This article was downloaded by: [Huazhong University of Science & Technology]
On: 24 August 2012, At: 18:44
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

International Journal of Production Research
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tprs20

Supply chain coordination with emissions reduction incentives

Mohamad Y. Jaber [a], Christoph H. Glock [b] & Ahmed M.A. El Saadany [a]

[a] Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Ontario, Canada

[b] Chair of Business Management and Industrial Management, University of Wuerzburg, Wuerzburg, Germany

Version of record first published: 16 Feb 2012

To cite this article: Mohamad Y. Jaber, Christoph H. Glock & Ahmed M.A. El Saadany (2012): Supply chain coordination with emissions reduction incentives, International Journal of Production Research, DOI:10.1080/00207543.2011.651656

To link to this article: http://dx.doi.org/10.1080/00207543.2011.651656

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

International Journal of Production Research
2012, 1–14, iFirst

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

Supply chain coordination with emissions reduction incentives

Mohamad Y. Jaber[a]*, Christoph H. Glock[b] and Ahmed M.A. El Saadany[a]

[a]*Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Ontario, Canada;*
[b]*Chair of Business Management and Industrial Management, University of Wuerzburg, Wuerzburg, Germany*

(*Received 8 March 2011; final version received 16 December 2011*)

The European Union Emissions Trading System (EU-ETS) is considered one of the main legislative systems that are set up to reduce emissions and protect the environment. Most of the works in the literature approach this system from a legislation and/or global point of view. Little has been done to examine this system from the perspective of the user. This work is believed to be the first to consider the EU-ETS system in a supply chain and operations management context. A two-level (vendor–buyer) supply chain model with a coordination mechanism is presented while accounting for greenhouse gas (GHG) emissions from manufacturing processes. Different emissions trading schemes are considered, and possible combinations between these schemes are presented. The developed model could be found useful by mangers who wish to jointly minimise the inventory-related and GHG emissions costs of their supply chains when penalties for exceeding emissions limits are considered. Numerical examples are presented, and results are discussed.

Keywords: supply chain coordination; emissions trading system; inventory; environment

1. Introduction

Actions on climate change have been topping priority lists in many countries, especially with increasing pressures from the public. Carbon dioxide (CO_2) emissions were estimated at 40 billion tons in 2002 and are expected to reach 58 billion tons by 2030 (Enkvist *et al*. 2007). The European Union Emissions Trading System (EU-ETS), which was initiated in 2005 as a method to reduce greenhouse gas emissions, has been viewed by the European Commission for Climate Change as the 'first and biggest international scheme for the trading of greenhouse gas emission allowances'.

The EU-ETS involves more than 11,000 electricity power-generation stations and industrial plants in about 30 countries. This system is expected to result in 21% lower CO_2 emissions than the 2005 levels by 2020. The EU-ETS depends on the 'cap and trade' concept, where companies have a limit on greenhouse gas emissions, and anything above and beyond this limit is charged; however, the cost to limit these emissions is less than the charge. Kruger and Pizer (2004) reported that penalties for CO_2 emissions in excess of surrendered allowances are €40 per ton. Some countries (e.g. Germany) impose a one-time fine that is up to €500,000 (European Environmental Agency, http://www.eea.europa.eu/). In case the CO_2 emissions are less than the specified limit, companies are allowed to trade or keep unused allowances. The implementation of the EU-ETS had some good results, with some significant changes and improvements (including auctioning of allowances) expected by 2013. A similar program to EU-ETS was implemented in Los Angeles, California, which has the worst pollution level among the major cities in the USA, to cut the emissions of oxides of nitrogen (NO_x) and oxides of sulphur (SO_x). Although the average prices for emissions are expensive (ranging between \$160 and \$2220 per ton) and the average trade size is high, there seems to be a constant growth in the size and number of trades, with trade prices being associated with the location of the emitting facility and the type of pollutants it emits (Gangadharan 2004).

Dobos (2005) examined how much pollution rights are there to trade and what are the effects of trading on the production–inventory policies. He found that introducing emissions trading, while assuming that the pollution may be described by a non-decreasing and convex function of the production rate, results in smoothing the optimal production–inventory strategy but with higher costs. Soleille (2006) emphasised the importance of accessibility (i.e. affordable transaction costs, easier compliance verification, penalty application in case of non-compliance, etc.), market activity to maintain the fluidity of demand and supply in order to decrease price volatility, and the presence

*Corresponding author. Email: mjaber@ryerson.ca

ISSN 0020–7543 print/ISSN 1366–588X online
© 2012 Taylor & Francis
http://dx.doi.org/10.1080/00207543.2011.651656
http://www.tandfonline.com

of strong governmental legislations to guarantee the success of emissions trading schemes. The importance of integrating environmental issues into logistics and inventory systems decision-making process was strongly emphasised in Bonney (2009) and Bonney and Jaber (2011).

Of course, not every emissions tax system is welcomed and appreciated. Mayor and Tol (2007) noted that the amount of emissions produced by the UK aviation industry increased by 90% between 1990 and 2004, and is expected to continue growing. They examined the combined effect of applying four different taxes of carbon dioxide emissions and found such a policy to be less costly. Their rationale to explain this finding is that some taxes are considered as a 'revenue-raising tax reform promoted under the guise of climate policy'. This finding was echoed in the way US Carbon tax was presented.

Carbon dioxide (CO_2) emissions are estimated to be responsible for half of the man-made greenhouse effect. The United States has considered limiting the US carbon emissions to complement the EU-ETS through a revenue-neutral carbon tax, which is easier to model than the cap-and-trade model, where the tax is applied for every ton of CO_2 emissions (Metcalf 2009). In his paper, Metcalf (2009) stated that the carbon tax rate should reflect the social cost of carbon emissions. He identified this cost as the social marginal damages of emissions, which has various estimates ranging from \$3 to \$95 per ton. Metcalf (2009) also surveyed the literature and found that the average recommended carbon tax for CO_2 emissions is in the range of \$15–20 per ton. He argued that the tax is more efficient than the trading system, as the later promotes trading with price volatility, while the former is a more disciplined stream.

Floros and Vlachou (2005) studied the impact of a carbon tax on CO_2 emissions and found that considering a carbon tax as a policy instrument in the Greek industry, which was estimated at \$50 per ton, enticed industries to reduce direct and indirect CO_2 emissions. Tomlinson *et al*. (2010) considered the renewal or refurbishment of electrical and mechanical equipment in industrial facilities and showed how to quantify the environmental cost of refurbishment with respect to the associated carbon emissions by considering the whole life of equipment. The authors also considered the design, the raw materials used, the manufacturing method, the transportation mode used, and the disposal technique of an industrial unit to calculate the associated CO_2 emissions, and recommended using their method for a better estimation of investment appraisal and procurement strategies.

Although there are several works in the literature on greenhouse gas emissions that consider policy design and the effect of introducing a new legislation on the environment, our review of the literature did not come across a study that considers the same issue from a user's (or a manufacturer's) point of view. That is, how should one deal with new policies, and which factors should be considered in running day-to-day operations? In the next section, a model that optimises the joint production-inventory policy for a two-level (vendor–buyer) supply chain with greenhouse gas (CO_2) emissions cost, penalties for exceeding the emissions limit(s), and inventory-related costs is developed. Numerical examples that address six research questions are solved and the results are discussed in Section 3. The paper is summarised and concluded in Section 4.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

2. Model

This section develops a mathematical programming problem for a two-level supply chain (vendor–buyer) when emissions trading is considered. It is assumed that greenhouse gas emissions are a function of the vendor's production rate. The objective of the developed model is to determine the optimal production rate (subsequently the joint lot sizing policy) that minimises the total supply chain cost taking into consideration emissions certification limit, penalties for exceeding the emissions quota and the capital invested to increase the emissions limit by purchasing new certificates. Next, we list the notations and decision variables, make assumptions where necessary, and develop the mathematical model.

