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Supply chain models with greenhouse gases emissions, energy usage, imperfect process under different coordination decisions

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ABSTRACT

Environmental issues, mainly greenhouse gas (GHG) emissions, are in large part the result of the excessive use of energy in production systems. The scarcity of resources, governmental regulations, and public awareness about sustainability make them expensive for companies. The speed of producing items (production rate) impacts GHG emissions generation in manufacturing, i.e., usually faster production results in more emissions, which is controllable in many cases. The production rate also affects the process quality and reliability; i.e., fast production speeds deteriorate the system fast, resulting in reworking defective items and machine failure. Such quality and reliability issues increase energy consumption and subsequently costs. This paper develops two-level (vendor-buyer) supply chain models that tackle these issues. It considers two coordinated policies: classical and vendor-managed inventory with consignment stock (VMI-CS), where the objective is to find the values of the decision variables that yield the minimum total supply chain cost. It includes the costs of holding inventory, GHG emissions and tax, energy usage, product and process quality, and transportation operations. The decision variables are the order quantity, the number of shipments, and the production rate. The paper compares the numerical results of the two coordination policies. It also provides managerial insights on the economic and environmental performance of the supply chains.

1. Introduction

The focus of manufacturers on reducing the environmental impact, such as energy consumption and greenhouse gas (GHG) emissions, of their production and logistics systems increased considerably in the last decade. The reasons for this interest came from societal pressure and customer awareness on the relevance of sustainability to their communities that pushed governments to pass legislation in this perspective to reduce the environmental impact of the manufacture, use, and disposal of products and to better conserve natural resources. The evaluation of the energy consumption in manufacturing processes has become strategic also for firms since the energy prices are rising and volatile, the introduction of tax for CO_2 emissions, and the changes in the purchasing behaviour of final customers regarding 'green' products (Bunse et al., 2011). As energy resources become scarce, the purchasing price increases, thus increasing manufacturing costs, since energy consumption accounts for a significant share of the total production costs, especially for energy-intensive companies. Conserving energy is also the best way to ensure reliable and sustainable energy supply and to reduce greenhouse gas emissions since GHG emissions are mainly generated by the burning of fossil fuel to produce energy. The reliance on fossil fuel remains primary for many industries around the world. Clean energy sources, although available, but not yet affordable by many (IEA, 2016).

Several measures aiming at the improvement of energy efficiency exist. Energy efficient production planning (EEPP) is one of them. It provides an inexpensive option when compared to new technologies requiring huge investments even for small to mid-size companies (Biel and Glock, 2016). Biel and Glock recommended including energy and emissions costs in production planning decisions. Not doing so, they added, could bias manufacturing costs. They classified EEPP models into three main groups: energy-efficient master production scheduling and capacity planning, energy-efficient lot-sizing, and energy-efficient machine scheduling (for instance, job allocation, sequencing, and load management). Ignoring energy costs may induce managers to make decisions that are not the best (sub-optimal) for their firms. Economic and environmental performance of a firm may also be affected as a result of making decisions with incomplete information.

One of the main lot-sizing decision variables affecting both the quality of the process and the environmental performance, such as

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energy consumption and GHG emissions generation, is the production rate (or speed). A variable production rate affects the quality of the process bringing additional costs. A faster production negatively affects the reliability of machines and increases the likelihood of producing defective items. The production process starts in an 'in-control' state producing items that meet quality requirements. However, at a certain moment, the process shifts to an 'out-of-control' state, and from that point on a percentage of the items produced, which depends on the production rate (Khouja and Mehrez, 1994), is defective and requires reworks. The 'out-of-control' state may also in turn end in an ultimate breakdown requiring a corrective repairing intervention which probability is affected by the production rate (Groenevelt et al., 1992). The GHG emissions follow a similar pattern. In particular, the literature proposes a convex function of the production rate or equipment speed to model the carbon-dioxide (CO_2) emissions (Bogaschewsky, 1995; Jaber et al., 2013a; Bazan et al., 2015a). At the same time, energy consumption follows the opposite trend: i.e., higher production speed leads to reduced specific energy consumption (SEC) per produced item. In fact, a manufacturing process (equipment) requires fixed (for start-up or to remain in a ready state) and variable (proportional to the production rate) power components to run (Gutowski et al., 2006); however, if the production is faster, the equipment run for less time and finally the SEC is lower. Reworking defective items require additional electrical energy and emitting GHG emissions, which makes process quality and environmental performance strictly correlated. For these reasons, therefore, quality and environmental issues should be considered together.

Aligning the decision-making process among the different actors of the supply chain represents a prerequisite in improving the economic performance, and in developing competitive advantages that satisfy customer needs better than competitors (Mentzer et al., 2001). Collaboration in a supply chain can also improve its sustainability (Roehrich et al., 2014), where vendors and buyers can work closely together to meet the requirements and needs of more environmentally conscientious customers. Cooperation among different actors in a supply chain also has the potential of overcoming the main existing barriers hindering the implementation of energy efficiency measures. It also allows detecting additional energy efficient practices not pointed out from a single firm perspective (Marchi and Zanoni, 2017). For instance, in Ferretti et al. (2007), the holistic approach aiming to improve the efficiency of the whole supply chain allowed promoting an alternative greener supply method for raw material in a manufacturing system; i.e., the supply of molten aluminium instead of the traditional solid ingot. The JELS model could be used to investigate different coordination policies. In the traditional coordination policy, the vendor manufactures a lot of size nq at a finite production rate P with a single setup that is delivered to the buyer in n shipments of equal size q every time the buyer places an order. Braglia and Zavanella (2003) extended the JELS model to consider a different coordination policy; i.e., vendor-managed inventory (VMI) with the consignment stock (CS) agreement. In the VMI-CS policy, the buyer retains control over the timing and quantity of replenishments and leaves the ownership of the inventory to the vendor. The buyer only pays the vendor for the items it withdraws from stock transferring ownership to the buyer. This policy is advantageous to both actors. When the vendor moves its inventory to the buyer saves on storage costs and frees space at its end. The buyer saves on the opportunity cost of capital, which is the cost of owning the stock. The buyer also benefits by freeing its capital and invests it in other operations.

