.e.* only 17% of modules are shared between the units.

4.2.3. *Variation of the demand*

The variations of demand are now studied. The demand is the same for each product at each unit. Results are presented in Fig. 7.

As demand grows, sub-assemblies are less and less shared between the units. When the demand is less than 800, the best solution is to standardize *P′*. When demand varies between 800 and 8000, *B′* is replaced by *B*. Afterwards, until the demand equals 10 000, only *A′* is standardized. Also, when the demand varies from 100 to 10 000, the gain falls dramatically from 30% to 0%. When demand equals 500, the gain is of 5%, and drops down to 3% when demand attains 1000.

4.3. *Case study 2: differentiated facilities*

This case study represents the issue of relocation. The local unit faces the whole demand, with higher production costs than the distant unit. The fixed costs are higher in the distant unit because of

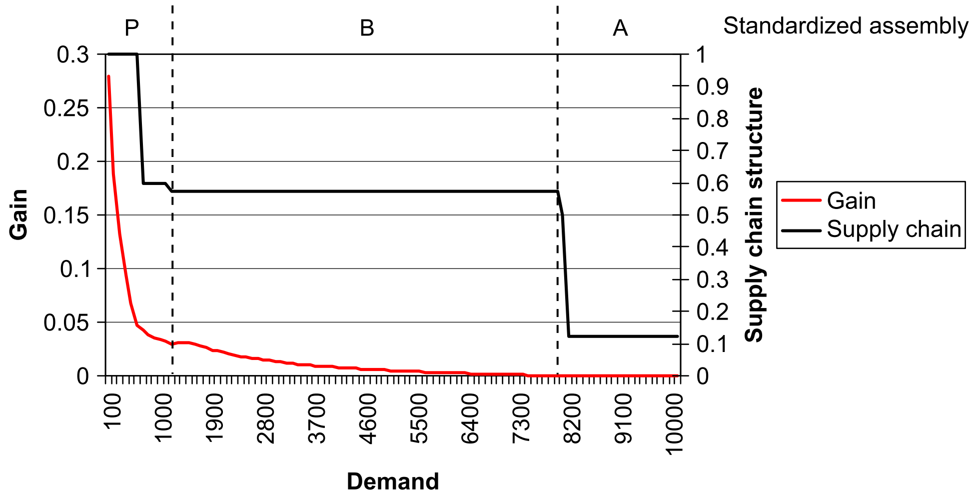

Fig. 7. Gain of standardization and supply chain configuration—demand variation.

Table 7
Case study 2—production units characteristics.

	P demand	*P′* demand	Labour cost
Local unit	3000	3000	25 €/h
Distant unit	0	0	10 €/h
	Transportation cost	Fixed cost for *P*, *P′*, *A*, *A′*, *B* and *B′*	Fixed cost for *D* and *E*
Local unit	60 €/m^3	10 000 €	3000 €
Distant unit	60 €/m^3	20 000 €	6000 €

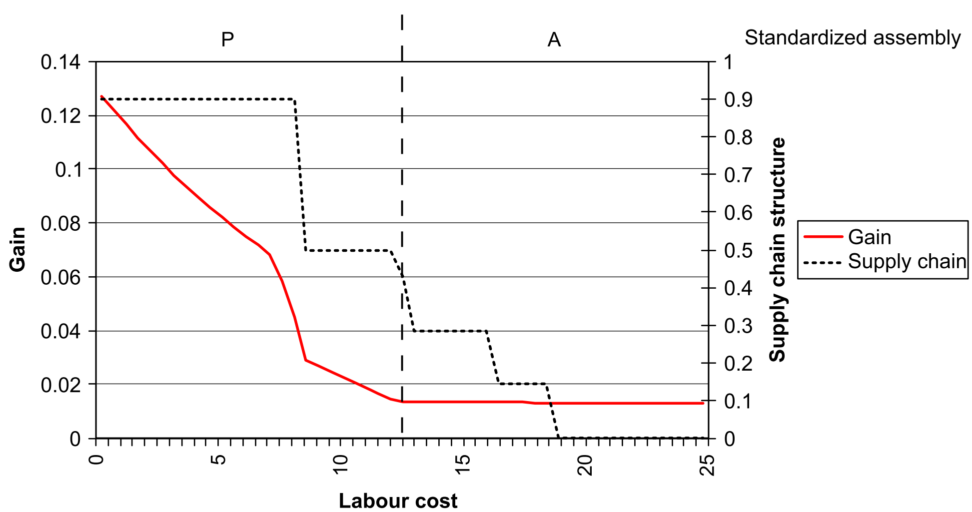

Fig. 8. Gain of standardization and supply chain configuration—labour cost variation ($D=3000$).