Notations:

d	demand rate (unit/year);
h_m	manufacturer's holding cost (\$/unit/year);
h_r	retailer's holding cost (\$/unit/year);
S_m	manufacturer's setup cost (\$);
S_r	retailer's ordering cost (\$);
a	emissions function parameter (ton·year^2/unit^3);
b	emissions function parameter (ton·year/unit^2);

c emissions function parameter (ton/unit);
C_{ec} emissions tax (\$/ton);
$C_{ep,i}$ emissions penalty (\$/year) for exceeding emissions limit i;
E greenhouse gas (CO_2) emissions (ton/unit);
E_{li} emissions limit i (ton/year);
α minimum production–demand ratio, where $\alpha \geq 1$;
n number of emissions limits;
P_{max} maximum attainable production rate (unit/year);
Y_i emissions limit variable for emissions limit i, which is 1 if the emissions exceed the allowable limit i and 0 otherwise;
P_{Eli} minimum production rate that satisfies emissions limit i (unit/year);
P_o production rate that minimises greenhouse gas emissions per unit produced (unit/year);
P_{min} minimum production rate (unit/year), $P_{min} = \alpha d$

where

$$E_m C = EdC_{ec} + \sum_{i=1}^{n} Y_i C_{ep,i}.$$

Decision variables:

P manufacturer's production rate, $P > d$ (unit/year);
λ vendor–buyer coordination multiplier.

Supply chain coordination is achieved when the operations of the manufacturer and the retailer are optimised collectively, instead of independently (e.g. Jaber and Zolfaghari 2008; Glock 2012). A simplified two-level (vendor–buyer) supply chain model is presented, with λ being the manufacturer lot size multiplier of the retailer's order quantity, and the value of λ being reflected in the manufacturer's cycle inventory, as shown in Figure 1 (e.g. Goyal *et al*. 2003, El Saadany and Jaber 2008).

As depicted in Figure 1, the vendor (manufacturer) delivers its order in λ (positive integer) shipments to the buyer (retailer) to satisfy the supply chain demand at a rate d over time T. The supply chain cost, ψ_{sc}, is the sum of the manufacturer's setup and holding costs per unit of time, and the retailer's ordering and holding costs per unit of time as a function of λ and P, and it is computed as

$$SSC = \psi_{sc} = \sqrt{2d(S_m + \lambda S_r)\left[h_m\left(1 - \frac{d}{P} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right]}. \quad (1)$$

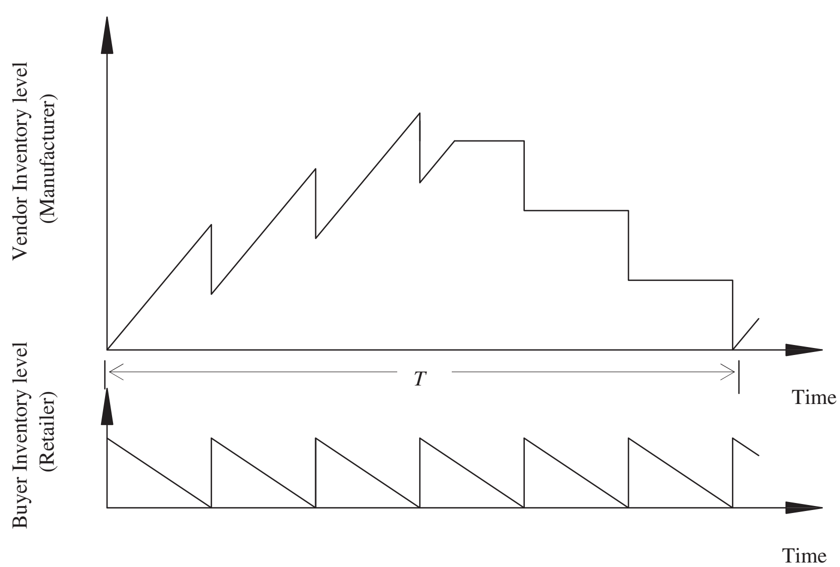

Figure 1. Example of a two-level supply chain with $\lambda = 6$.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

The derivation of Equation (1) is provided in Appendix 1. The relationship between the production rate of a process and the rate of generating greenhouse gas (CO_2) emissions (ton per unit) is given from Bogaschewsky (1995) as:

$$E = aP^2 - bP + c. \tag{2}$$

The case where emissions can be expressed as a convex function of the production rate or equipment speed, as described in Equation (2), has been empirically validated for car engines (TÜV Rheinland 1987). Furthermore, it has also been shown that the energy consumption for various production processes follows a similar pattern to that described above (e.g. Gälweiler 1960, Pack 1966, Fandel 1991). Since the consumption of energy is usually associated with the generation of greenhouse gas emissions, it is therefore reasonable to infer to a function of the form given in Equation (2).

An emissions cost, EdC_{ec}, is added to the total cost function to account for every ton of greenhouse gas emissions released into the environment, as in the US carbon emissions tax system. In addition, as in the case of EU-ETS, we assume that a supply chain is penalised by paying $C_{\mathrm{ep},i}$ once its emissions exceed a given limit, $E_{\mathrm{l}i}$, per year. Therefore, the total cost per unit of time, ψ, is the sum of the supply chain inventory-related and greenhouse gas emissions costs per unit of time including applicable penalties, which is given from Equations (1) and (2) as:

Minimise

$$TC = \psi(P, \lambda) = \sqrt{2(S_{\mathrm{m}} + \lambda S_{\mathrm{r}})\left(h_{\mathrm{m}}\left(1 - \frac{d}{P} + \frac{1}{\lambda}\right) + \frac{h_{\mathrm{r}}}{\lambda}\right)d} + EdC_{\mathrm{ec}} + \sum_{i=1}^{n} Y_i C_{\mathrm{ep},i} \tag{3}$$

Subject to:

$$Y_i = \begin{cases} 1 & \text{if } Ed > E_{\mathrm{l}i} \\ 0 & \text{else} \end{cases}, \quad \text{where } i = 1, 2, \ldots, n \tag{4}$$

$$\alpha d \le P \le P_{\max} \tag{5}$$

$$\lambda \ge 1, \quad \text{integer value.} \tag{6}$$

The total cost function in Equation (3) is composed of three components, which are the supply chain cost, the cost of emissions and the penalty cost for exceeding the allowed limit(s). If only the supply chain costs as given in Equation (1) are considered, then the (locally) optimal production rate $P_{\min} = \alpha d$ balances the inventory holding, setup and ordering costs (Glock 2010, 2011). Considering only the emissions cost, in contrast, results in a (locally) optimal production rate P_{o}, which minimises the emissions cost function in Equation (2) at $P_{\mathrm{o}} = b/(2a)$. Any deviation from P_{o} by either increasing or decreasing the production rate results in higher emissions cost. Penalties depend on the value of emissions and, accordingly, on the value of P_{o}. The fact that varying the production rate may be associated with an additional production cost is not considered in this model for reasons of simplicity, as it will only add another effect to the model, which enforces or dampens a deviation from $P_{\min}$. The reader is referred to Glock (2010, 2011) for a discussion of this aspect. Condition (4) ensures that Y_i takes on the value 1 when the corresponding emissions limit $E_{\mathrm{l}i}$ is exceeded, and condition (5) restricts the production rate to vary between a minimum and a maximum value, which may be due to technical reasons.

Therefore, the optimal solution P^* is equal to $P_{\min}$ or P_{o}, or lies between these two values, which brings us to the following lemma:

Lemma 1: *The optimum production rate can be determined by the following two conditions.*

$$\text{If } P_{\mathrm{o}} \ge P_{\min} = \alpha d, \text{ then } \alpha d \le P^* \le \frac{b}{2a}. \quad \text{If } P_{\mathrm{o}} < P_{\min} = \alpha d, \text{ then } P^* = \alpha d.$$

Accounting for carbon emissions taxes and emissions allowances in the total cost function permits studying the impact of the EU and US greenhouse gas emissions reduction programmes on the total cost of operating a supply chain and on the managerial decisions taken by the supply chain partners. Further, by combining both approaches, we are able to study the impact of a third greenhouse gas emissions reduction system that combines emissions allowances and emissions taxes, and that, to the authors' knowledge, has not yet been studied in the literature

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

(or been applied in practice). In the following section, we provide numerical examples to illustrate the behaviour of the supply chain for alternative greenhouse gas emissions reduction schemes.

