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► To cite this version:

Youcef Mechouar, Vincent Hovelaque, Carl Gagné, Christian Vigouroux. Effect of raw material substitution on sustainable facility location under carbon tax policy. CIGI QUALITA 2019, Jun 2019, Montréal, Canada. halshs-02129628

HAL Id: halshs-02129628

<https://shs.hal.science/halshs-02129628>

Submitted on 15 May 2019

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Effect of raw material substitution on sustainable facility location under carbon tax policy

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Abstract—Current environmental issues and challenges have a direct impact on firms’ strategic and operational decisions in terms of location, transport and production. In this work, we propose to investigate a firm that reconsiders its location and production decisions under a carbon tax policy on transport-related carbon emissions. Traditionally sustainable facility location models under carbon pricing scheme assume that firm supply is given (complementary essential inputs). In our framework, input mix and location decision are allowed to vary simultaneously. The relationship between the production level and the input quantities is captured through a production function that enables different degrees of substitutability among the raw material quantities. The results show that variation in the elasticity of substitution across the different types of inputs affects the firm location and supply choices. Moreover, it plays a crucial role in controlling the level of the pollution stemming from commodity shipping through adjustments in the input supply quantities. Our analysis also reveals the sensitivity of the facility location decision to a higher carbon tax when firm has a high flexibility on its ability to substitute among the input quantities.

Keywords—facility location, raw material substitution, environmental issues, carbon tax, sustainability.

1 INTRODUCTION

Despite the many international agreements aimed at reducing greenhouse gas emissions (GHGs), the main cause of global warming, the alarming situation persists [IPCC, 2018]. According to the annual report published by the Global Carbon Project (GCP), greenhouse gas emissions worldwide in 2018 have been unprecedented for seven years, at more than 2% [Le Quéré et al., 2018]. Freight transport sector still remains one of the major contributors to GHG emissions and it expected to increase in the coming decades [UNFCCC, 2018] primarily as a result of the growing globalization of trade and geographical dispersion of supply chains [Cristea et al., 2013; Hoen et al., 2013]. Technological innovations relate to energy improvements for vehicles and fuels can slow significantly transport-related carbon emissions but do not counterbalance them [Chapman, 2007; Gagné et al., 2012]. Hence, public authorities design policies to mitigate the growth of emissions

generated by transportation, and ultimately its external effect [Lee et al., 2008; Hoen et al., 2014].

Carbon tax on fossil fuels, such as gas, oil and their derivatives, which emit a lot of CO_2 , appears as a central public instrument in the face of the climate threat, and this in addition to other instruments such as emissions trading system (ETS) [Sumner et al., 2011]. Its principle is to reach all consumers of fossil energy, individuals and businesses, to encourage them to change their practices. In addition, it is expected that the carbon tax rate increases progressively and regularly to give a price signal incentives to reduce the use of fossil fuels [Sterner, 2007]. For example, in France, carbon tax started in 2014 and went from 7 euro per ton of CO_2 to 44.60 euro per ton in 2018, and it had nearly to double to 86.2 euro per ton in 2022 [Chaire économie du climat, 2018]. In this context of regular upward revaluation of the carbon tax, manufacturers with a high dependency on transportation, have to adapt, in the more or less long term, their logistics of physical flows and networking in response to changes in the price of raw materials and rising of fuel prices [Diabat and Al-Salem, 2015; Alhaj et al., 2016].

Sustainable facility location appears to be a way to address the environmental issues related to transportation [Terouhid et al., 2012]. The establishment of a new production facility requires from the companies to specify the geographical coordinates of their supply chain elements as it is based on transportation distances [Daniel et al., 1997]. Therefore, location choice affects distances traveled by commodities and transport mode selection and thus the ecological footprint stemming from commodity shipping.

As revealed in several studies, the impact of public regulations that rely on price signal on location decisions are often linked to their effects on the production decisions [Hurter et Martinich, 1989; Wu et al., 2017]. It is therefore relevant and appropriate to carry out evaluation of carbon taxation impacts on the firm spatial and logistical organization that takes into account the characteristics of the firm production method.

Traditionally sustainable facility location models under carbon taxation as developed to date, describe firm production technology by the bill of materials (BOM) which assumes that the input proportions are fixed [see, e.g., Ramudhin et al., 2010; Chaabane et al., 2012]. This representation does not allow to capture the production technology of some industrial sectors such as the agri-food sector where the input proportions can be varied to produce a given level of output for regulatory, shortage, innovation or even raw material price volatility reasons [Hsu, 1997; Balakrishnan and Geunes, 2000].