Many studies have investigated sustainability and imperfect production processes in the supply chain management context. Some of them considered variable production rates. However, we are not aware, as the literature shows, of a study that jointly investigates energy, GHG emissions, and imperfect production. In particular, in a Joint Economic Lot Sizing (JELS) setting. This paper, therefore, addresses this research gap by developing two two-level (vendor-buyer) supply chain model. One that follows a traditional coordination mechanism, while the other follows a vendor-managed inventory policy with consignment stock (VMI-CS).

There are seven remaining sections. The next section, Section 2, provides a brief review of the relevant literature. The problem definition, notation, and assumptions are in Section 3. The development of the model is in Section 4. The traditional and VMI-CS coordination policies are in Sections 5 and 6, respectively. Numerical results are in Section 7. A summary of the paper, its main findings, and future development of the present work are in Section 8.

2. Literature review

2.1. Sustainability in supply chain management

The increased focus on sustainability has interested the research community. The literature is rich with studies that review on green supply chain management (GSCM) and sustainable supply chain management (SSCM). The earliest comprehensive review is the one of Srivastava (2007), which classified the GSCM literature as either problem context or the methodology. Later on, Brandenburg et al. (2014) provided a content analysis of the mathematical models by evaluating economic, environmental and social factor, the three pillars of sustainability, in supply chains. Fahimnia et al. (2015) provided a bibliometric analysis to cluster the research works, and to define the key topics already investigated and the currently existing gaps in the GSCM literature. Recently, Marchi and Zanoni (2017) proposed a systematic review of the papers that focused on energy efficiency practices with a supply chain perspective and defined several insights for future research streams for closing the existing gap in the current literature.

2.2. Inventory models with imperfect production processes and variable production rate

The literature on unreliable production and inventory took to focus streams. One that focused on imperfect production that results in defective items, while the second focused on machine breakdown. Next, we provide a concise background to both in the order mentioned.

Porteus (1986) and Rosenblatt and Lee (1986), each taking a different modelling approach, were the first to introduce the idea of an imperfect production process as an extension of the classical Economic Order Quantity/Economic Production Quantity (EOQ/EPQ) model. They assumed that the process starts as an "in-control" state, with a certain probability it shifts to an "out-of-control" state and remains in that state until the production batch is complete. Items produced in an "out-of-control" state are defective. Khouja and Mehrez (1994) assumed that a faster production rate deteriorates the quality of the process, resulting in defective items. Khouja (2005) revisited the work of Porteus (1986) and assumed frequent interruptions to restore the quality of the production process. He showed that the number of defective items is inversely proportional to the number of process restorations. However, there is a cost to restore the process. El Saadany and Jaber (2008) investigated the work of Khouja (2005) in a JELS problem with a traditional coordination mechanism, while Bazan et al. (2014) considered a VMI-CS agreement. They both introduced managerial decisions concerning the opportunity to rework defective items and to perform minor-setup to restore the "in-control" state. Jaber et al. (2013b) considered the demand rate to resemble heat flow in thermal systems and used the laws of thermodynamics to investigate an EOQ model for imperfect items using this novel and interesting approach. Their demand (heat flow) equation was price and quality dependent and introduced a third (entropy) cost component into the total cost equation.

Groenevelt et al. (1992) was the first work to investigate the effect of stochastic machine breakdowns on the production economic production quantity (EPQ) model. After that, Giri et al. (2005) introduced machine failure and repair time distributions in the classical EPQ model with a variable production rate since the stress condition of the machine changes with the speed of the production process. Boone et al. (2000) were the first to investigate the EPQ model by considering an imperfect production process and machine breakdowns that disrupt production. Later, Chakraborty et al. (2009) extended the work of Boone et al. (2000) incorporating corrective and preventive repair times in the model.

3. Problem definition

The present study proposes a two-level (vendor-buyer) supply chain model for a single product with an infinite time horizon. The vendor produces a lot of size nq in a single setup. It delivers to the buyer n shipments of size q each and screens its production batches in full for defective items and reworks them at a cost. In addition to the traditional inventory costs (setup, ordering, and holding), the supply chain incurs the costs of CO_2 emissions, energy consumption, process quality, and transportation operations. Two aspects of process quality are modelled in this paper; i.e., the generation of defective items and the machine failure random rate. They are dependent on the production rate $P \in [P_{min}; P_{max}]$. The objective is to determine the optimal values of q, n, and P that to minimize the supply chain total cost.

The following notations are used here:

Parameters:

α	percentage of defective products produced once the machine is in the "out-of-control" state
A	ordering cost ($)
a	emission function parameter for the production process (ton·h^2/unit^3)
a_r	emission function parameter for the reworking process (ton·h^2/unit^3)
β	non-negative parameter for the estimation of the quality function
b	emission function parameter for the production process (ton·h/unit^2)
b_r	emission function parameter for the reworking process (ton·h/unit^2)
c	emission function parameter for the production process (ton/unit)
c_r	emission function parameter for the reworking process (ton/unit)
c_{ec}	emission tax ($/ton)
c_{en}	energy cost for the vendor ($/kWh)
$C_{ep,i}$	emission penalty ($/h) for exceeding emission limit i
c_s	unit screening cost ($/unit)
D	demand rate (unit/h)
E	greenhouse gas (CO_2) emissions from the production process (ton/)
E_r	greenhouse gas (CO_2) emissions from the reworking process (ton/unit)
E_{li}	emissions limit i (ton/h)
E_{tr}	amount of emissions generated per period of time by transportation (ton/h)
e_t	amount of GHG emissions from one gallon of diesel-truck fuel (ton/gallon)
γ	parameter defining the relationship between the reworking rate and the production rate
g	number of gallons per truck per distance travelled (gallon/truck)
η	number of truck per trip
$h_{b,fin}$	financial component of the holding cost at the buyer's side ($/unit·h)
$h_{b,phy}$	physical component of the holding cost at the buyer's side ($/unit·h)
$h_{v,fin}$	financial component of the holding cost at the vendor's side ($/unit·h)
$h_{v,phy}$	physical component of the holding cost at the vendor's side ($/unit·h)
k	constant defining the variable component of the power used by the production process (kWh/unit)
k'	constant defining the variable component of the power used by the reworking process (kWh/unit)
λ	exponential parameter for the reliability function
M	corrective maintenance cost to restore a machine after a breakdown ($)
m	number of emissions limits
P_{min}	minimum production rate (unit/h)
P_{max}	maximum production rate (unit/h)
P_r	vendor's reworking rate (unit/h)
r	unit reworking cost ($/unit)
S	setup cost ($)
SEC	specific energy consumption to produce a unit at the vendor side (kWh/unit)
SEC_r	specific energy consumption to rework a unit at the vendor side (kWh/unit)
t_c	truck capacity (unit/truck)
t_p	production time
t_r	reworking time
ω	non-negative parameter for the estimation of the quality function
W	total power used by the production process (kW)
W_r	total power used by the reworking process (kW)
$W_{0,p}$	"idle" power for the production process in the ready position, related to equipment features required to support the process (kW)
$W_{0,r}$	"idle" power for the reworking process in the ready position, related to equipment features required to support the process (kW)

Decision variables:

n	number of shipments of size q in a cycle
P	vendor's production rate (unit/h)
q	order lot size (unit)

4. Model's formulation

4.1. Process quality modelling

At a point in time, the production process shifts out-of-control and starts to produce defective items. The expected number of defectives in a production lot size nq, which is given by (Khouja and Mehrez, 1994):

$$E(N) = \alpha f(P)\frac{(nq)^2}{2P} \tag{1}$$

where $1/f(P)$ represents the mean time to shift to an "out-of-control" state and is given by:

$$\frac{1}{f(P)} = \frac{1}{\beta + \omega P^2} \tag{2}$$

The second aspect affecting the quality of the production process is represented by the possibility to incur in machine breakdowns. The probability that a breakdown occurs by production time t_p is $F(t_p)$, which is the cumulative density function of $f(t)$, where t is a random variable denoting the time to breakdown. This paper considers accidental or casual failures to occur during the lifetime of a machine. The function $R(t)$ describes the reliability of the system:

$$f(t) = 1 - R(t) \tag{3}$$

$$R(t) = e^{-\lambda t} \tag{4}$$

where λ is the machine failure rate Hence, the probability of a breakdown can be calculated as:

$$F(t_p) = \int_0^{nq/P} \lambda dt = \lambda\frac{nq}{P} \tag{5}$$

4.2. Energy requirements

Production processes in energy-intensive industries require huge amounts of electrical energy. Gutowski et al. (2006) showed that energy consumption is a function of the production rate (speed). They showed that about 15% of the energy usage is inversely proportional to the speed at which the machines operate. The remaining energy is for startup and "ready" state functions (e.g., centrifuge energy, coolant, oil pressure pump, cooler, mist collector, etc.). It is independent of the production rate. The defined situation can be modelled as follows:

$$W = W_{0,p} + kP \tag{6}$$

where k is a constant (kWh/unit) coming from the physics of the production process.

From (6) we can obtain the expression for the specific energy consumption per unit of processed material as:

$$SEC = \frac{(W_{0,p} + k\cdot P)\cdot t_p}{nq} \tag{7}$$

where

$$t_p = \frac{nq}{P} \tag{8}$$

Even the reworking process requires an additional electrical energy consumption to rework the defective items. The defined situation can

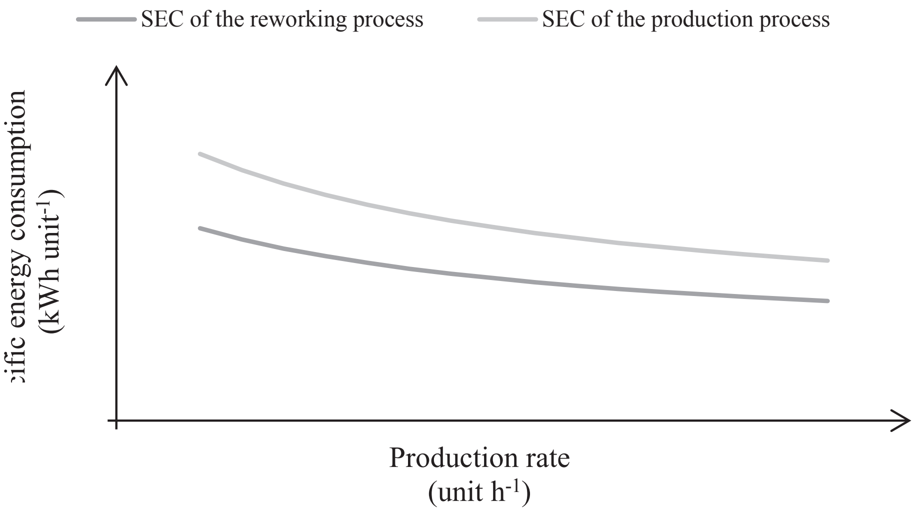

Fig. 1. Specific energy requirement as a function of the production rate, P.

be modelled as follows:

$$W_r = W_{0,r} + k'P_r \tag{9}$$

where k' is a constant (kWh/unit) coming from the physics of the reworking process while the reworking rate is a function of the production rate as defined in the following equation:

$$P_r = \gamma \cdot P \tag{10}$$

From (9)–(10), we can obtain the expression for the specific energy consumption per unit of reworked material as:

$$SEC_r = \frac{(W_{0,r} + k'\gamma P)\cdot t_r}{E(N)} \tag{11}$$

where

$$t_r = \frac{E(N)}{\gamma P} \tag{12}$$

Fig. 1 illustrates the specific energy requirement of the production and reworking processes, as a function of the production rate. The energy required by these processes reduce when production speeds (European Commission, 2009).