the investments required for the setting of the production system. Characteristics are presented in Table 7.

The impact of the following parameters has been tested separately: demand, transportation cost, labour cost and fixed cost. For each data value, three results are given: (1) the modules to standardize, (2) the percentage of relocated sub-assemblies, and (3) the gain of standardization against basic product. In all cases, optimized supply chain is considered.

4.3.1. Variation of the labour cost

The variation of the labour cost only concerns the distant unit. The results are presented in Fig. 8. The figure shows the variations of the gain (0.1 means a gain of 10% from the solution without standardization) and the variation of the relocation (1 for a total relocation, 0 for a total production in the local unit). The demand *D* is fixed to 3000.

When labour cost is low, *i.e.* under 8 €/h, relocation is high and standardization of *P′* has a great impact on the cost. The value of the optimal solution is then 12% above the value of the initial solution. When labour cost is high, above 12€/h, *A′* has to be produced in the local unit. Therefore, *A′* standardization is possible while *P′* or *B′* labour cost would be too high. These results can be expressed as follows: since *A′* standardization cost comes only from transportation, the standardization is not penalized when transportation cost is high. On the contrary, *P′* standardization cost comes from both

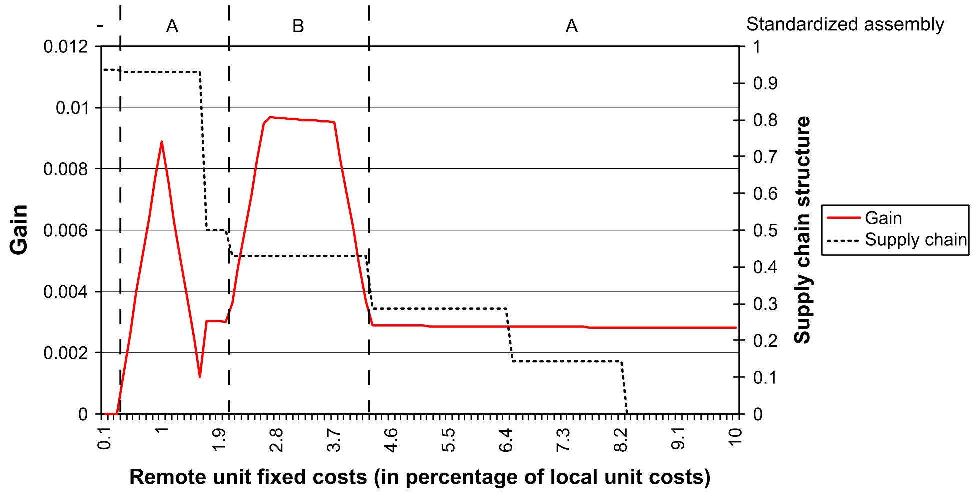

Fig. 9. Gain of standardization and supply chain configuration—fixed cost variation ($D = 5000$).