The per unit of time supply chain inventory-related cost, SSC, is the only cost term dependent on λ. To simplify and accelerate the search for an optimal solution, i.e. P^*, we determine upper and lower bound values for λ. To do so, assume that λ holds a real number and that SSC is differentiable over λ, where SSC is convex since $\partial^2 SSC/\partial\lambda^2 > 0\ \forall\lambda > 0$. By setting the first partial derivative of SSC equal to zero, i.e. $\partial SSC/\partial\lambda = 0$, and solving for λ to get

$$\lambda(P) = \sqrt{\frac{S_{\mathrm{m}}(h_{\mathrm{m}} + h_{\mathrm{r}})}{S_{\mathrm{r}} h_{\mathrm{m}}(1 - d/P)}}, \tag{7}$$

where $\lambda(P)$ holds a minimum value of $\lambda(P_{\min} = \alpha d) = \sqrt{S_{\mathrm{m}}(h_{\mathrm{m}} + h_{\mathrm{r}})/S_{\mathrm{r}} h_{\mathrm{m}}(1 - 1/\alpha)}$ and a maximum value of $\lambda(P_{\max} = b/2a) = \sqrt{S_{\mathrm{m}}(h_{\mathrm{m}} + h_{\mathrm{r}})/S_{\mathrm{r}} h_{\mathrm{m}}(1 - 2ad/b)}$. If for example $\lambda = 3.45$ for a given value of P, then $\lambda = 3$ if $\psi(P,3) < \psi(P,4)$ and $\lambda = 4$ otherwise. So, substituting $\lambda(P)$ in Equation (1) reduces Equation (3) to a function of a single decision variable, P, for which constraint (6) will no longer be needed.

The mathematical problem described above can be simply solved using mathematical software, such as Maple, MathCad, or Mathematica, or by using Excel. However, it may be useful to provide the reader with a step-by-step solution procedure, which is given below:

Step 1: Set $Y_i = 0$ for $i = 1, \ldots, n$ and $k = \lambda = \lambda' = 1$.
Set $TC(\widehat{P}) = TC' = \infty$.

Step 2: Compute P_{o}. If $P_{\mathrm{o}} < P_{\min} = \alpha d$, then $P^* = \alpha d$. If $P_{\mathrm{o}} \geq P_{\min} = \alpha d$, then conduct a full search over the interval $[\alpha d, b/(2a)]$ to find P^* that minimises Equation (3).

Step 3: Find λ from Equation (7) that minimises Equation (3). If $\lambda \neq \lambda'$, set $\lambda' = \lambda$ and go to Step 2.
If $C_{\mathrm{ep}\,i} = 0$ for $i = 1, \ldots, n$, set $\widetilde{P} = P$ and go to Step 6.

Step 4: Compute E as in (2). If $E_{\mathrm{d}} > E_{\mathrm{lk}}$, set $Y_{\mathrm{k}} = 1$. If $k < n$, set $k = k + 1$ and repeat Step 4.
Set $\widetilde{P} = P$ and compute $TC(\widetilde{P})$ according to Equation (3).

Step 5:

$$\text{Set} = \widehat{P} = \mathrm{Max}\left[\frac{b}{2a} - \sqrt{\frac{b^2}{4a^2} + \frac{E_{\mathrm{l}k-1} - cd}{ad}}, ad\right]$$

If $\widehat{P} > \alpha d$, set $Y_{\mathrm{k}} = 0$, and compute $TC(\widehat{P})$ according to Equation (3) and as shown in Steps 2 and 3.

Step 6: If $TC(\widehat{P}) < TC(\widetilde{P})$, $\widetilde{P} = \widehat{P}$
If $k > 1$, set $k = k - 1$, and go to Step 5.

Step 7: Set $P^* = \widetilde{P}$ and compute $TC(P^*)$ according to Equation (3) and as shown in Steps 2 and 3.

Step 1 initialises the algorithm. First, emissions penalties are neglected by setting all Y_i equal to zero. Steps 2 and 3 compute the optimal values of P and λ. For the solution found in Steps 2 and 3, Step 4 computes the number of emissions limits that are violated and adds the corresponding penalty costs to the total costs. In Steps 5 and 6, the break points in the emissions penalty function are tested for optimality. The best solution found in this procedure is then selected as the final solution in Step 7.

3. Numerical examples

In the previous section, a mathematical model was proposed that considers greenhouse gas emissions as well as emissions penalties and emissions taxes in a supply chain model. In this section, we intend to answer the following research questions:

(1) Which production rate should a manufacturer choose if it faces a carbon tax?
(2) Which production rate should a manufacturer choose if it faces a carbon emissions penalty?
(3) Which production rate should a manufacturer choose if it faces a combination of a carbon tax and emissions penalty?

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

(4) Can it be beneficial for a manufacturer not to fulfil the entire annual demand if it faces emissions penalty and a capacity constraint?
(5) Which production rate should a manufacturer choose if it can buy additional emissions allowances on the market, and how much emissions allowances should be bought?
(6) How does cooperation between a manufacturer and a retailer impact the generation of greenhouse gas emissions in a supply chain?

3.1 *Example 1: impact of carbon taxes*

In this example, we address the first research question and examine the case of a carbon tax system with no emissions penalty. Let $d = 1000$ units/year, $h_m = \$60$/unit/year, $h_r = \$30$/unit/year, $S_m = \$1200$, $S_r = \$400$, $a = 3 \times 10^{-7}$ ton·year^2/unit^3, $b = 0.0012$ ton·year/unit^2, $c = 1.4$ ton/unit, $\alpha = 120\%$, $C_{ec} = \$18$/ton, and $C_{ep} = \$0$/year (no emissions penalty). The mathematical programming problem described in Equations (3)–(6) generates an optimal solution at $P^* = 1724.63$ units/year and $\lambda^* = 3$ where the total cost is $TC = \psi^* = \$20{,}288.53$/year. When the system operates at its minimum production capacity, $P_{min} = 1200$ units/year, the minimum total cost, $TC = \$20{,}442.56$/year, occurs at $\lambda = 5$. On the other hand, when the system operates at the production rate that minimises the emissions function described in Equation (2), the minimum total cost, $TC = \$20{,}570.56$/year, occurs at $\lambda = 3$. The model was investigated for varying values of $P \in [1200, 3000]$, while minimising the total cost. The behaviour of E_mC, SSC and $TC = SSC + E_mC$ are shown in Figure 2.

The results indicate that the optimal emissions rate does not necessarily result in a minimum total cost, TC, since $P^* = 1724.80 < P_o = 2000$. This suggests that considering a non-optimal production rate that corresponds to minimum emissions results in an unnecessary increase in the total cost, TC. This also shows the importance of considering both supply chain inventory-related and emissions costs when defining an optimal production rate. Further, it is clear that when a carbon tax is imposed on the system, we have $P^* \in [P_{min}, P_o]$, i.e. $1200 < 1724.80 < 2000$.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

3.2 *Example 2: impact of emissions penalty*

In this example, we address the second research question and consider the case of a penalty that is imposed if emissions exceed a specified limit. In this example, a carbon tax is not applied ($C_{ec} = 0$). Let $\alpha = 110\%$, $C_{ep} = \$4000$/year