4.3. CO_2 emissions

The amounts of greenhouse gas emissions from production and rework at the vendor's side is a function of the production rate (Bogaschewsky, 1995). They are given respectively as (Bazan et al., 2015b):

$$E = aP^2 - bP + c \tag{13}$$

$$E_r = a_r P_r^2 - b_r P_r + c_r \tag{14}$$

The annual amount of CO_2 emissions that movements of trucks generate is (Bazan et al., 2015a):

$$E_{tr} = n\eta \frac{D}{nq} g e_t \tag{15}$$

where

$$\eta = \frac{q}{t_c} \tag{16}$$

5. Traditional agreement

The annual total cost of the vendor, TC_V, is the sum, in the order they appear, of the setup (S_V), holding (H_V), screening for defective items (SC), rework (RC), energy costs (EC) and the carbon emissions tax (i.e., CO_2 emissions-related costs, (EmC)). There is also corrective maintenance to restore the machines after breakdowns (MC). It is given as:

$$\begin{aligned} TC_V &= S_V + H_V + SC + RC + EC + EmC + MC \\ &= \frac{S\,D}{n\,q} + h_v\frac{q}{2}[(1 - \frac{D}{P})n + \frac{2D}{P} - 1] + c_S\,D + r\frac{D}{n\,q}E(N) \\ &\quad + c_{en}(SEC\,D + SEC_r E(N)\frac{D}{n\,q}) + c_{ec}(DE + E(N)E_r\frac{D}{n\,q}) + M\lambda\frac{D}{P} \end{aligned} \tag{17}$$

where $h_v = h_{v,phy} + h_{v,fin}$.

The buyer's total cost per unit of time, TC_B, is the sum of order, S_B, and holding, H_B, costs as:

$$TC_B = S_B + H_B = \frac{A\,D}{q} + h_b\frac{q}{2} \tag{18}$$

where $h_b = h_{b,phy} + h_{b,fin}$.

The transportation cost is the sum of the fuel purchasing cost, $FC = c_t D/t_c$, and carbon emissions tax, $TEmC = c_{ec}E_{tr}$ (Gurtu et al., 2015). Moreover, when the expected emissions released into the atmosphere exceed the limit imposed by a regulator, the supply chain incurs a progressive penalty, $PC = \sum_{i=1}^{m} Y_i C_{ep,i}$, where $Y_i = 1$ if $ED + E(N)E_r\frac{D}{n\,q} + E_{tr} \geq E_{li}$, $i \in [1, m]$ and $Y_i = 0$, otherwise. Thus, the expected annual total cost of the supply chain, TC_S, is the sum of those of the vendor, TC_V, the buyer, TC_B, transportation cost, $FC + TEmC$, and emission penalty cost, PC. It is written as:

$$\begin{aligned} TC_S &= TC_V + TC_B + FC + TEmC + PC \\ &= \frac{SD}{n\,q} + h_v\frac{q}{2}[(1 - \frac{D}{P})n + \frac{2D}{P} - 1] + c_S D + r\frac{D}{n\,q}E(N) \\ &\quad + c_{en}(SEC\,D + SEC_r E(N)\frac{D}{n\,q}) + c_{ec}(DE + E_{tr} + E(N)E_r\frac{D}{n\,q}) \\ &\quad + M\lambda\frac{D}{P} + \frac{AD}{q} + h_b\frac{q}{2} + c_t\frac{D}{t_c} + c_{ec}E_{tr} + \sum_{i=1}^{m} Y_i C_{ep,i} \end{aligned} \tag{19}$$

The terms in Eq. (19) have been defined in-situ above.

To obtain the optimal solution, the following mathematical problem should be solved.

Minimize $TC_S(q, n, P)$

Subject to

$$Y_i = \begin{cases} 1 & ED + E(N)\,E_r\,\frac{D}{n\,q} + E_{tr} \geq E_{li} \\ 0 & \text{else} \end{cases}, \text{ where } i \in [1,m] \tag{20}$$

$$n \geq 1, \text{ inter value } P_{min} \leq P \leq P_{max}. \tag{21 and 22}$$

Condition (20) ensures that Y_i assumes value 1 when the corresponding emissions limit E_{li} is exceeded. Condition (21) makes sure that the number of shipment n is at least 1 and assumes an integer value. Condition (22) restricts the production rate to vary between a minimum and a maximum value, which may be due to technical reasons.

If emissions penalties are neglected, it is easy to demonstrate that (19) is convex in q, and it is possible to find the optimal value of the order quantity q' from (19).

$$\frac{\partial TC_S}{\partial q} = -\frac{(S/n + A)D}{q^2} + \frac{h_v}{2}[(1 - \frac{D}{P})n + \frac{2D}{P} - 1] + \frac{h_b}{2} + r\alpha(\beta + \omega P^2)\frac{nD}{2P} + c_{en}(\frac{W_{0,r}}{\gamma P} + k')\alpha(\beta + \omega P^2)\frac{nD}{2P} + c_{ec}\alpha(\beta + \omega P^2)\frac{nD}{2P}(a_r(\gamma P)^2 - b_r\gamma P + c_r) \tag{23}$$

$$\frac{\partial^2 TC_S}{\partial q^2} = \frac{2(S/n + A)D}{q^3} \tag{24}$$

$$q' = \sqrt{\frac{2(S/n + A)D}{h_v[(1 - \frac{D}{P})n + \frac{2D}{P} - 1] + h_b + \alpha(\beta + \omega P^2)\frac{nD}{P}[r + c_{en}(\frac{W_{0,r}}{\gamma P} + k') + c_{ec}(a_r(\gamma P)^2 - b_r\gamma P + c_r)]}} \tag{25}$$