Motivated by the importance to study policies that mitigate carbon emissions, the objective of this paper is to investigate the impact of the carbon tax on a firm's production-location decision when the input materials are substitutable. Specifically, the firm chooses its location in the Euclidean plane with respect to its suppliers and final markets for its output. The firm incurs sourcing and transportation costs. In addition to these costs, the firm also incurs a carbon tax, based on the distance and the carbon intensity of transportation mode. The relationship between the production level and the combinations of inputs is captured in our framework through a production function, namely Constant Elasticity of Substitution (CES) which allows different degree of substitution across input quantities of production [Peeters et Thisse, 2000].

We first show that the conflict between the environmental and cost criteria vanishes for a low degree of substitution (firm can hardly change the production decisions) and the same transport mode for the supply and delivery sides. In a "high" degree of substitution (firm has more flexibility to substitute among the input quantities), the introduction of a carbon tax significantly reduced transport-related carbon emissions as the firm chooses facility location and input proportions that induce a lower level of emissions. Our analysis also reveals that higher carbon tax is more likely to cause a significant jump in the firm location choice and dramatical changes in production decisions when firm has a high flexibility on its ability to substitute among the input quantities.

The remainder of this paper is organized as follows. In the next section, we present the related literature. The production-location problem (PLP) incorporating transport-related carbon emissions under carbon taxation is described in section 3. Subsequently, we specify the production technology with material substitution effect and the optimization process. In section 5, we conduct a numerical study to determine the effects of rising carbon prices with different degrees of substitution. The last section provides our conclusions.

2 RELATED LITERATURE

The literature on sustainable facility location that incorporates environmental regulations related to carbon emissions mitigation, is connected to this research. In the sequel, we will discuss the relevant publications on this topic. It is now classically admitted that sustainability is based on three pillars (economic, environmental, and social), which have a complex correlation and interdependence [Hassini et al., 2012]. The decision of where to locate a facility is at the intersection

of several research disciplines in economics and operations management and has been extensively studied by making use of, in particular, operations research techniques with a purely economic perspective [ReVelle and Eiselt, 2005]. For many years now, researchers have focused increasing attention on improving the sustainability behind facility location decisions by considering not only the economic criteria but also environmental and social criteria. A comprehensive description and classification of the most recent studies and contributions can be found in some reviews [Terouhid et al., 2012; Chen et al., 2014; Eskandarpour et al., 2015].

Environmental issues such as pollution, greenhouse effect and emissions of carbon dioxide stemming from transportation, manufacturing, raw material extraction, disposal and other sources are new constraints for industrial companies that environmental regulations have made unavoidable. Researchers in the field of operations management have shown, in recent years, growing interest for carbon policies such as carbon tax, carbon cap and cap-and-trade [Waltho et al., 2018]. They investigate their effects and efficiency on supply chain network design (SCND) in general and in firm location decision in particular. Dekker et al. (2012) consider Ramudhin et al. (2010) to be among the first to study the sensitivity of location decisions on carbon market trade. The latter authors consider the problem of sustainable supply chain configuration (e.g., suppliers, subcontracting, distribution, production and transport technology choices) and introduce emission constraints imposed by law (or by the company itself) with a given carbon price using a Mixed-Integer Linear Programming model (MILP). The analyses of an example from the steel industry reveal that when the emission cap shrinks or the carbon price increases, decision-makers select production schemes and transport modes that are more environmentally friendly. Chaabane et al. (2012) extend the previous model to a Multi-Objective Linear Programming approach (MOLP) and consider the Life-Cycle Assessment (LCA) method to measure carbon emissions. They study the effect of carbon emission allowance and tradable carbon credits and conclude from a case study of the aluminum industry that supply managers have two options. First, when reducing GHG emissions cost through clean technology investments and sustainable supply chain configuration (internal mechanisms) is more expensive than buying carbon credits (external mechanisms), decision-makers buy carbon credits to be compliant with the regulatory limits. Otherwise, they should opt for the greener production and transport strategies. Diabat and Simchi-Levi (2009) consider a MILP model for a supply chain network design with a cap on the amount of CO_2 emitted. They use an experimental example to show that when the cap becomes tighter, the total supply chain cost increases as the firm opens more manufacturing and distribution centers (increasing fixed costs) to reduce transport emissions. Rezaee et al. (2017) propose a discrete location problem with uncertainty on demand and carbon price. They conclude from an office furniture industry case study that a higher carbon price leads to a sustainable supply chain design but not necessarily according to a linear

relationship. Wu et al. (2017) investigate the effect of rising carbon prices on off-shoring and near-shoring decisions for a single producer between two distinct regions (north and south) according to different scenarios of production costs, emissions, and the distance that separates the two regions.

Although the existing literature incorporates carbon policies that mitigate carbon emissions in facility location decisions, the production technology is usually neglected or assumed either explicitly or implicitly to be an assembly supply chain modeled by a bill of materials (BOM) which implies a fixed proportions between the input quantities of production (firms supply are assumed to be given). As noted in the introduction, they did not pay attention to the substitution effect through the input quantities in some industries. Peeters and Thisse (2000) are among the first to emphasize the importance of a raw material substitution effect on facility location decision. Using numerical examples, they show that small variations on the elasticity of substitution among input quantities may lead to significant jumps in the optimal firm location. However, the environmental issues related to the transport of commodities are left aside on their study.