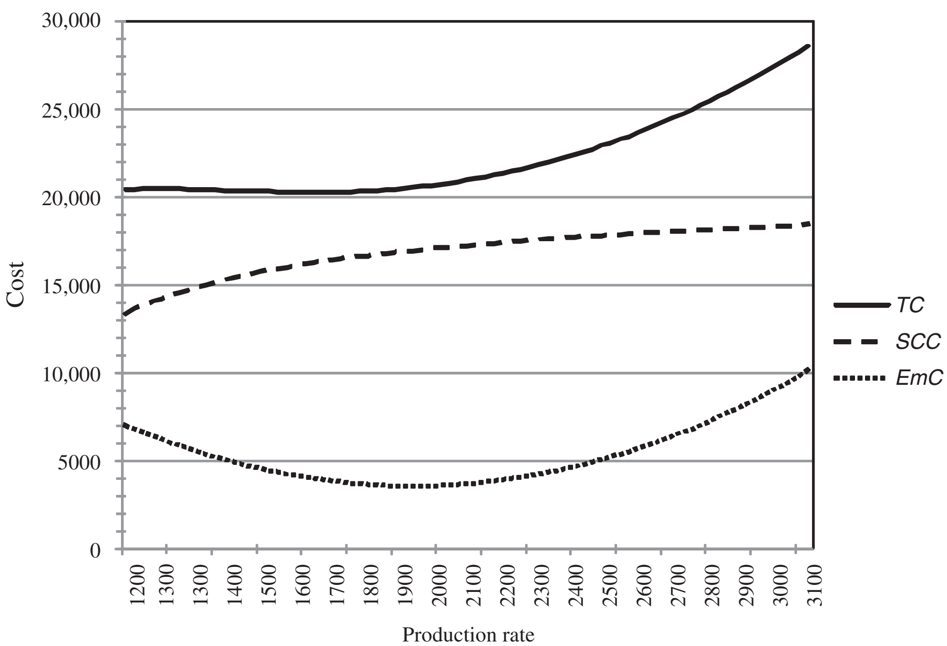

Figure 2. Behaviour of emissions cost (E_mC), supply chain cost (SCC), and total cost (TC) for varying values of P, where $C_{ep} = 0$ and $C_{ec} = 18$.

and $E_{i1} = E_{\max} = 220$ tons/year, while the remaining input parameters are the same as those of Example 3.1. The total cost function, TC, is at its minimum when $P^* = P_{\min} = 1100$ units/year, $\lambda^* = 7$, and $Y_1 = 1$ where the total cost is \$16,103.45/year. When the system operates at $P_o = b/2a = 2000$ units/year, the best solution occurs at $\lambda = 3$ where the minimum cost is \$16,970.56/year. The model was investigated for varying values of $P \in [1100, 3000]$ for $C_{ep} = \$4000$/year and $C_{ep} = \$6000$/year, while minimising the total cost. The behaviour of E_mC, SSC, and TC are shown in Figure 3.

As shown in Figure 3, considering a penalty for emissions with no carbon tax imposed on the system or with no additional costs for emissions beyond the allowable limit penalty results in an optimal solution that occurs: (*i*) at

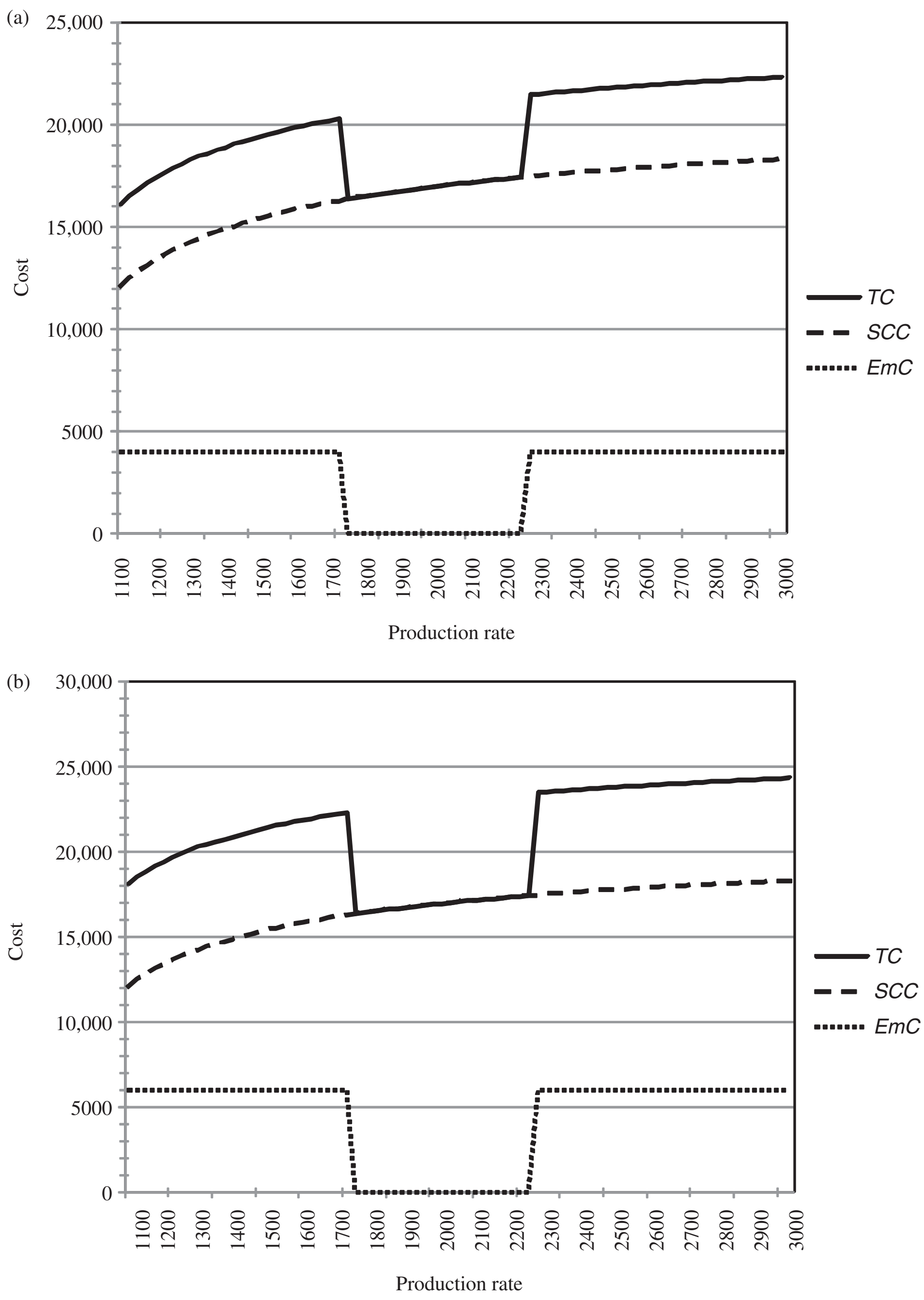

Figure 3. Behaviour of emissions cost (E_mC), supply chain cost (SCC), and total cost (TC) for varying values of P when (a) $C_{ep} = 4000$ and (b) $C_{ep} = \$6000$/year, and $C_{ec} = 0$.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

$P_{\min} = 1100$ units/year, $\lambda^* = 7$, and $Y_1 = 1$ where the total cost is \$16,103.45/year (Case 1: $C_{ep} = \$4000$/year), or (*ii*) at $P^* = 1741.80$ units/year, $\lambda^* = 3$ and $Y_1 = 0$ where the total cost is \$16,329.50/year (Case 2: $C_{ep} = \$6000$/year). Case 1 produces a lower total cost than Case 2, because the production and demand rates are almost synchronised where the savings in holding costs are more than the additional emissions tax resulting from operating at $P_{\min}$ rather than P^*. Case 2 suggests that imposing a large penalty for exceeding the permissible emissions limit entices the manufacturer to operate at a production rate P, where $1741.80 < P \leq 2258.2$ (upper and lower bounds of P are computed from Equation (7)), that minimises the emissions function given in Equation (2). In contrast to the scenario studied in the first example, it is clear here that in the case when an emissions penalty is imposed on the system, the manufacturer's optimal production rate is either $P_{\min}$ or the smallest production rate that keeps its emissions below the specified limits to avoid paying penalties for exceeding them. This production rate can be calculated by setting Equation (2) equal to E_{li} and solving for P to get

$$P_{Eli} = \frac{b \pm \sqrt{[b^2 - 4a(c - E_{li}/d)]}}{2a}, \tag{8}$$

where $P_{Eli} = \text{Min}\ \{1741.80, 2258.20\}$ by substituting the values of the parameters a, b, c, and d in Equation (7). Thus, we conclude that $P^* \in \{P_{\min}, P_{Eli}\}$ when an emissions penalty is imposed on the system.