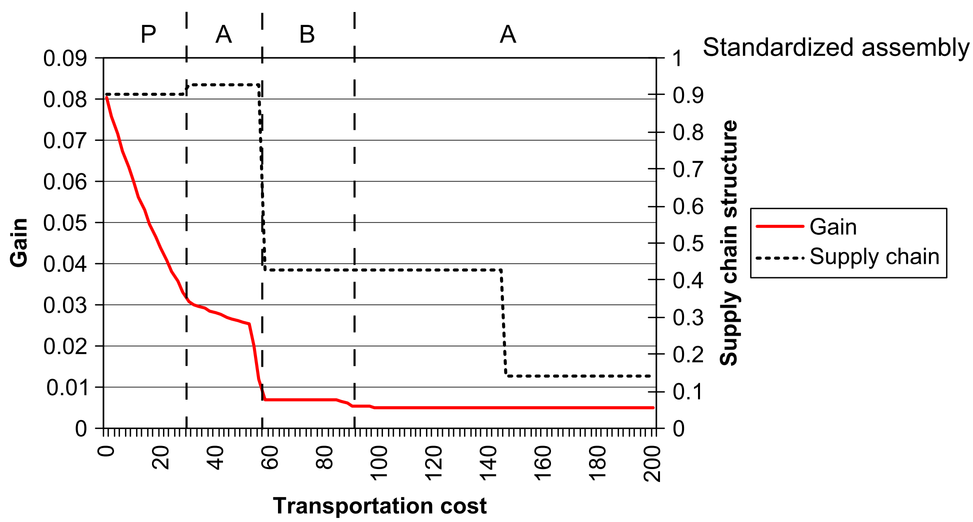

Fig. 10. Gain of standardization and supply chain configuration—transportation cost variation ($D = 2500$).

labour and transportation and is less penalized when labour cost is low.

4.3.2. *Variation of the fixed cost*

The variations of the fixed cost concern also the distant unit. Results are presented in Fig. 9. The figure presents the gain obtained and the impact on relocation. The fixed cost varies from $0.1 \times Cf_i$ to $10 \times Cf_i$, which means that the fixed cost for the distant unit is calculated from the fixed cost in the local production unit. For this test, the demand is fixed to 3000.

The shape of the supply chain configuration curve is similar to the previous one. When the fixed cost grows in the distant unit, the relocation decreases from 1 to 0. The gain obtained by standardization is low. This gain is at most 1%. We note that the gain fluctuates from 0 to 1% and that the fluctuation seems to be not predictable. When fixed cost in the distant unit is between 0.3% and 1% of the cost in the local unit, gain increases as *A* standardization saves one fixed cost. After 1%, fixed cost is higher in the distant unit. Therefore, the relocation becomes less advantageous. Between 2.1% and 4%, relocation becomes costly and only *B* and its sub-assemblies can be relocated, *B* is then standardized. After 4%, only sub-assemblies *D* and *E* can be relocated: so *A′* is the best standardization option as extra cost mainly corresponds to transportation cost.

4.3.3. *Variation of the transportation cost*

The variations of the transportation cost are now studied. Results are presented in Fig. 10. The transportation cost varies from 0 to 200 and the demand is fixed to 2500.

The shape of the curves is quite similar to the observation in Fig. 8. When transportation cost increases, the distant unit is less interesting and the relocation of the production falls to 0. However, a slight difference appears when transportation costs are between 0 and 60. Within this interval, the number of relocated products grows. In fact, between 0 and 30, transportation cost is low enough to avoid the transportation in the supply chain: location choices for each sub-assembly can then be made independently. After 30, transportation cost is high enough to impact the decision. Then, relocation decisions have to be analyzed for each group of sub-assembly. For small transportation cost (less than 30) the whole product is standardized. From 30 to 60, *A′* is replaced by *A*; from 60 to 90, *B′* is replaced by *B*. Afterwards, *A′* is again standardized. At the end, the pattern is similar to the pattern observed for fixed cost variation.