Based on this review, we highlight a lack of location models that simultaneously consider environmental issues and address the role of production technology in the relationship between location decision and environmental intervention mechanisms. Our work contributes to the literature by investigating the effects of the carbon tax policy on production-location decision and the resulting ecological impact when the input quantities can be substituted captured through a production function that allows different degrees of substitutability.

3 MODEL DESCRIPTION

In this section, we propose to reconsider the Production-Location Problem (PLP) with transport-related carbon emission considerations. Consider a firm F that produces and delivers one output to K downstream markets noted M_k ($k = 1, \dots, K$). Each market has a deterministic demand q_k ; therefore, F has to satisfy the sum of all individual demands :

$$q^0 = \sum_{k=1}^K q_k.$$

Downstream demand is assumed to be fixed to focus only on carbon emissions stemming from commodity shipping. Consider also different upstream markets, in which each raw material input i is provided from a fixed market S_i ($i = 1, \dots, I$) with an amount noted s_i . All stakeholders have a fixed and determined location, and the firm F seeks to define its “best” location noted y in a given eligible area of the Euclidean space. We consider a single facility problem with a mono-product setting to focus on the interrelations between carbon price and firm location choice through the production decisions. The firm produces the sum of all individual demands in one shot (static period) without constituting inventories and with an infinite capacity system. The possible production techniques are described by a production function $f : R^I \rightarrow R$

that links the total production level to raw material needs such as:

$$q^0 = f(s_1, \dots, s_I).$$

Each unit of raw material i has a mill price w_i , a transport cost per unit of distance and per unit of input t_{iy} supported by the firm, and a carbon footprint coefficient per unit of distance and per unit of input α_{iy} from S_i to F . Each unit of output has a transport cost per unit of distance and per unit of output t_{yk} borne by the firm and a carbon footprint coefficient per unit of distance and per unit of output α_{yk} from F to M_k . Fixed transport costs are not considered since the firm is at an aggregate strategic level of decision; that is, no economies of scale emerge. In addition, the firm is in a price taker situation and therefore has no influence on input prices. Let τ the unit carbon price per unit of carbon emissions. The public authorities often set the initial rate. However, its effectiveness depends on its evolution. Then, in a sustainability context, it is expected that carbon tax will increase progressively and regularly over time since the damage caused by GHG emissions will have a greater negative impact in the future than currently.

Firm F , supplier S_i and market M_k are located on the Euclidean plane at points $y(a_0, b_0)$, $m_i(a_i, b_i)$ and $m_k(a'_k, b'_k)$ respectively. Let $d_{iy} = [(a_i - a_0)^2 + (b_i - b_0)^2]^{\frac{1}{2}}$ and $d_{yk} = [(a'_k - a_0)^2 + (b'_k - b_0)^2]^{\frac{1}{2}}$ be the Euclidean distances between the firm location y , and input source location m_i and the output market location m_k respectively.

Following Peeters and Thisse (2000), the objective of the firm is to identify the best location y and define its supply strategy, determined by the vector $s = (s_1, \dots, s_I)$, to minimize its cost function while respecting its production technology. The firm cost function $C(y, s)$ can then be expressed as:

$$C(y, s) = \sum_{i=1}^I w_i s_i + \sum_{k=1}^K t_{yk} d_{yk} q_k + \sum_{i=1}^I t_{iy} d_{iy} s_i + \tau \left(\sum_{i=1}^I \alpha_{iy} d_{iy} s_i + \sum_{k=1}^K \alpha_{yk} d_{yk} q_k \right),$$

where $\sum_{i=1}^I w_i s_i$ is the inputs purchasing cost; $\sum_{k=1}^K t_{yk} d_{yk} q_k$ is the downstream transportation costs; $\sum_{i=1}^I t_{iy} d_{iy} s_i$ is the upstream transportation cost; and $\tau \left(\alpha_0 d_0 q^0 + \sum_{i=2}^I \alpha_i d_i s_i \right)$ is transport-related carbon emissions cost due to related upstream and downstream transportation activities based on the distance, the quantity of freight carried, and the carbon intensity of transportation mode. We assumed that the transport emissions are linearly proportional to the number of product shipped over a distance as usually considered in the literature [Waltho et al., 2018].

The optimal economic efficient location that minimizes firm cost C is then described by:

$$C^* = \underset{y,s}{\text{Min}} C(y, s) \quad (1)$$

subject to

$$\sum_{k=1}^K q_k = f(s_1, \dots, s_I) \quad (2)$$

$$y \geq 0 \quad (3)$$

$$s \geq 0 \quad (4)$$

Constraint (2) requires that production possibilities should be respected, which means that the firm will use the production techniques that will allow it to meet the total demand (technology constraint). Constraints (3) and (4) are the nonnegativity constraints.