3.3 *Example 3: impact of carbon taxes and emissions penalty*

This example addresses research question 3 and considers the case when a penalty is charged for exceeding the emissions limit in addition to a carbon tax. Let $C_{ep} = \$1000$/year and $E_{li} = E_{\max} = 220$ tons/year (where $i = 1$) while keeping the values of the remaining input parameters as specified in Example 3.1. The mathematical programming problem described in Equations (3)–(6) generates an optimal solution at $P^* = 1741.80$ units/year, $\lambda^* = 3$, and $Y_1 = 0$ where the total cost is \$20,289.54/year. For $P_{\min} = 1200$ units/year and $\lambda = 5$, the total cost is \$21,442.56/year. When the system operates at the production rate that minimises the emissions function in Equation (2), $P_o = b/2a = 2000$ units/year, the optimal solution occurs at $\lambda = 3$ where the total cost is \$20,570.56/year. The model was investigated for varying values of $P \in [1200, 3000]$, while minimising the total cost. The behaviour of E_mC, SSC and TC are shown in Figure 4.

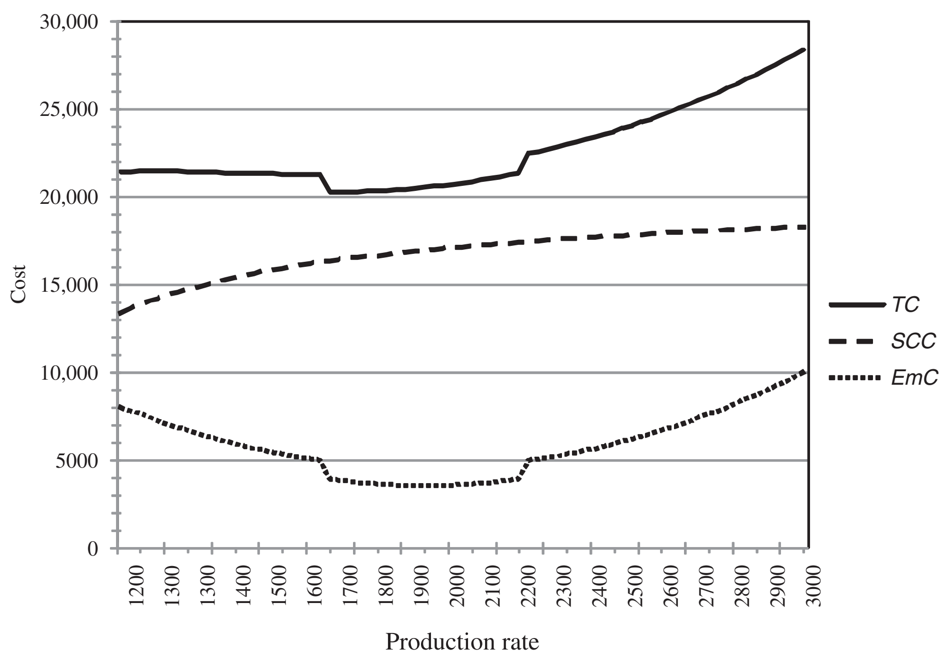

Figure 4. Behaviour of emissions cost (E_mC), supply chain cost (SCC), and total cost (TC) for varying values of P when $C_{ep} = \$1000$/year and $C_{ec} = \$18$/ton.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

As shown in Figure 4, when a penalty is charged for exceeding the permissible limit of emissions and when a carbon tax is imposed on the system, a manager may decide to: (1) operate the system at $P_{\min}=1200$ ($\lambda=\lambda(P_{\min})=5$) with minimum inventory cost, $SSC=\$13{,}386.56$, but with an emissions penalty and an emissions tax, $E_mC=\$8056$, or (2) operate the system at $P^*=1741.80$ ($\lambda^*=\lambda(P^*)=3$), which minimises the emissions function ($E_mC=\$3960$) and avoids paying the penalty (where $SSC=\$16{,}329.54$ is not minimum, and an emissions tax still has to be paid). In Case 2, a P value between P_{Eli} and P_o can in principle be optimal; i.e. $P^*\in\{P_{Eli},P_o\}=\{1741.80, 2000\}$. Assuming a smaller penalty (\$1000 instead of \$4000) results in enticing the manufacturer to increase its production rate to the point that reduces the emissions its system generates. The effect of the emissions cost would be more noticeable for values of the production rate that deviate from the optimal one. Thus, for such a system, a legislator may impose a reasonable penalty that does not heavily burden the manufacturer while ensuring that environmentally viable results are attained.

In addition, a low emissions window ($200<Ed\le 220$) gives the decision-maker the flexibility to adjust its production rate ($1741.80\le P\le 2000$) for less than a 1.5% increase in the manufacturer's total cost (from \$20,289.50 to \$20,570.60).

3.4 *Example 4: impact of demand reductions and capacity constraints*

In this example, we answer research question 4 and examine the case where the vendor (manufacturer) faces a capacity constraint and has the option to fulfil only a fraction of its customer's demand. This example adopts the input parameters from Example 3.2 except for $\alpha=1.2$, but under the assumption that the manufacturer lacks the flexibility to vary the production rate over a range as in the previous examples. The maximum attainable production rate (owing to limited resources or capacity constraints) is assumed to be 1700 units/year. The minimum of the total cost function, when no capacity constraint is imposed, was found to occur at $P^*=1741.80$ units/year, $\lambda^*=3$, and $Y_1=0$ where the total cost is \$16,329.54/year; however, this production rate is not attainable in the present example. This suggests that it is beneficial to reduce the production rate to $P^*=1200$ and deliver 5 buyer's cycles in a vendor's cycle (i.e. $\lambda^*=5$), where the minimum cost is \$17,386.56/year. Another practical option can be reached by not fulfilling a fraction of the annual demand. Reducing d from 1000 to 950 units/year, for example, results in an optimal solution with a total cost of \$15,977.34/year attained when $P^*=1675.56$ units/year, $\lambda^*=3$ and $Y_1=0$. The model was also investigated for varying values of $P\in[1140, 3000]$, while minimising the total cost. The behaviour of

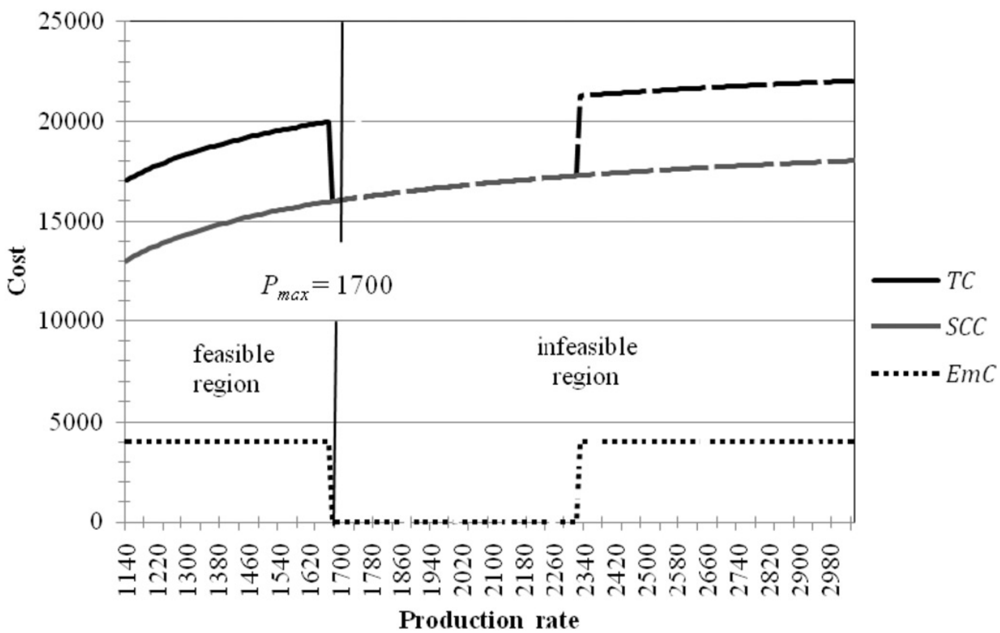

Figure 5. Behaviour of emissions cost (E_mC), supply chain cost (SCC), and total cost (TC) for varying values of P when $C_{ep}=4000$, $C_{ec}=0$ and $P_{\max}=1700$.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

Table 1. Emissions penalty schedule.

i	Emissions limit i	Penalty charged (\$), $C_{\mathrm{ep},i}$
1	$Ed < 220$	0
2	$220 \leq Ed < 330$	1000
3	$330 \leq Ed < 440$	2000
4	$440 \leq Ed < 550$	3000
5	$550 \leq Ed < 660$	4000
6	$Ed \geq 660$	5000

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

$E_{\mathrm{m}}C$, SSC and TC are shown in Figure 5. Note that the dashed lines in Figure 5 indicate the infeasible region, i.e. $P > 1700$.