Substituting (25) in (19) is then possible to obtain the analytical formulae for the optimal value of the number of shipments n' since $TC_S(q')$ is convex in n, as demonstrated in (26)–(27).

$$\frac{\partial TC_S(q')}{\partial n} = AD[h_v(1 - \frac{D}{P}) + \alpha(\beta + \omega P^2)\frac{D}{2P}[r + c_{en}(\frac{W_{0,r}}{\gamma P} + k') + c_{ec}(a_r(\gamma P)^2 - b_r\gamma P + c_r)]] - \frac{S}{n^2}D[h_v(\frac{2D}{P} - 1) + h_b] \tag{26}$$

$$\frac{\partial^2 TC_S}{\partial n^2} = \frac{2SD[h_v(\frac{2D}{P} - 1) + h_b]}{n^3} \tag{27}$$

$$n' = \sqrt{\frac{S[h_v(\frac{2D}{P} - 1) + h_b]}{A[h_v(1 - \frac{D}{P}) + \alpha(\beta + \omega P^2)\frac{D}{2P}[r + c_{en}(\frac{W_{0,r}}{\gamma P} + k') + c_{ec}(a_r(\gamma P)^2 - b_r\gamma P + c_r)]]}} \tag{28}$$

The mathematical problem described above could be simply solved by starting from the optimal solution without emissions penalties using a mathematical software (e.g., Mathematica) or by Excel. The following algorithm can be useful to provide the user with a step-by-step solution procedure.

Step 1. Set $Y_i = 0$ for $i \in [1, m]$, $n = n'$ (28), $q = q'$ (25), and $P = P_{min}$.
Step 2. Calculate $TC_S(q', n', P)$ from (19).
Step 3. Repeat Step 2 for P in the range from P_{min} to P_{max}, incrementing by one unit. The value of the decision variable P' that minimizes the supply chain total cost is determined.
Step 4. Compute the emissions generated and if $ED + E(N)E_r\frac{D}{n\,q} + E_{tr} \geq E_{li}$, set $Y_i = 1$ and repeat Step 4 for every $i \in [1, m]$. If at least one emission limit is violated, set $n = 1$ and $P = P_{min}$ and go to Step 5, otherwise the optimal solution is given by $(q^*, n^*, P^*) = (q', n', P')$.
Step 5. Evaluate the optimal value for, q^*, minimizing the total cost (19) using the Solver Add-In in nested loops, re-computing each time the total cost. If the new value of the total cost is less than the previous value, then the values of n and P are increased by one unit, and the process is repeated until the minimum total cost is found.

The suggested solution procedure is very similar to (Bazan et al., 2017).

Step 1 initialises the algorithm. First, emissions penalties are neglected by setting all Y_i equal to zero, and the lot size (q) and the number of shipment (n) are set to their optimal values for the specific case. Step 2 and 3 compute the optimal value for the production rate (P). Step 4 computes if any emission limit is violated and adds the corresponding penalty costs to the total costs. Step 5 provides the solution procedure if any emission limit is violated.

6. VMI-CS policy

The only difference between the VMI-CS and the traditional agreements is in calculating the holding costs. The total cost of the supply chain thus becomes:

$$TC_S = \frac{S\,D}{n\,q} + \frac{A\,D}{q} + h_v\frac{q}{2}\frac{D}{P} + (h_{v,fin} + h_{b,phy})\frac{q}{2}[(1 - \frac{D}{P})n + \frac{D}{P}] + c_S D + r\frac{D}{n\,q}E(N) + c_{en}(SEC\,D + SEC_r\,E(N)\frac{D}{n\,q}) + c_{ec}(DE + E_{tr} + E(N)E_r\frac{D}{n\,q}) + M\,\lambda\frac{D}{P} + c_t\frac{D}{t_c} + \sum_{i=1}^{m} Y_i C_{ep,i} \tag{29}$$

Eq. (26) differs from eq. (19) in the holding costs (i.e., in the third and fourth terms) since the two scenarios present different inventory policies.

The same mathematical problem and solution procedure defined for the traditional policy are then used to find the optimal solution.

Eq.s (30)–(31) demonstrate that (29) is convex in q when no emission penalties are considered, and it is possible to define the optimal value of the order quantity q'.

$$\frac{\partial TC_S}{\partial q} = -\frac{(S/n + A)D}{q^2} + \frac{h_v}{2}\frac{D}{P} + \frac{(h_{v,fin} + h_{b,phy})}{2}[(1 - \frac{D}{P})n + \frac{D}{P}] + r\alpha(\beta + \omega P^2)\frac{nD}{2P} + c_{en}(\frac{W_{0,r}}{\gamma P} + k')\alpha(\beta + \omega P^2)\frac{nD}{2P} + c_{ec}\alpha(\beta + \omega P^2)\frac{nD}{2P}(a_r(\gamma P)^2 - b_r\gamma P + c_r) \tag{30}$$

$$\frac{\partial^2 TC_S}{\partial q^2} = \frac{2(S/n + A)D}{q^3} \tag{31}$$

$$q' = \sqrt{\frac{2(S/n + A)D}{h_v\frac{D}{P} + (h_{v,fin} + h_{b,phy})[(1 - \frac{D}{P})n + \frac{D}{P}] + \alpha(\beta + \omega P^2)\frac{nD}{P}[r + c_{en}(\frac{W_{0,r}}{\gamma P} + k') + c_{ec}(a_r(\gamma P)^2 - b_r\gamma P + c_r)]}} \tag{32}$$