This model also contains an interesting formulation representing the total carbon footprint generated during upstream and downstream transport phases noted as E and expressed as follows:

$$E(y, s) = \sum_{i=1}^I \alpha_{iy} d_{iy} s_i + \sum_{k=1}^K \alpha_{yk} d_{yk} q_k$$

Transport-related carbon emissions minimizing location are then given by

$$E^* = \underset{y,s}{\text{Min}} E(y, s)$$

with respect to constraints (2), (3) and (4). The establishment of this second formulation would enable us to compare optimal firm location according to two scenarios: (i) The location y^* that minimizes the firm's total cost (economic efficiency), and (ii) the location y^e that minimizes firm's carbon footprint (environmental efficiency). The aim of this comparison is to examine whether the carbon tax can be used as an effective instrument to induce a cost-minimizing location to arrive at an emission-minimizing outcome.

In the sequel, we specify the functional form of the production function f that links the production level to the inputs combination and we design the optimization process for the extended PLP.

4 TECHNOLOGY AND OPTIMIZATION PROCESS

We represent the production technology f via a production function called Constant Elasticity of Substitution (CES). The underlying assumption of the CES production function is that input quantities be can substituted, in part, for each other to achieve the same level of production. The CES function has the advantage of being very economical in terms of the parameters to be calibrated. In return, it imposes a constant elasticity of substitution (measure of the degree of substitutability) between the inputs used for production [Hoff, 2004]. Its functional form is defined as follows in our case with I inputs :

$$q^0 = f(s_1, \dots, s_I) = \left[\sum_{i=1}^I \beta_i s_i^\phi \right]^{\frac{1}{\phi}} \quad (5)$$

with:

- $\beta_i > 0$ referred as distribution parameters. They represent the specific efficiency with which each quantity of inputs is used or, in other words, the state of the technology that is specific to them. To simplify they are normalized such that $\sum_{i=1}^I \beta_i = 1$.
- ϕ is a parameter representing the possibilities of substitution among inputs such as $\phi = \frac{\rho-1}{\rho}$ where ρ is the elasticity of substitution between input quantities with $\rho \in (0, +\infty)$ then $\phi \in (-\infty, 1)$.

The advantage of using an CES formulation for the production function is that it is exible and encompasses several other functional forms, depending on the value of the parameter of the elasticity of substitution ρ which expresses the difficulty of replacing one input with the other. In the Table I are summarized the three polar special cases of the CES function with their characteristics. If the proportions of the inputs quantities are fixed (the Leontief function), the elasticity of substitution is nil (no substitution is possible). The other extreme case is infinite elasticity of substitution: no difficulty in replacing one input with the other (the linear function). The function of Cobb-Douglas is "in between" and has a unitary elasticity of substitution. For example, mixing feeds requires combining several quantities of cereals (wheat, barley, soybeans, etc.) to cover their nutritional needs. The amounts of cereals in a food recipe can be varied but to a limited extent to meet the nutritional requirements of foods (this is a classic problem of mixing inputs).

TABLE I
SPECIAL CASES OF CES PRODUCTION FUNCTION

ρ	Production function	Characteristic
$\rho = 0$	Leontief	Inputs are perfect complements
$\rho = 1$	Cobb-Douglas	Inputs are imperfect substitutes
$\rho = +\infty$	Linear	Inputs are perfect substitutes

Specifying the functional form of the production function f allows us to solve the PLP model in two steps: first, the firm defines its supply strategy (technology design) and then determines its best location. We define the inputs demand by determining the optimal set of supply quantities s^* that minimizes the total upstream cost (production cost) noted c at location y . It can be expressed as follows:

$$c(y) = \underset{s}{\text{Min}} \sum_{i=1}^I (w_i + T_{iy} d_{iy}) s_i \quad (6)$$

with respect to constraints (5) and (4) where $T_{iy} \equiv t_{iy} + \tau \alpha_{iy}$ with $i = 1; \dots, I$ is the total unit transportation cost per unit of distance and per unit of input from S_i to F . It is composed of a variable logistic cost part and an environmental cost part of carbon emissions. Therefore, establishing a carbon tax on carries means increasing the variable unit transport cost. Each input demand i will be noted $s_i(y)$. As the production function

f is homogeneous, the production cost function at location y can be written as [Hurter et Martinich, 1989]:

$$c(y) = \psi(y) q^0, \quad (7)$$

where $\psi(y)$ is the location-specific marginal production cost at location y . It can be shown that in the case of CES production function [Peeters and Thisse, 2000]:

$$\psi(y) = \left[\sum_{i=1}^I (\beta_i)^{\frac{-1}{\phi-1}} (w_i + T_{iy} d_{iy})^{\frac{\phi}{\phi-1}} \right]^{\frac{\phi-1}{\phi}} \quad (8)$$

