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Sustainability strategies in an EPQ model with price- and quality-sensitive demand

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Abstract

Purpose – The purpose of this paper is to present a mathematical model that illustrates the trade-offs between sustainability, demand, costs, and profit in a supply chain with a single supplier and a single manufacturer.

Design/methodology/approach – It is assumed that a single product is produced and sold on a market where demand is sensitive to price and quality. Sustainability is treated as a quality attribute and is measured in terms of the levels of scrap and emissions generated in the supply chain. It is assumed that the emissions and scrap can be controlled by varying production rates or by investing in production processes. The impact of cooperative and non-cooperative behaviour between the supplier and the manufacturer is explored. Numerical studies are used to illustrate the behaviour of the model.

Findings – The analysis shows that the supplier and the manufacturer can attract additional customers by controlling scrap and emissions. The behaviour of the supplier and the manufacturer are dictated by the decision criteria, such as changes in the level of sustainability, used by customers to evaluate the product. It is shown that the profit of the system is higher and that the level of quality is lower in the case of cooperation than in the case of non-cooperation.

Research limitations/implications – Several areas for future work are highlighted. The study of alternative demand functions, linking sustainability to a monetary component, including additional players, and incorporating additional sustainability indicators all offer possibilities for extending the model.

Originality/value – There is an identified need for analytical models that consider sustainability in the supply chain. The results are especially important for companies operating in markets where customers perceive the sustainability of a product as a quality criterion.

Keywords Supply chain management, Profit, Demand, Costs, Sustainability, Indicator, Environment, Manufacturing, Price-sensitive demand, Quality-sensitive demand, Economic production quantity

Paper type Research paper

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1. Introduction

There is a growing recognition that corporations play a critical role in achieving global sustainability (Shrivastava, 1995). Over the last two decades, individual corporations and industry associations in virtually all economic sectors have developed policies, plans, and programmes to address sustainability issues. These initiatives typically focus on addressing the "triple bottom line" of corporate economic, environmental, and social performance (Elkington, 1997). One industry that has been particularly active in implementing sustainability initiatives is the manufacturing sector (Sarkis, 2001).

There are ongoing debates on what sustainability means in a manufacturing context. There is no universally accepted definition of sustainable manufacturing or sustainable production. However, one possible definition of sustainable production is "creating goods by using processes and systems that are non-polluting, that conserve energy and natural resources in economically viable, safe, and healthy ways for employees, communities, and consumers which are socially and creatively rewarding for all stakeholders in the short- and long-term future" (Glavic and Lukman, 2007). Although each corporation will define sustainability according to its own needs, this definition provides insight into the goals, objectives, and targets typically associated with sustainability initiatives in the manufacturing sector.

Much of the focus of sustainability research in the manufacturing sector has been on environmentally conscious manufacturing. In a recent review of the state of the art, Ilgin and Gupta (2010) classified nearly 550 papers published over the last decade into four major categories: environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing, and disassembly. The interest in environmentally conscious manufacturing is further demonstrated by the many other recent literature reviews on related topics, such as green supply-chain management (Srivastava, 2007), third-party logistics (Selviaridis and Spring, 2007), design for remanufacture (Hatcher *et al.*, 2011), and sustainable business development in manufacturing and services (Gunasekaran and Spalanzani, 2012), among others.

One of the key areas of focus in research on environmentally conscious manufacturing is measuring environmental impacts of processes and products. A variety of approaches have been developed to facilitate achieving this goal, including design for environment (Fiksel, 2009; Bevilacqua *et al.*, 2007) and life-cycle assessment (Reap *et al.*, 2008a, 2008b; Hischier and Baudin, 2010). There have also been numerous publications that focus specifically on the development of environmental and/or sustainability indicators. For example, sets of sustainable production indicators have been published by Veleva and Ellenbecker (2001) and Krajnc and Glavic (2003), among others. In both of these papers, lists of individual indicators are organised around key issues that represent aspects of sustainable production. For example, Veleva and Ellenbecker organised a list of 22 core indicators around the issues of energy and material use, natural environment, economic performance, community development and social justice, workers, and products. However, while the coverage of sustainability issues is typically broad in such sets of indicators, the interrelationships between the issues are often poorly conveyed.