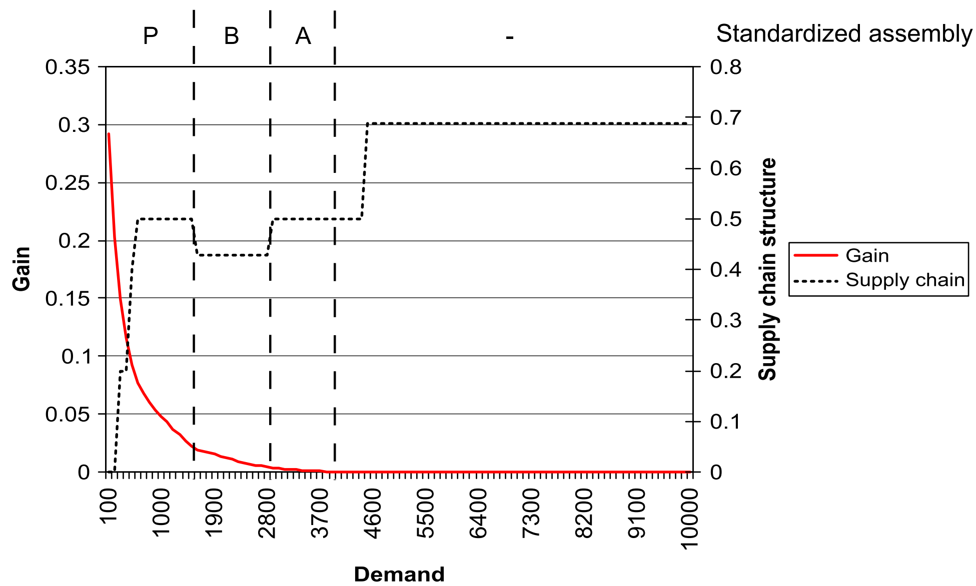

Fig. 11. Gain of standardization and supply chain configuration—demand variation.

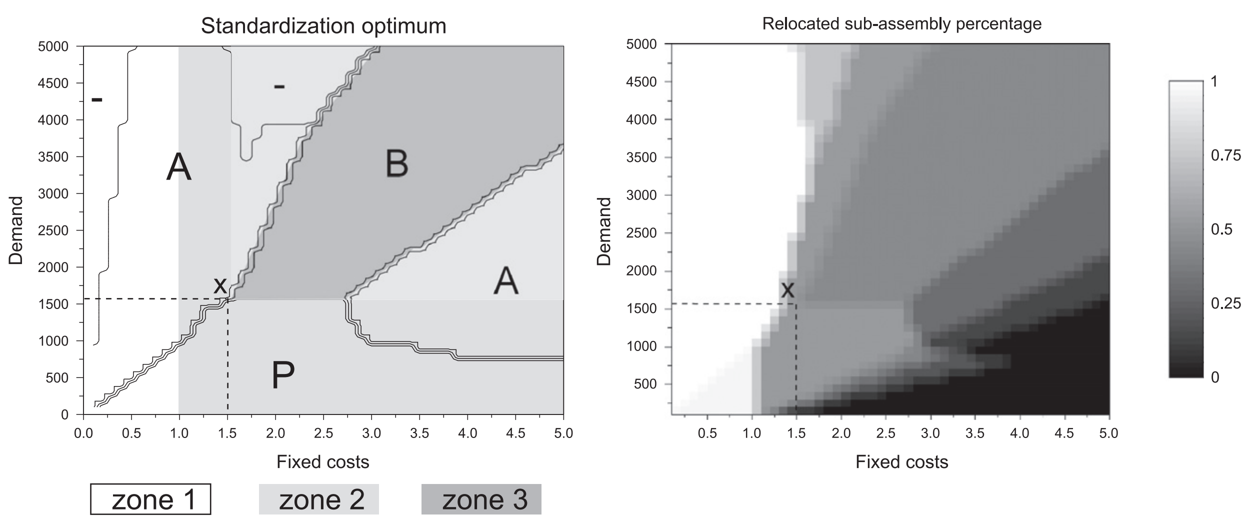

Fig. 12. Demand and fixed cost variation.

The gain obtained by the standardization varies between 8%, when the transportation cost is null, and to 0.5%, when the transportation cost goes to 60. The speed of the decrease is not regular and depends on the standardization politic. The gain is less than 1% when the transportation cost greater or equal to 60.

4.3.4. *Variation of the demand*

The variations of the demand (from 100 to 10 000) are now studied. Results are presented in Fig. 11.

The gain due to standardization falls very quickly when the demand grows. When the demand is small (100), the gain is approximatively 30%, and the best strategy is then to replace P' by P and to product in the local unit. The same standardization strategy holds when the demand increases to 1800, but a part of the production is moved to the distant unit. When the demand varies between 1800 and 3000, only B' is standardized, a part of the production is relocated to the local unit and the gain is less than 2.5%. When the demand varies between 3000 and 4000, only A' is standardized. After 4000, the supply chain design remains the same until 4800. Then, the relocation percentage increases to 70%. Two phenomena are mixed. The inverse correlation between demand and standardization can be explained as follows: when a standardization option is selected, fewer different parts have to be managed, so fewer fixed costs have to be considered. At the same time, for each standardized part, larger quantities will occur, so variable costs for those parts increase. Therefore standardization benefit decreases with demand increase. The correlation between demand and relocation is also natural, as fixed costs become dominated by variable costs when demand increase.