Then the demand for each input i is given by:

$$s_i(y) = \left[\frac{\psi(y) \beta_i}{w_i + T_{iy} d_{iy}} \right]^{\frac{-1}{\phi-1}} q^0 \quad (9)$$

Thus, the optimal firm location y^* that minimizes the firm's total cost (economic efficiency) is given by:

$$C_y^* = \text{Min}_y C(y) = \text{Min}_y \sum_{k=1}^K [\psi(y) + T_{yk} d_{yk}] q_k \quad (10)$$

The vector of input quantities s does no longer appear explicitly in the total cost function C . Then, the minimization of total cost C returns to minimize the downstream cost.

In the same way, we identify optimal firm location y^e that minimizes the firm's footprint (environmental efficiency). Thus, the minimization of total transport-related carbon emissions E returns to minimize downstream transport-related carbon emissions.

5 EXPERIMENTAL ANALYSIS

In this section, we conduct a numerical study to gain insights from the extended PLP. More specifically, we investigate how firm's location decision, input mix and ecological outcome will be affected in response to a change in the carbon tax rate according to different degree of substitutability among the input quantities. We are using a set of hypothetical data, selected as representative of a large number of experiments data conducted by Peeters and Thisse (2000). In the following, we describe these data and discuss the findings.

We consider ten final markets and five input sources whose coordinates can be found in Table II and in Table III, respectively. All stakeholder points are depicted in the Euclidean space in Figure 1 with a weighting of the market points according to their requirements described in the Table II. The per-unit procurement of inputs are equal to 1. We further assumed unit transportation and emissions rates for all the inputs and the output. This situation may correspond to a firm that uses a single mode of transportation for its supply and delivery sides.

We consider three cases for the CES production function by increasing the value of the elasticity of substitution: $\phi = -5$ (no substitution) used as a benchmark case; $\phi = -1$ (low substitution); and $\phi = 0.25$ (high substitution), where the distribution parameters $\beta_i = \frac{1}{I}$ with $I = 5$ in our study.

Because the production-location problem do not necessarily have globally concave or convex objective function, classical methods of convex optimization or numerical analysis do not guarantee a global solution. We then solved the previous instances by discretizing the solution space and implementing the Generalized Reduced Gradient (GRG) algorithm in the case of nonlinear program with non-negativity constraints for variables. Using standard practice we choose multiple starting locations including markets, suppliers and gravity center point which minimizes the access to the output markets (see Figure 1). We did not take into account the geographical constraints related to the accessibility to the stakeholder locations.

Case of no substitution $\phi = -5$

The results of this case are summarized in Table IV. The first column indicates the tax level; the second and third columns report the optimal firm location for cost and emissions minimizing locations respectively.

When inputs must always be combined with a fixed proportion to be fully used, it appears that cost-minimizing location corresponds to pollution-minimizing location regardless of the level of carbon tax. The efficient economic and environmental optimal firm locations correspond to the solution of the center of gravity method that minimizes the total transport costs to and from the different destinations according to the weighted average formula (Love et al., 1988). Moreover, the efficient economic and environmental optimal firm locations are close to the gravity center point (46,97 ; 44,68) which minimizes the access to the output markets represented in Figure 1.

Because of the structure supply (the production inputs are perfectly complementary), the introduction of carbon tax does not modify the location decision and supply planning and then the total transport-related carbon emissions (GHG emissions are independent of τ) but it does increase the total firm cost as shown in Figure 2 for $\phi = -5$. As all unit transportation costs are equal as well as all unit emissions levels, a carbon tax is not justified for firms which use only one transportation mode.

Case of low substitution degree $\phi = -1$

The results of this case are summarized in Table V.

As the combination of the different inputs becomes less strict, firm is looking for a location where the input delivered price ($w_i + T_i d_{iy}$) is low as possible. In other words, the cost-minimizing location is not necessarily that minimizes the total transportation costs as for the previous case but a compromise emerges between the transportation and sourcing costs. Thus, it is more economically and environmentally efficient for the firm to locate at the supplier S_3 , to carry the other inputs from their sources, and to deliver the output to the markets regardless of carbon tax level (see Table V). Despite its more distant position from the gravity center point which minimizes the access to the output markets, the location at supplier S_3 allows the firm to void the transport and environmental costs related to the input 3 and to reduce the delivered price of the input 5 given its proximity to supplier S_3 (see Figure 1) and