Substituting (32) in (29) is then possible to obtain the analytical formulae for the optimal value of the number of shipments n' since $TC_S(q')$ is convex in n, as demonstrated in (33)–(34).

$$\frac{\partial TC_S(q')}{\partial n} = AD[(h_{v,fin} + h_{b,phy})(1 - \frac{D}{P}) + \alpha(\beta + \omega P^2)\frac{D}{2P}[r + c_{en}(\frac{W_{0,r}}{\gamma P} + k') + c_{ec}(a_r(\gamma P)^2 - b_r\gamma P + c_r)]] - \frac{S}{n^2}\frac{D^2}{P}(h_v + h_{v,fin} + h_{b,phy}) \tag{33}$$

$$\frac{\partial^2 TC_S}{\partial q^2} = \frac{2S\frac{D^2}{P}(h_v + h_{v,fin} + h_{b,phy})}{n^3} \tag{34}$$

$$n' = \sqrt{\frac{S\frac{D}{P}(h_v + h_{v,fin} + h_{b,phy})}{A\left[(h_{v,fin} + h_{b,phy})\left(1 - \frac{D}{P}\right) + \alpha(\beta + \omega P^2)\frac{D}{2P}\left[r + c_{en}\left(\frac{W_{0,r}}{\gamma P} + k'\right) + c_{ec}(a_r(\gamma P)^2 - b_r\gamma P + c_r)\right]\right]}} \quad (35)$$

7. Numerical study

In this section, we present a numerical study we illustrated the behaviour of the developed model by comparing the traditional agreement and the VMI-CS policies. The parameters of the vendor-buyer system are taken and adjusted from existing studies in literature (Bazan et al., 2014, 2015a; 2015b): $\alpha = 30\%$, $A = 400\$$, $a = 3{\cdot}10^{-7}$ ton·h^2/unit^3, $a_r = 8.33{\cdot}10^{-7}$ ton·h^2/unit^{-3}, $\beta = 0.25$, $b = 0.0012$ ton·h/unit^2, $b_r = 0.002$ ton·h/unit^2, $c = 1.4$ ton/unit, $c_r = 1.4$ ton/unit, $c_{ec} = 18\$/\text{ton}$, $c_{en} = 0.15$ \$/kWh, $c_s = 0.5\$/\text{unit}$, $c_t = 500\$/\text{truck}$, $D = 1000$ unit/h, $e_t = 0.01008414$ ton/gallon, $\gamma = 1.2$, $g = 375$ gallons, $h_{b,fin} = 10\$/\text{unit·h}$, $h_{b,phy} = 20\$/\text{unit·h}$, $h_{v,fin} = 5\$/\text{unit·h}$, $h_{v,phy} = 55\$/\text{unit·h}$, $k = 10$ kW·h/unit, $k' = 8$ kW·h/unit, $\lambda = 0.75$, $M = 1000\$$, $P_{min} = 1000$ unit/h, $P_{max} = 3000$ unit/h, $r = 75\$/\text{unit}$, $S = 1200\$$, $t_c = 100$ unit/truck, $\omega = 10^{-6}$, $W_{0,p} = 100$ kW, $W_{0,r} = 80$ kW, and the emissions penalty schedule is given in Table 1.

Table 2 shows the results of the policies analysed in the previous sections. Shifting from the traditional agreement to the VMI-CS policy, the supply chain incurs a reduction (−3.31%) of the annual total cost. When it is expensive or the buyer to store items at its facility, it tends to make more frequent delivers to the buyer to free some space.

In the VMI-CS scenario, the vendor produces a higher lot size (nq) at a lower speed (P), in this way the vendor can reduce both the energy consumption and the emissions generated by the production and reworking processes. However, it must face a reduction also in the process quality; i.e., an increased number of defective items and a higher probability of machine breakdowns. The costs related to energy consumption and emissions amount to 20% of the total costs while process quality costs amount to 15–18% for both policies. For that reason, they are too relevant not to be considered.

In literature, the aspects considered in the present work have already been separately studied in works considering the traditional agreement and the VMI-CS policies. Bazan et al. (2014) integrated the models proposed by Hill (1997), and Braglia and Zavanella (2003) with the process quality issues, considering the opportunity to incur in imperfect production. Bazan et al. (2015b) considered the energy used in production processes and the GHG emissions from production and transportation activities (subject to a penalty tax). Table 3 shows the optimal values of the decision variables and the resulting total costs for both the policies in the four scenarios: (i) account only for the traditional inventory costs; (ii) scenario 1 plus process quality costs; (iii) scenario 1 plus the environmental costs; and (iv) integrate scenarios 2 and 3; i.e., scenario 1 plus quality and environmental costs. The main findings include that accounting for imperfect processes highly reduces the number of batch shipments per cycle, and reduces the overall cycle time, for both the policies, as was observed in Bazan et al. (2014). While introducing the environmental aspects in the traditional inventory scenario significantly increases the lot size ordered by the buyer, it reduces the number of shipments and makes the vendor's production rate faster. The total cost of scenario 4 falls in between those of scenario 2 and scenario 3. There are differences in the values of the decision variables as a result. An increase in the number of shipments and a slow production speed, which reduces the generation of defective items, are the reasons. Let ΔTC_S define the percentage variation in supply chain total costs shifting from the traditional agreement to the VMI-CS policy. The results in Table 3 highlight that the coordination policy changes when considering different costs components in the optimisation (i.e. different scenarios for different optimal policies). The results in Table 3 show that, when environmental issues are considered, the VMI-CS policy outperforms the traditional policy (i.e., $\Delta TC_S < 0$). The results also show the relevance of considering quality and environmental costs in supply chain decision-making processes. Not doing so will result in an expensive inventory and shipping policy. Optimizing inventory costs (i.e., disregarding quality and environmental costs) significantly increases the supply chain total cost. The results show that is beneficial to the supply chain to minimize the sum of inventory, quality, and environmental costs. The total supply chain cost is reduced by about 80% when comparing scenario 1 and 4.