4.3.5. *Mutual impacts of demand and fixed cost on standardization strategies*

To highlight the complexity of the joint product and supply chain design, Fig. 12 shows the best standardization strategy and the supply chain design (which depends on two parameters: the demand and the fixed cost). The results are presented separately but the optimization is done simultaneously.

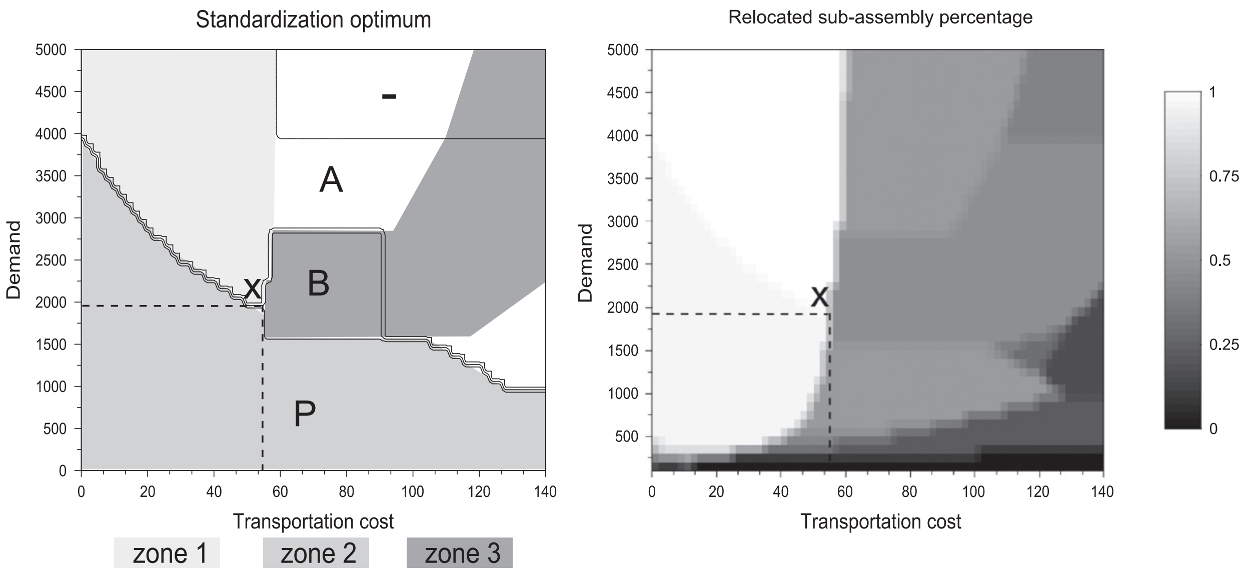

Fig. 13. Demand and transportation cost variation.

On the left chart of Fig. 12, the optimal bill-of-materials is given by either the appropriate BOM or *A*, *B* or *P* standardization. Three zones are considered to facilitate analyzes. On the right chart of Fig. 12, the supply chain structure is given, using the same indicator than the one used in Section 4.2. One hundred percent means that the whole production is relocated, while 0% means that all the manufacturing is done on the local unit.

Consider the point *X* (fixed cost = 1.5, demand = 1550). The optimal solution for *X* is to standardize *A* (left chart), and to relocate half of the sub-assemblies (right chart). If demand increases at 2500, standardization remains the same, but nearly all the sub-assemblies are relocated. If demand decreases at 1300, *P* is standardized and the supply chain remains the same. If fixed costs move to 2.0, *B* is standardized and 43% of the supply chain is relocated.