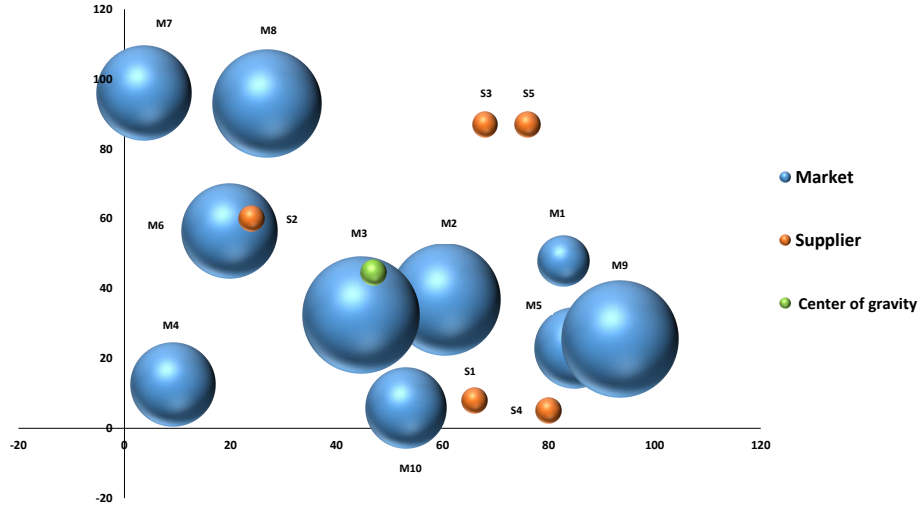


Fig. 1. Stakeholder locations in the Euclidean space.

TABLE II
COORDINATES AND DEMAND OF OUTPUT MARKET POINTS

k	1	2	3	4	5	6	7	8	9	10
M_k	82.80 48.00	60.40 36.90	44.60 32.50	9.10 12.50	84.90 22.90	19.80 56.50	3.70 96.00	26.90 93.00	93.40 25.50	53.10 5.90
q_k	4.00	19.00	21.00	11.00	10.00	14.00	14.00	18.00	21.00	10.00

TABLE III
COORDINATES OF SUPPLIERS

i	1	2	3	4	5
S_i	66.00 8.00	24.00 60.00	68.00 87.00	80.00 5.00	76.00 87.00

TABLE IV
COST AND EMISSIONS MINIMIZING LOCATIONS ACCORDING TO CARBON TAX CHANGES

Tax level	Cost minimizing location	Emissions-minimizing location
0	(59.48, 49.71)	(59.48, 49.74)
1 – 10	(59.48, 49.72)	(59.48, 49.74)

TABLE V
COST AND EMISSIONS MINIMIZING LOCATIONS ACCORDING TO CARBON TAX CHANGES

Tax level	Cost minimizing location	Emissions-minimizing location
0	S_3	S_3
1 – 10	S_3	S_3

to reduce the delivered price of the other inputs. Indeed, the analyzes show that the location of the supplier S_3 is the best location that minimizes the cost to access to the other suppliers by assuming that the input quantities are uniformly distributed (the inputs are equi-distributed for the five suppliers).

Even without the introduction of the carbon tax (i.e., $\tau =$

0), the total cost falls by 7.36% and the level of emissions by 9.50% compared to the previous case of no substitution (see Figure 2). The marginal cost and emissions of production at S_3 location is less than at (59.48, 49.74) location when input proportions are almost fixed. When the carbon tax rate increases, it is more cost-effective for the firm to purchase more quantities of the input 3 and input 5 for which it paid less carbon tax, and reduce the use of other inputs. However, as the firm has a low flexibility on its ability to substitute among the input quantities, the level of transport-related emissions slightly shrinks with a higher carbon tax (see Figure 2 for $\phi = -1$).

Case of high substitution degree $\phi = 0.25$

The results of this case are summarized in Table VI.

When the substitutability of inputs is high and $\tau < 3$, it is more profitable for the firm to locate at the supplier S_1 , to carry the other inputs from their sources, and to deliver the output to the markets, however, from a purely ecological point of view, emissions-minimizing location is at S_2 (see Table VI). Even