Table 1
Emission penalty schedule (Jaber et al., 2013a).

i	Emission limit, E_{li}	Penalty charged, $C_{ep,i}$
1	$ED + E(N)E_r\frac{D}{nq} + E_{tr} < 220$	0
2	$220 \le ED + E(N)E_r\frac{D}{n\,q} + E_{tr} < 330$	\$1000
3	$330 \le ED + E(N)E_r\frac{D}{n\,q} + E_{tr} < 440$	\$2000
4	$440 \le ED + E(N)E_r\frac{D}{n\,q} + E_{tr} < 550$	\$3000
5	$550 \le ED + E(N)E_r\frac{D}{n\,q} + E_{tr} < 660$	\$4000
6	$660 \le ED + E(N)E_r\frac{D}{n\,q} + E_{tr}$	\$5000

Table 2
Optimal results under the traditional agreement and the VMI-CS policies.

Policy	q (unit)	n (shipment)	P (unit/h)	TC_S (\$/h)
Traditional	165	1	1808	32,335
VMI-CS	110	2	1750	31,264

Fig. 2 compares the supply chain total costs by varying the production rate in the model presented in this work with the ones present in literature focused separately on the aspects under examination. The trend of the total costs as a function of the production rate differs depending on the scenario considered. The TC functions are of a concave form when environmental costs are excluded (inventory-related costs with or without the quality cost) and convex when they are. Even the policy considered affects the trend of the total cost curve, especially when the environmental issues are taken into account. Fig. 2 shows that the production rate or speed influences the coordination policy and the behaviour of the model's total cost.

The behaviour of the developed models, as the results show, is influenced by the values of the input parameters. It is necessary, therefore, to perform sensitivity analyses to gain insights into the problem. The two policies, the traditional and VMI-CS, are investigated by varying the values of the input parameters for quality and environmental issues. The performance measure is as before, the total supply chain cost. Fig. 3 shows how low process quality, defined by high values of the percentage of defectives produced once the machine is in the "out-of-control" state (Fig. 3a) and the exponential parameter of the reliability function that reflects the frequency of machine breakdowns (Fig. 3b), results in better performance for VMI-CS policy over the traditional one.

Fig. 4 shows the behaviour of both policies (VMI-CS and traditional coordination) for changes in the holding costs, mainly the ratio of the vendor's to the buyer's holding costs. The results show that the VMI-CS policy (traditional) behaves better for low (high) values of the ratio. The breakeven point occurs when the vendor's holding cost that is more than 2.5 times the one of the buyer.

8. Conclusions

This paper developed a vendor-buyer green supply chain model jointly looking at environmental and quality issues in production and

Table 3
The optimal values of the decision variables and the total cost for the traditional and VMI-CS coordination policies for different scenarios.

Scenario	Policy	q (unit)	n (shipment)	P (unit/h)	TC_S ($/h)	ΔTC_S ($/h)
Traditional inventory costs	Traditional	96.37	67	1000	127,729	
	VMI-CS	97.06	101	1000	173,603	+ 35.91%
with process quality costs	Traditional	95.79	3	1000	37,408	
	VMI-CS	97.19	3	1000	38,203	+ 2.13%
with environmental-related costs	Traditional	144.07	2	1747	33,977	
	VMI-CS	127.82	3	1728	33,787	− 0.56%
with quality and environmental costs	Traditional	164.68	1	1808	32,335	
	VMI-CS	109.84	2	1750	31,264	− 3.31%

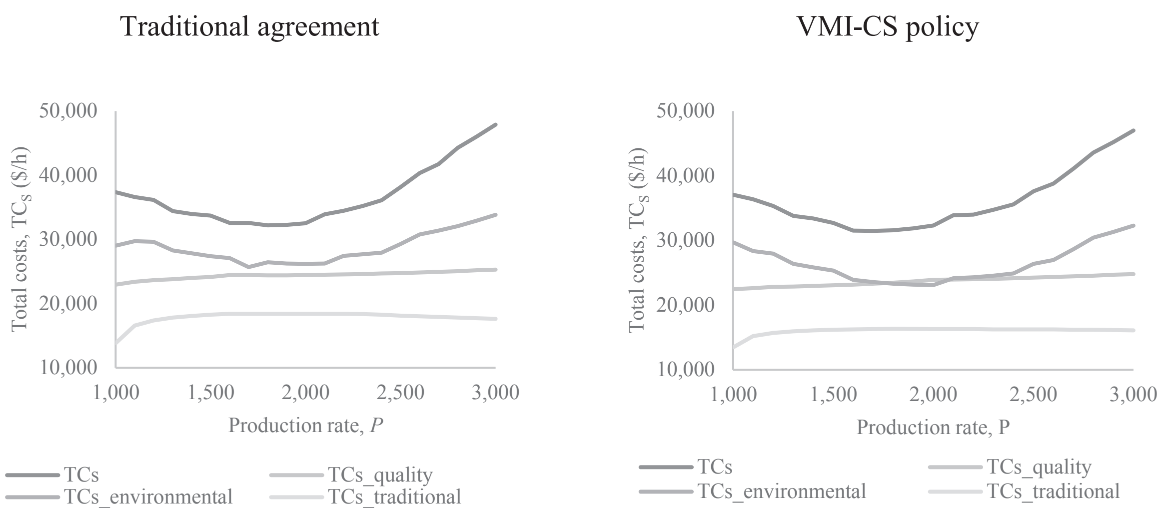

Fig. 2. Total costs of the supply chain considered in the optimisation step: i.e., $\boldsymbol{TC_S}$ identifies the model proposed in this work in which all the costs components are considered; $\boldsymbol{TC_{S\_quality}}$ optimizes the traditional inventory costs and the process quality costs; $\boldsymbol{TC_{S\_environmental}}$ considers the inventory and the environmental –related costs; while $\boldsymbol{TC_{S\_traditional}}$ accounts only traditional inventory costs.