Figure 5 illustrates that if the profit margin is narrow (e.g. as in the steel industry), it could be reasonable not to fulfil a portion of the annual demand in order to avoid paying a hefty penalty. In this case, switching from a minimum production rate with nominal demand and excessive emissions ($TC = \$17{,}386.60$/year, $Y_1 = 1$, and $Ed = 392$ tons/year) to a lower demand level and minimum emissions results in savings of \$1409.26 per year. These savings can be favourable, even with a loss of few units (50) of sales. However, if there is a cost associated with each unit of demand lost, c_{L}, then the savings in total cost should be weighed against the total cost of lost units, $c_{\mathrm{L}} \times (1000 - 950)$. That is, if $c_{\mathrm{L}} \times (1000 - 950) > 1409.26$, then not fulfilling a portion of demand may be a good policy to avoid paying a penalty.

3.5 *Example 5: impact of emissions allowance trading*

In this example, we address research question 5 and consider the case of multiple penalties imposed at different emissions limits or intervals, combined with an emissions penalty (see the schedule in Table 1) with and without carbon tax (i.e. $C_{\mathrm{ec}} = 18$ and $C_{\mathrm{ec}} = 0$). Multiple penalties correspond to the cap-and-trade system, where companies that exceed their emissions allowances have to buy additional emissions certificates on the market. Using alternative values for $C_{\mathrm{ep},i}$ with $C_{\mathrm{ep},i} > C_{\mathrm{ep},i+1}$ takes account of the fact that buying certificates may be associated with increasing costs as the demand for emissions certificates increases. Using the input parameters from Example 3.2, except for $\alpha = 1.2$, the model was investigated for varying values of $P \in [1200, 3000]$, while minimising the total cost. Note that to find the optimal solution, the break points of the emissions cost function have to be tested for optimality using Equation (8), as carried out in Steps 5 and 6 of the solution procedure. The behaviour of $E_{\mathrm{m}}C$, SSC, and TC are shown in Figure 6.

Figure 6 suggests that there are three main alternatives to consider: (1) a minimum production rate ($P = 1200$) with a double emissions penalty ($Y_1 = 1$ and $Y_2 = 1$ totalling $\sum_{i=1}^{3} Y_i C_{\mathrm{ep},i} = 3000$) with a total cost of \$16,386.56/year ($\lambda^* = 5$), (2) a production rate ($P = 1341.72$) that results in less emissions and one penalty ($Y_1 = 1$ and $Y_2 = 0$ totalling $\sum_{i=1}^{2} Y_i C_{\mathrm{ep},i} = 1000$) with a total cost of \$15,545.62/year ($\lambda^* = 4$), and (3) a higher production rate ($P = 1741.81$) that results in less emissions and no penalty ($Y_1 = 0$ and $Y_2 = 0$) with a total cost of \$16,329.57/year ($\lambda^* = 3$). In this case, going for minimum emissions and no penalties is not an optimal solution, and going for maximum emissions is also not an optimal solution. On the contrary, a mixture of emissions penalties and savings from supply chain costs is optimal. Figure 6 was reproduced for the case when an emissions tax and an emissions penalty are imposed. The optimal policy was found to occur at $P^* = 1741.81$ where $Y_i = 0$ with a total cost of \$20,289.54/year. The behaviour of $E_{\mathrm{m}}C$, SSC, and TC are shown in Figure 7.

3.6 *Example 6: manufacturer–retailer coordination*

In this example, the importance of coordination between the vendor (manufacturer) and the buyer (retailer) is examined. The input parameters from Examples 3.1 to 3.5 are used in this example. In the no coordinated case, the sum of Equation (A7), shown in the appendix, and the total emissions and penalty costs, i.e. $\psi^{NC}(\lambda, P) = \psi_{sc}^{NC} + E_{\mathrm{m}}C$, are optimised for λ and P. The optimised values of the coordinated case were determined earlier in the corresponding examples. The results are summarised in Table 2.

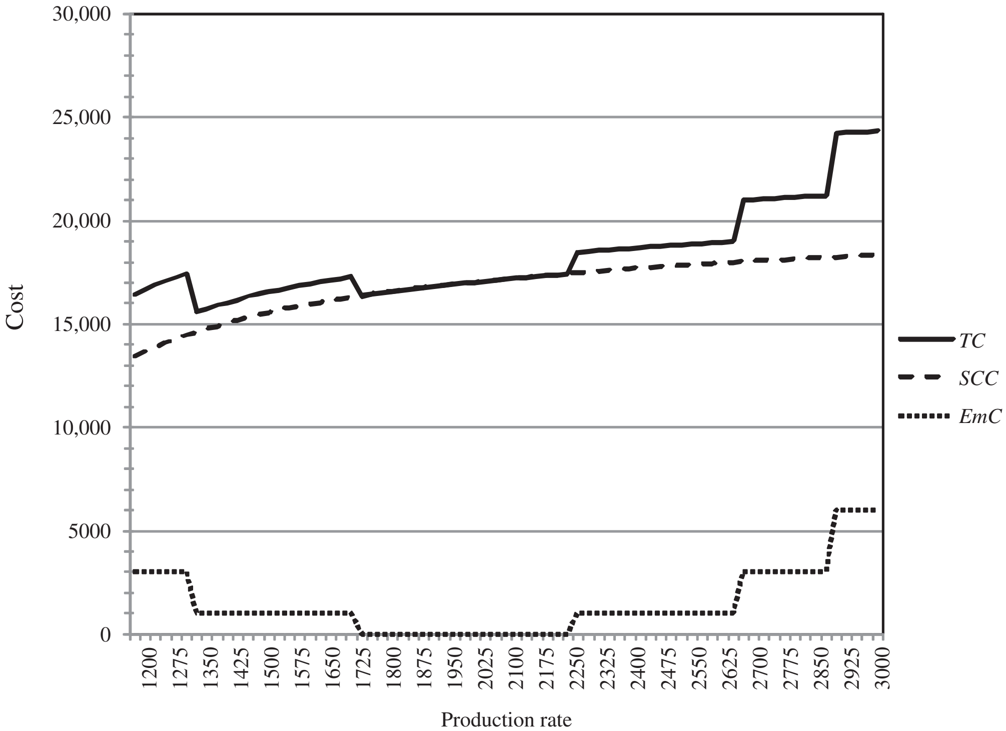

Figure 6. Behaviour of emissions cost ($E_{\mathrm{m}}C$), supply chain cost (SCC), and total cost (TC) for varying values of P for different $C_{\mathrm{ep},i}$ values and $C_{\mathrm{ec}} = 0$.