Fig. 12 presents some typical behaviours of the model. As seen in Fig. 11, standardization decreases with demand. However, some particular effects can be highlighted. In zone 1 (left chart), fixed costs are lower in the distant unit. The behaviour is different in zone 2 where fixed costs are higher in the distant unit. Zone 3 represents the area where *B′* is standardized and produced in the distant unit. When fixed cost is lower, *B′* standardization would be too costly in labour. When fixed cost is higher, distant manufacturing would be too expensive in fixed cost. Both standardization choice and supply chain design are highly sensitive.

4.3.6. *Mutual impacts of demand and transportation cost on standardization strategies*

The complexity of the joint design can also be shown when the parameters are the demand and the fixed cost. Fig. 13 uses the same type of graphics than Fig. 12.

As the previous chart, these results respect the correlation between demand and standardization. Transportation cost variation is less predictable. In zone 1 in Fig. 13, the whole production is done on the distant unit. In zone 2, *P′* is standardized and the supply chain goes from 90% to no sub-assembly relocated. In zone 3, supply chain design remains the same (about 43%), but the product standardization varies: *B′*, then *A′*, then nothing.

When point X is considered, the sensitivity of the model can be highlighted. With small variations of transportation cost and demand, the optimal design can be chosen between three different standardizations and four supply chain structures.

5. Conclusion and further research

The aim of this study was to illustrate the relevance of optimizing simultaneously the supply chain with the product standardization. Using a mixed integer programming model for the supply chain decisions, the impact of the standardization choices on the optimal supply chain has been highlighted. Great impacts were shown on two types of problems: a multi-facility network where facilities are quite similar, and a network in a context of relocation.

Experiment results are used to outline the new model behaviour. A general trend is the correlation between standardization level and gain. This behaviour comes from the nature of the gain, in comparison with the solution without any standardization. When comparing other links between parameters, no generalization can be put forward. Either low or high level of standardization can be optimum with a supply chain where units are independent, as shown in Figs. 6 and 11. The same conclusion can be made for the gain and for the supply chain structure. Gain can be obtained when supply chain is globalized, as seen in Figs. 5, 8 and 10. Besides, opposite conclusion or no correlation occurs in Fig. 9. As expected, demand is a key parameter. Variation of the demand has a great impact on cost and allows important benefit for standardization (up to 30% in our case studies). Transportation has a limited impact on standardization, because the adjustments mainly occur within the supply chain. Fixed cost has a very different impact in the two case studies: with similar units, the impact on gain and on supply chain is high; with different sort of units, fixed cost plays yet a role on the supply chain structure, but the impact on the gain is very limited.

A small example shoved that simultaneous decisions on standardization and on the supply chain structure may lead to better situations than sequential optimizations. This has been highlighted by different experiments. The impact of standardization can be huge in terms of cost. The issue is that the decision changes quickly when some parameters of the problem vary. Although the trends may sometime be anticipated, some behaviours can be difficult to predict. The complexity of the global optimization is shown with the three-dimensional-charts of Figs. 12 and 13.

There is a strong challenge to work on this problem because potential gains can be huge. When only a few sub-assemblies can be standardized, all possible configurations can be tested for standardization. For each configuration, the ideal structure of the supply chain and the cost can be determined. This method has been used for these experimentations. However, when standardization possibilities are numerous, it becomes necessary to include the standardization options in the mathematical model. The complexity of the model implies a thorough search for effective methods in order to improve routing.

As the decisions are very sensitive to variations of the parameters, it would be interesting to develop tools which allow sensitivity analysis of the proposed solutions. Figs. 12 and 13 show that certain points are at the frontiers of three or four zones, each zone corresponding to a different strategy in terms of standardization and allocation of production. The aim would thus be to determine, for each parameter, an interval within which the overall decision remains stable.

The more challenging perspective of this work is to model the combined problem considering simultaneously the product standardization and the product allocation. This problem can be expressed as a MILP. However, the solution is highly complex due to the increase in the number of variables and constraints, each standardization possibility producing a new binary decision variable. Particular interests have to be given on solution methods. An iterative method which optimizes sequentially product and supply chain could be investigated, but with the risk to never find an optimal solution.

References

Agard, B., Penz, B., 2009. A simulated annealing method based on a clustering approach to determine bills of materials for a large product family. International Journal of Production Economics 117, 389–401.