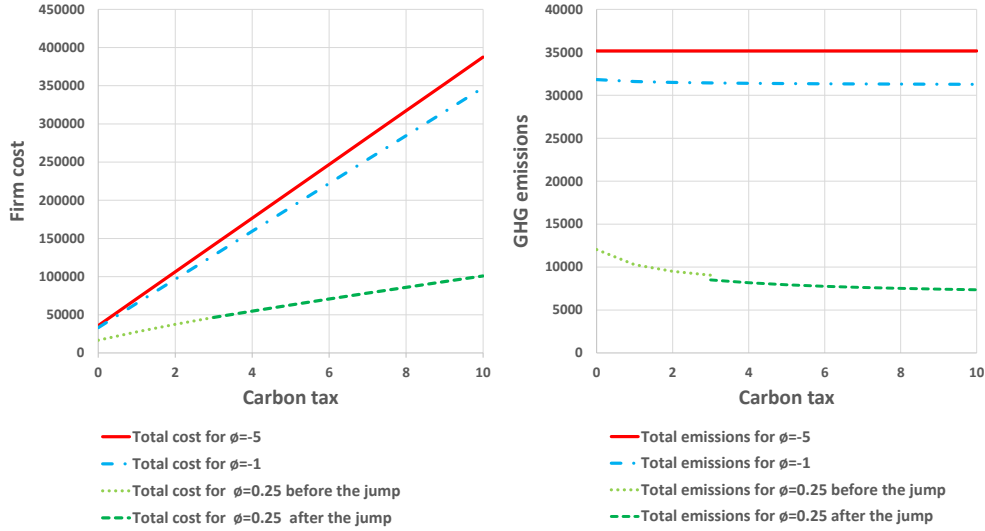


Fig. 2. Firm cost and pollution evolutions according to carbon tax changes with different degrees of substitution.

TABLE VI
COST AND EMISSIONS MINIMIZING LOCATIONS ACCORDING TO CARBON TAX CHANGES

Tax level	Cost minimizing location	Emissions-minimizing location
0 – 2	S_1	S_2
3 – 10	S_2	S_2

without the introduction of the carbon tax (i.e., $\tau = 0$), the total cost falls by 53.57% (resp. 49.88%) and the level of emissions by 65.78% (resp. 62.19%) compared to the case where $\phi = -5$ (resp. $\phi = -1$) (see Figure 2). The level of transport-related emissions substantially shrinks with a higher carbon tax as a larger weight on emissions (due to a higher carbon tax) in the effective shipping cost shifts the input proportions in the direction that lowers emissions.

When $\tau \geq 3$, the firm jumps to supplier S_2 in order to re-optimize its total cost (the marginal production cost at S_2 is less than at S_1 when $\tau \geq 3$), inducing a new substitution among input quantities and, thus, a new shipping pattern. Even if the initial trend is to substitute input 1 for other input, thus creating additional distortion of the other source of inputs, the increase in carbon tax affects the net locational pull. This direct effect forces the optimal location toward the source of input 2 that minimizes the total carbon emissions and creates new substitution back toward input 2. Such a relocation decision causes a discontinuity and a downward jump of carbon emissions level. The total rate of reduction of emissions at the critical price ($\tau = 3$) triggering the firm relocation is estimated at around 6.19%. Furthermore, the emission reduction rate after the critical price continues to decline as the optimal amount of input 2 (the less polluting input per unit of shipped input in this case) increases gradually due to a higher carbon tax.

This case illustrates how a marginal change in carbon tax can cause dramatic changes in firm optimal location and the combination of inputs when firm has a high flexibility on its ability to substitute among the input quantities.

6 CONCLUSION

In this paper, we have reconsidered the production-location problem with carbon emissions considerations. The firm simultaneously decides its location and input supply under a production technology constraint to satisfy a deterministic demand. The integration of the environmental issue related to transport-related carbon emissions in PLP is relevant, given the current challenges and issues of sustainable supply chain design.

Our paper addresses a major issue. When assessing the carbon taxation policies, the existing literature disregards one major problem: *a higher carbon tax changes the combination of inputs*. Our analysis reveals that the study of carbon taxation policy should be conducted within a framework in which production technology can allow substitution among inputs.

The model only considers emissions from transportation but not from production. As the driver of the main result is the possibility of input substitution, the emission implications due to changes of BOM should be considered under a more general setting where the carbon tax is levied on both transportation- and production-related emissions.

Our work is quite preliminary for specific policy recommendations. It should be considered a first step to illustrate the importance of production technology on the implications of environmental mechanisms with an economic signal on location decisions.

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Response to Reviewers

We would like to thank the reviewers for careful and thorough reading of this paper and for the thoughtful comments and constructive suggestions, which help to improve the quality of this paper. Our response follows (the reviewer's comments are in italics).

----- REVIEW 1 -----

PAPER: 43

TITLE: *Effect of raw material substitution on sustainable facility location under carbon tax policy*

AUTHORS: *Youcef Mechouar, Vincent Hovelaque, Carl Gaigne and Christian Vigouroux*

Overall evaluation: 2 (accept)

----- Overall evaluation -----

In this article the authors propose to examine the problem of production-location with carbon emission considerations. Carbon emissions related to transport are considered in this study. But the study is only a first step to illustrate the importance of production technology on the environment.

Remarks

1. Clarify this sentence “*Therefore, the output rate should be considered as endogenous in order to capture these additional facets of the problem*”.

2. Respect the text style (table title in bold and lowercase)

3. Respect the style below to put the authors' names

PRENOM NOM1, PRENOM NOM2, ...

1 AFFILIATION

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-----Reply-----

We appreciate the positive feedback from the reviewer.