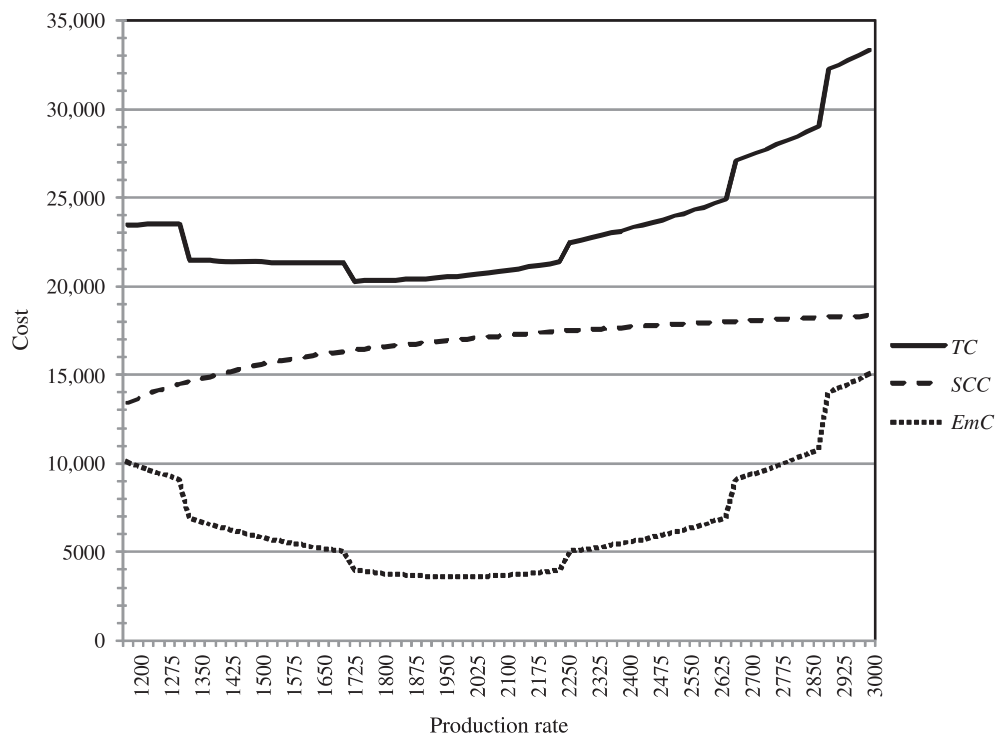

Figure 7. Behaviour of emissions cost ($E_{\mathrm{m}}C$), supply chain cost (SCC), and total cost (TC) for varying values of P for different $C_{\mathrm{ep},i}$ values and $C_{\mathrm{ec}} = 18$.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

Table 2. Optimal production-inventory policies for coordinated and no coordinated cases.

Example	Coordination	λ^*	P^*	TC	E_mC
3.1	No	2	1742	21,605	3960
	Yes	3	1725	20,289	4010
3.2	No	4	1100	17,417	4000
	Yes	7	1100	16,104	4000
3.3	No	2	1742	21,605	3960
	Yes	3	1742	20,290	3960
3.4[a]	No	3	1200	18,697	4000
	Yes	5	1200	17,387	4000
3.4[b]	No	2	1676	17,266	0
	Yes	3	1676	15,977	0
3.5	No	2	1742	21,605	3960
	Yes	3	1742	20,290	3960

Notes: The P, TC, and E_mC values are rounded to the nearest integer.
[a]$P_{max} = 1700$, $d = 1000$; [b]$P_{max} = 1700$, $d = 950$.

The results show that for the data of Example 3.1 ($C_{ec} > 0$, $C_{ep} = 0$), coordination reduced the supply chain cost by about 6% (from \$21,605 to \$20,289) and increased emissions and penalty costs by about 1% (from \$3960 to \$4010) respectively. The results also show that for Examples 3.2 ($C_{ec} = 0$; $C_{ep} > 0$), 3.3 ($C_{ec} > 0$; $C_{epi} > 0$), 3.4a ($C_{ec} = 0$; $C_{ep} > 0$; $P_{max} = 1700$), 3.4b ($C_{ec} = 0$; $C_{ep} > 0$; $P_{max} = 1700$; $d = 950$), and 3.5 ($C_{ec} > 0$; $C_{ep6} > \cdots > C_{ep2} > C_{ep1} > 0$), coordination reduces the supply chain inventory-related cost and the sum of the emissions and penalty costs by about 8% (from \$17,417 to \$16,104) and 0% (from \$4000 to \$4000), about 6% (from \$21,605 to \$20,290) and 0% (from \$3960 to \$3960), about 7% (from \$18,697 to \$17,387) and 0% (from \$4000 to \$4000), about 7% (from \$17,266 to \$15,977) with no emissions and penalty costs, and about 6% (from \$21,605 to \$20,290) and 0% (from \$3690 to \$3960), respectively.

4. Summary and conclusion

The paper investigated the European Union Emissions Trading System (EU-ETS) in a two-level (vendor–buyer) supply chain context. This work is believed to be the first to examine such a system from a user's or an operations management point of view. The supply chain model considered in the paper is investigated for a coordination mechanism while accounting for greenhouse gas emissions (e.g. CO_2) generated from the manufacturer's processes. A mathematical model was modified to account for emissions tax and penalty paid for exceeding emissions limit(s). The numerical examples considered in the paper illustrate the behaviour of the supply chain cost function for several possible scenarios that may describe different legislative systems. It was found that a policy that considers a penalty for emissions only results in more than one option for the supply chain decision-maker, which might result in an optimal solution that recommends producing excessive amounts of greenhouse gas emissions. A policy that considers a combination of carbon tax and emissions penalty was found to be the most effective one, as the optimal solution generated was usually associated with low emissions. Supply chain coordination was also found to minimise the total system cost when emissions and penalty costs were considered; however, the reduction was in inventory-related costs with no change in the sum of the emissions and penalty costs. Perhaps the effect of coordination on emissions reduction would be different if a more complex supply chain structure (Jaber and Goyal, 2009) was considered rather than the simple vendor–buyer one of the paper. This will be dealt with in a follow up paper. The model developed in the paper may be found to be a useful tool for decision-makers who wish to optimise the performance of their supply chains in conjunction with the financial obligations that emitting greenhouse gases brings.

Future work could concentrate on studying alternative types of pollutants, such as the production of scrap in manufacturing processes, for example, and investigating workable incentive schemes that legislators may offer to companies to entice them to reduce the negative impact that their manufacturing processes and operations have on the environment. Further, it would be interesting to investigate how other relationships than that considered in the paper, which assumes that the emissions generated by a facility is a convex function of its output rate, affect the

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

performance of logistics and inventory systems. Finally, introducing stochastic variables into the model developed in the paper seems to be promising. One example is to treat the amount of emissions caused by the production process at a certain production rate as a random variable. Another example is to address the question of whether a company that exceeds its emissions allowance is fined or not. This could be done by subjecting the fine to a random variable as well. If exceeding the emissions allowance leads to a fine with a probability of less than 1, it would then be interesting to study the behaviour of supply chains so as to give legislators some guidelines as to how fines should be structured so that companies adhere to regulations.

Acknowledgements

The first and third authors thank the Social Sciences and Humanities Research Council (SSHRC) of Canada–Canadian Environmental Issues – for supporting this research. The second author wishes to thank the in-kind support provided to him, as a visiting researcher, by Ryerson University, Toronto, Canada, and the Natural Sciences and Engineering Research Council (NSERC) of Canada for their partial financial support. This work was further supported by a fellowship within the Postdoc-Programme of the German Academic Exchange Service (DAAD). The authors are very thankful to the reviewers for their valuable and constructive comments and suggestions that helped us improve the paper.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

References

Bogaschewsky, R., 1995. *Natürliche Umwelt und Produktion*. Wiesbaden: Gabler-Verlag.

Bonney, M., 2009. Inventory planning to help the environment. *In*: M.Y. Jaber, ed. *Inventory management: non-classical views*. Boca Raton, FL: CRC Press, 43–74.

Bonney, M. and Jaber, M.Y., 2011. Environmentally responsible inventory models: Non-classical models for a non-classical era. *International Journal of Production Economics*, 133 (1), 43–53.

Dobos, I., 2005. The effects of emission trading on production and inventories in the Arrow–Karlin model. *International Journal of Production Economics*, 93–94, 301–308.