Appelqvist, P., Lehtonen, J., Kokkonen, J., 2004. Modelling in product and supply chain design: literature survey and case study. Journal of Manufacturing Technology Management 15, 675–686.

Barajas, M., Agard, B., 2009. Fuzzy product configuration based on market segmentation to form a family of products. In: 42nd CIRP Conference on Manufacturing Systems, Grenoble, France.

Briant, O., Naddef, D., 2004. The optimal diversity management problem. Operations Research 52, 515–526.

Cordeau, J., Pasin, F., Solomon, M., 2006. An integrated model for logistics network design. Annals of Operations Research 144, 59–82.

da Cunha, C., Agard, B., Kusiak, A., 2007. Design for cost: module-based mass customization. IEEE Transactions on Automation Science and Engineering 4, 350–359.

Dowlatshahi, S., 1996. The role of logistics in concurrent engineering. International Journal of Production Economics 44, 189–199.

El Hadj Khalaf, R., Agard, B., Penz, B., 2009. An experimental study for the selection of modules and facilities in a mass customization context. Journal of Intelligent Manufacturing, doi:10.1007/s10845-009-0247-0.

ElMaraghy, H.A., Mahmoudi, N., 2009. Concurrent design of product modules structure and global supply chain configurations. International Journal of Computer Integrated Manufacturing 22, 483–493.

Fixson, S.K., 2007. Modularity and commonality research: past developments and future opportunities. Concurrent Engineering 15, 85–111.

Fournier, X., Agard, B., 2007. Improvement of earliness and lateness by postponement on an automotive production line. International Journal of Flexible Manufacturing Systems 19, 107–121.

Gupta, S., Krishnan, V., 1999. Integrated component and supplier selection for a product family. Production and Operations Management 8, 163–182.

Kusiak, A., Huang, C.C., 1996. Development of modular products. IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part A 19, 523–538.

Lamothe, J., Hadj-Hamou, K., Aldanondo, M., 2006. An optimization model for selecting a product family and designing its supply chain. European Journal of Operational Research 169, 1030–1047.

Melo, M., Nickel, S., Saldanha-da-Gama, F., 2009. Facility location and supply chain management—a review. European Journal of Operational Research 196, 401–412.

Montreuil, B., Poulin, M., 2005. Demand and supply network design scope for personalized manufacturing. Production Planning & Control 16, 454–469.

Paquet, M., Martel, A., Desaulniers, G., 2004. Including technology selection decisions in manufacturing network design models. International Journal of Computer Integrated Manufacturing 17, 117–125.

Paquet, M., Martel, A., Montreuil, B., 2008. A manufacturing network design model based on processor and worker capabilities. International Journal of Production Research 46, 2009–2030.

Peidro, D., Mula, J., Poler, R., Lario, F., 2009. Quantitative models for supply chain planning under uncertainty: a review. The International Journal of Advanced Manufacturing Technology 43, 400–420.

Pine, B.J., 1993. Mass Customization: The New Frontier in Business Competition. Harvard Business School Press.

Riopel, D., Langevin, A., Campbell, J., 2005. The network of logistics decisions. In: Logistics Systems: Design and Optimization. Springer, US, pp. 1–38.

Riopel, D., Langevin, A., Campbell, J.F., 1998. Integrating Logistics in Concurrent Product and Process Design. Cahiers du GERAD.

Salvador, F., Rungtusanatham, M., Forza, C., 2004. Supply-chain configurations for mass customization. Production Planning & Control 15, 381–397.

Shapiro, J.F., 2001. Modeling the Supply Chain. Duxbury Resource Center.

Su, J.C., Chang, Y.L., Ferguson, M., 2005. Evaluation of postponement structures to accommodate mass customization. Journal of Operations Management 23, 305–318.

Thanh, P.N., Bostel, N., Peton, O., 2008. A dynamic model for facility location in the design of complex supply chains. International Journal of Production Economics 113, 678–693.

Zhang, X., Huang, G.Q., Rungtusanatham, M.J., 2008. Simultaneous configuration of platform products and manufacturing supply chains. International Journal of Production Research 46, 6137–6162.