- With regard to the clarification of the sentence: “*Therefore, the output rate should be considered as endogenous in order to capture these additional facets of the problem*”. As suggested by the reviewer, we explained the underlying idea in this sentence. The model only considers emissions from transportation but not from production. As the driver of the main result is the possibility of input substitution, the emission implications due to changes of bill of materials (BOM) should be considered under a more general setting where the carbon tax is levied on both transportation- and production-related emissions.
- With regards to the respect the text style and the style to put the authors names As suggested by the reviewer, we took into account these remarks.

----- REVIEW 2 -----

PAPER: 43

TITLE: *Effect of raw material substitution on sustainable facility location under carbon tax policy*

AUTHORS: *Youcef Mechouar, Vincent Hovelague, Carl Gaigne and Christian Vigouroux*

Overall evaluation: 3 (strong accept)

----- Overall evaluation -----

Papier théorique très intéressant.

Mon souhait principal est d'avoir une explication plus détaillée, à base d'exemples si nécessaire, de la fonction f qui traduit les niveaux de substituabilité des composants. Que veulent dire en pratique les cas $p=0, 1, \infty$. C'est d'autant plus important que si l'on n'a pas très bien saisi ces différents cas, l'interprétation des résultats devient difficile.

Par ailleurs la description de la résolution du problème, numérique si j'ai bien compris (Generalized Reduced Gradient), devrait un peu plus détaillée.

Détails :

- page 5 : "in Table 5 et in Table 5" . Au passage les numéros des tableaux sont en chiffres romains (I II III IV V) et ces tableaux sont référés 1, 2, 3, 4 et 5.

- les 2 derniers paragraphes avant la section conclusion sont très répétitifs.

-----Reply-----

Nous apprécions les commentaires positifs du reviewer.

Explication détaillée de la fonction de production f

L'utilisation des facteurs de production dépend des techniques de production. La fonction de production exprime ces relations techniques. A court terme, les proportions des facteurs de productions sont souvent fixes mais à plus ou moins long terme il est possible de changer de technique. Par exemple, la fabrication de voitures devient de plus en plus robotisée : plus de capital et moins de travail. Le taux de substitution technique indique les facilités ou les difficultés de remplacement d'un facteur par un autre.

1. Facteurs absolument complémentaires (l'élasticité de substitution entre les facteurs de production est nulle)

Dans ce cas, les proportions entre les facteurs, d'une part, et les proportions entre les facteurs et la production, d'autre part, sont considérées comme fixes. Décrire un processus de production à l'aide d'une fonction dans laquelle les facteurs sont de cette nature, revient à dire qu'il n'y a qu'une seule méthode pour produire un certain bien. Par exemple, les cimenteries utilisent plusieurs ingrédients dans la fabrication du béton et les proportions de ces ingrédients sont rigidelement fixées par la technologie du béton et la qualité du produit. Toute variation de ces proportions résulterait dans un changement de la nature du produit.

2. Facteurs partiellement substituables

Lorsque l'élasticité de substitution entre les facteurs de production tend vers 1 on obtient une fonction Cobb-Douglas : les facteurs sont partiellement substituables. Le mélange d'aliments pour le bétail nécessite de combiner plusieurs quantités de céréales (blé, orge, soja, etc.) pour couvrir leurs besoins nutritionnels. Les quantités de céréales dans une recette alimentaire peuvent être variées mais dans une mesure limitée afin de respecter l'apport nutritionnel des aliments (il s'agit d'un problème classique de mélange d'intrants).

3. Facteurs parfaitement substituables

Dans ce cas extrême, l'élasticité de substitution entre les facteurs de production est infinie. En d'autres termes, un nombre constant d'unités d'un facteur peut remplacer une unité de l'autre tout en gardant la production constante, quelle que soit la combinaison initiale des facteurs. L'un ou l'autre de ces facteurs est donc superflu : ils constituent un seul et même facteur, à toutes fins pratiques. Ce cas est d'un usage très restreint.

Explication de la méthode Generalized Reduced Gradient (GRG)

La méthode GRG est un algorithme permettant de résoudre des programmes non linéaires de structure générale. Le concept de base de la méthode GRG implique la linéarisation de la fonction objective et les contraintes non linéaires au niveau d'une solution locale avec l'équation de développement de Taylor. Ensuite, on utilise le concept de méthode à gradient réduit qui divise l'ensemble de variables en deux sous-ensembles de variables (basique et non-basiques) le concept d'élimination de variables implicites afin d'exprimer la variable basique par la variable non-basique. Enfin, les contraintes sont éliminées et l'espace variable est déduit uniquement des variables non basiques.

Smeers, Y. (1977). Generalized reduced gradient method as an extension of feasible direction methods. *Journal of optimization theory and applications*, 22(2), 209-226.

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Détails

- Page 5 : Nous avons harmonisé les références aux tableaux et leurs numérotations.
- Nous avons supprimé le paragraphe qui se répète avant la conclusion.