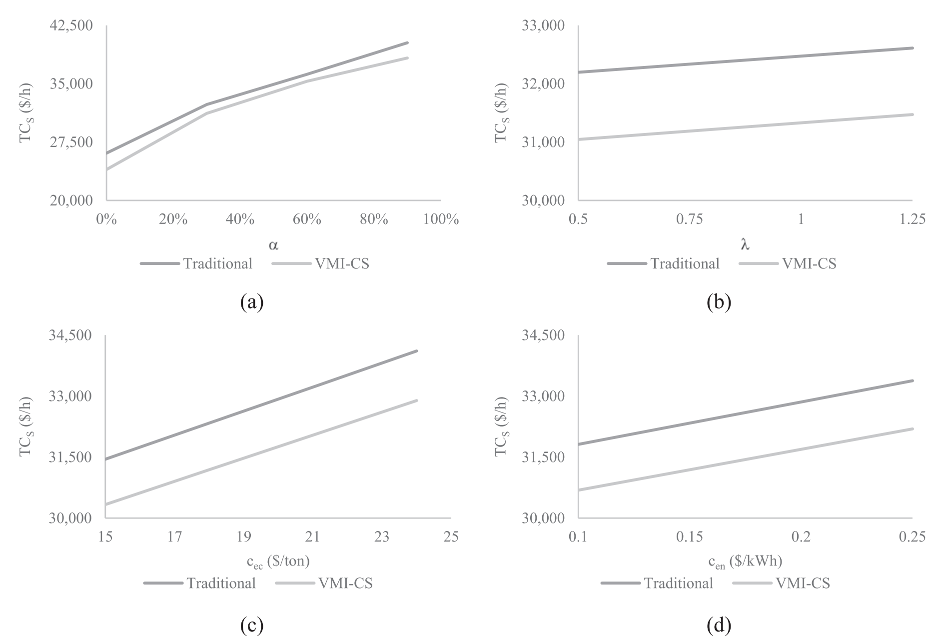

Fig. 3. Sensitivity analyses on the supply chain total cost by varying the following parameters: (a) percentage of defective items produced when the machine is in the "out-of-control" state $\boldsymbol{\alpha}$, (b) exponential parameter for the reliability function $\boldsymbol{\lambda}$, (c) the emission tax $\boldsymbol{c_{ec}}$, and (d) the unit energy cost for the vendor $\boldsymbol{c_{en}}$.

reworking processes. It assumes that the vendor's production rate impacts the environmental performance (i.e., energy consumption and CO_2 emissions) and process quality. A faster production increases energy usage and related emissions. It also affects the quality of the production process in term of defective items and machine reliability. Specifically, a higher speed of the production deteriorates the system faster, resulting in more defective items and a higher probability to incur in machine failures. Moreover, quality and reliability issues increase the energy consumed and the emissions generated when reworking defective items and repairing machines. A numerical example

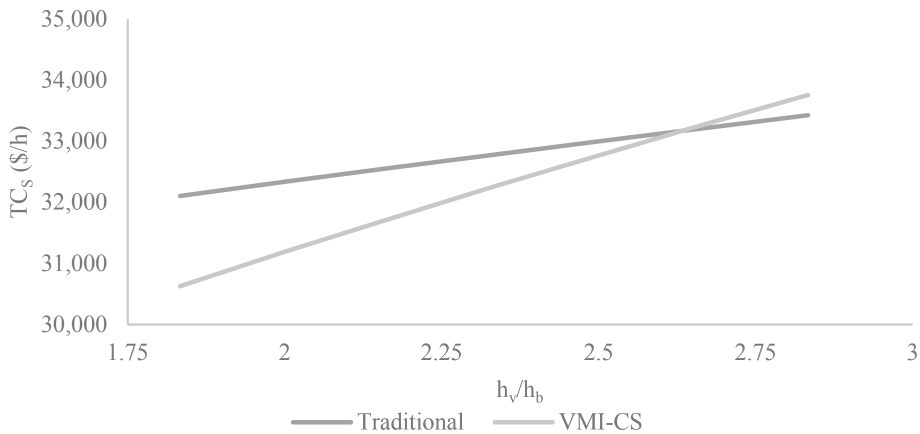

Fig. 4. Sensitivity analyses on the supply chain total cost varying the financial component of the holding cost of the vendor $h_{v,fin}$.

was presented to compare the behaviour of the two production-inventory policies considered: traditional agreement and VMI-CS policies.

The results showed that adopting a VMI-CS policy instead of a traditional one significantly reduces the supply chain total cost. In the VMI-CS scenario, the vendor produces a higher lot size (number of shipments × batch/shipment size or nq) at a lower speed (P close to the demand rate), in this way the vendor can reduce both the energy consumption and the emissions generated by the production and reworking processes. However, large production lot sizes result in more defective items and more frequent machine breakdowns. Moreover, costs related to energy consumption and emissions amount to 20% of the total costs while process quality costs amount to 15–18% for both policies. So, it is illogical not to consider them when making decisions in a supply chain. By considering quality and environmental costs along with the classical inventory costs and finding the minimum of their sum affect the values of the decision variables. It results in shipping larger lots less frequently than the traditional policy, which only reduces the inventory costs to a minimum. In this way, it is possible to reduce the overall costs of the supply chain by about 80%.

A possible future development of the present work consists in the integration of investments aiming at improving the energy efficiency (e.g. along the line of Marchi et al., 2018), which allows reducing energy usage and emissions, and the quality of the process, and at exploiting learning effects for speeding up the production process and reducing the probability of producing defective items.

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