El Saadany, A.M.A. and Jaber, M.Y., 2008. Coordinating a two-level supply chain with production interruptions to restore process quality. *Computers & Industrial Engineering*, 54 (1), 95–109.

Enkvist, A., Nauclér, T., and Rosander, J., 2007. A cost curve for greenhouse gas reduction. *The McKinsey Quarterly*, 2007 (1), 35–45.

Fandel, G., 1991. *Production and cost theory*. Berlin: Springer.

Floros, N. and Vlachou, A., 2005. Energy demand and energy-related CO_2 emissions in Greek manufacturing: Assessing the impact of a carbon tax. *Energy Economics*, 27 (3), 387–413.

Gangadharan, L., 2004. Analysis of prices in tradable emission markets: An empirical study of the regional clean air incentives market in los angeles. *Applied Economics*, 36 (14), 1569–1582.

Gälweiler, A., 1960. *Produktionskosten und Produktionsgeschwindigkeit*. Wiesbaden: Gabler.

Glock, C.H., 2010. Batch sizing with controllable production rates. *International Journal of Production Research*, 48 (20), 5925–5942.

Glock, C.H., 2011. Batch sizing with controllable production rates in a multi-stage production system. *International Journal of Production Research*, 49 (20), 6017–6039.

Glock, C.H., 2012. The joint economic lot size problem: a review. *International Journal of Production Economics*, 135 (2), 671–686.

Goyal, S.K., Huang, C.K., and Chen, K.C., 2003. A simple integrated production policy of an imperfect item for vendor and buyer. *Production Planning & Control*, 14 (7), 596–602.

Jaber, M.Y. and Goyal, S.K., 2009. Coordinating a four level supply chain with a vendor, multiple buyers and multiple tier-1 and tier-2 suppliers. *International Journal of Production Research*, 47(13), 3691–3704.

Jaber, M.Y. and Zolfaghari, S., 2008. Quantitative models for centralized supply chain coordination. *In*: S. Kordic, ed. *Supply chains: theory and applications*. Vienna: I-Tech Education and Publishing, 307–338.

Kruger, J. and Pizer, W.A., 2004. The EU emissions trading directive: Opportunities and potential pitfalls, resources for the future. Discussion Paper 04–24, Washington, DC.

Mayor, K. and Tol, R.S.J., 2007. The impact of the UK aviation tax on carbon dioxide emissions and visitor numbers. *Transport Policy*, 14 (6), 507–513.

Metcalf, G.E., 2009. Designing a carbon tax to reduce US greenhouse gas emissions. *Review of Environmental Economics and Policy*, 3 (1), 63–83.

Pack, L., 1966. Die Ermittlung der kostenminimalen Anpassungsprozeßkombination. *Zeitschrift fürbetriebswirtschaftliche Forschung*, 19 (3), 466–476.

Soleille, S., 2006. Greenhouse gas emission trading schemes: A new tool for the environmental regulator's kit. *Energy Policy*, 34 (13), 1473–1477.

Tomlinson, S., Wang, C.J., and Morgan, C., 2010. An approach to carbon emission estimation for plant refurbishment strategies. *International Journal of Internet Manufacturing and Services*, 2 (3–4), 216–230.

TÜV Rheinland, 1987. *Das Abgasemissionsverhalten von Personenkraftwagen in der BRD im Bezugsjahr 1985*. Berlin: Bericht 7/87 des Umweltbundesamtes.

Downloaded by [Huazhong University of Science & Technology] at 18:44 24 August 2012

Appendix 1

The per unit of time cost functions for the manufacturer and the retailer are given respectively as:

$$\psi_{\rm m} = \frac{S_{\rm m} d}{\lambda q} + h_{\rm m}\frac{q}{2}\left[1+\lambda\left(1-\frac{d}{P}\right)\right] \tag{A1}$$

$$\psi_{\rm r} = \frac{S_{\rm r} d}{q} + h_{\rm r}\frac{q}{2}. \tag{A2}$$

The total supply chain per unit of time cost is the sum of Equation (A1) and Equation (A2) and is given as

$$\psi_{sc} = \frac{S_{\rm m} d}{\lambda q} + h_{\rm m}\frac{q}{2}\left[1+\lambda\left(1-\frac{d}{P}\right)\right] + \frac{S_{\rm r} d}{q} + h_{\rm r}\frac{q}{2}. \tag{A3}$$

ψ_{sc} is convex, since $\mathrm{d}^2\psi_{sc}/\mathrm{d}q^2 = 2(S_{\rm m}+\lambda S_{\rm r})/\lambda q > 0\ \forall q > 0$. The solution of Equation (A3) is given by setting its first derivative equal to zero and solving for q to get

$$q = \sqrt{\frac{2d\left(\frac{S_{\rm m}}{\lambda}+S_{\rm r}\right)}{h_{\rm m}\left[1+\lambda\left(1-\frac{d}{P}\right)\right]+h_{\rm r}}} = \sqrt{\frac{2dS}{H}}. \tag{A4}$$

By substituting Equation (A4) in Equation (A3), we get

$$\begin{aligned}\psi_{\rm sc} &= \frac{Sd}{q} + \frac{H}{2}q = \frac{Sd}{\sqrt{\frac{2dS}{H}}} + \frac{H}{2}\sqrt{\frac{2dS}{H}} = \sqrt{2dSH}\\ &= \sqrt{2d\left(\frac{S_{\rm m}}{\lambda}+S_{\rm r}\right)\left[h_{\rm m}\left(1+\lambda\left(1-\frac{d}{P}\right)\right)+h_{\rm r}\right]}\\ &= \sqrt{2d(S_{\rm m}+\lambda S_{\rm r})\left[h_{\rm m}\left(1-\frac{d}{P}+\frac{1}{\lambda}\right)+\frac{h_{\rm r}}{\lambda}\right]}.\end{aligned} \tag{A6}$$

Equation (A6) represents the joint cost function of the manufacturer and the retailer when they coordinate their orders. When there is no coordination, i.e. the retailer orders according to its EOQ formula, $q_0 = \sqrt{2S_{\rm r}d/h_{\rm r}}$, and the manufacturer in its turn has to adjust, using λ, its production-inventory policy to this quantity. The no coordinated cost function is determined from Equation (A1) and Equation (A2) as

$$\psi_{sc}^{NC} = \frac{S_{\rm m} d}{\lambda\sqrt{2S_{\rm r}d/h_{\rm r}}} + h_{\rm m}\frac{\sqrt{2S_{\rm r}d/h_{\rm r}}}{2}\left[1+\lambda\left(1-\frac{d}{P}\right)\right] + \sqrt{2S_{\rm r}h_{\rm r}d}. \tag{A7}$$

For the no coordination case, the term $SSC = \psi_{\rm sc}$ in Equation (3) is replaced by Equation (A7). Similar to what has been done earlier, the per unit of time inventory cost, ψ_{sc}^{NC}, can be simplified to accelerate the search for an optimal solution, P^*, by assuming λ to hold a real number and that ψ_{sc}^{NC} is differentiable over λ, where ψ_{sc}^{NC} is convex, since $\partial^2\psi_{sc}^{NC}/\partial\lambda^2 > 0\ \forall\lambda > 0$. By setting the first partial derivative of Equation (A7) equal to zero, $\partial\psi_{sc}^{NC}/\partial\lambda = 0$, and solving for λ to get

$$\lambda(P) = \sqrt{\frac{S_{\rm m}h_{\rm r}}{S_{\rm r}h_{\rm m}(1-d/P)}}. \tag{A8}$$

In this paper, the focus is on the speed of the production rate as being the factor that controls the rate at which CO_2 emissions are generated. The term $f = 1 - d/P \in (0,\infty)$ as $P \in (d,\infty)$ is a monotonically increasing function, since $\mathrm{d}f/\mathrm{d}P = d/P^2 > 0$ and $\mathrm{d}^2 f/\mathrm{d}P^2 = -2d/P^3 < 0$. Accordingly, q decreases, and ψ_{sc} increases.