To help address this issue, several publications have focused on the development of composite indices. For example, Singh *et al.* (2007) developed a broadly focused composite index of sustainability performance, including a case study demonstrating its application to the steel industry. Several other indices focus more narrowly on environmental issues. For instance, the Ecological Footprint (Wackernagel and Rees, 1996) computes the amount of land and water required to sustain an entity. Although initially intended as a measure of individual, regional, national, or global environmental sustainability, the Ecological Footprint has been applied in manufacturing contexts (e.g. Herva *et al.*, 2008). A detailed overview of sustainable assessment methodologies is provided by Singh *et al.* (2009). However, while the existing literature provides needed insight into the measurement of environmental and sustainability performance in manufacturing, there are several issues that require further exploration.

Measuring sustainability in the supply chain is a growing area of interest in the academic literature (Shuaib *et al.*, 2011). Research in this area has largely focused on measuring environmental dimensions (e.g. Hervani *et al.*, 2005), with research on the social aspects being more limited (e.g. Hutchins and Sutherland, 2008). Akyuz and Erkan (2010) summarised a number of remaining challenges regarding performance measurement in the supply chain, including the need to better address the issues of partnerships (Duffy and Fearne, 2004) and collaboration (Min *et al.*, 2005) between suppliers and manufacturers. Chen *et al.* (2010) explored the issue of coordination in a two-level supply chain consisting of a manufacturer, a retailer, and customers. However, their analysis highlights several opportunities for further research in that they did not consider inventory costs, did not compare coordinated and uncoordinated scenarios, and did not adequately address the complexities of investment associated with sustainability. Further details on performance measurement in the supply chain (Gunasekaran *et al.*, 2001; Lambert and Pohlen, 2001; Morgan, 2007) and broader information on sustainable supply-chain management (Seuring and Muller, 2008) are available in the literature.

Overall, the literature highlights a need for further research on the trade-offs between conflicting sustainability objectives (Hahn *et al.*, 2010). The fact that environmental and economic objectives are not always mutually supportive is rarely recognised in the development of sustainability indicators. There is also a need for additional research on the linkages between a manufacturer's sustainability performance, demand for its products, and the impact of coordination between suppliers and manufacturers. The linkages between corporate sustainability performance and financial performance have been widely studied (e.g. Lopez *et al.*, 2007). Meta-analyses of such studies have found that the results have been mixed, though there is evidence of a positive relationship between corporate social and financial performance (Orlitzky *et al.*, 2003). Studies on green consumerism (e.g. Peattie, 2001) and consumer willingness to pay for environmental and social product features (e.g. Auger *et al.*, 2003) have also been conducted. While the results of these studies have also been mixed, the overall findings of a recent literature review suggested that consumers were willing to pay a premium for sustainably produced products (Cotte and Trudel, 2009). This study also suggested that consumers will demand a discount for products produced in an unsustainable fashion. However, the trade-offs between sustainability, demand, costs, and profit have not been adequately addressed nor has the impact of coordination on sustainability in the supply chain been sufficiently addressed. An improved understanding of these issues are critical to guide future investments in sustainable production processes, such as reducing emissions and the amount of scrap material generated.

The purpose of this paper is to present a mathematical model that addresses these trade-offs by studying how the production-inventory policy of a manufacturer influences demand and how the sustainability of the production process interacts with the manufacturer's pricing decision. To gain more insights, the developed model was investigated in a simple two-level supply chain (supplier-manufacturer). Our review of the literature showed that there is no analytical model available that considers sustainability in a supply-chain context (e.g. Jaber and Zolfaghari, 2008; Ben-Daya *et al.*, 2008; Defee *et al.*, 2010; Chen *et al.*, 2010; Glock, 2012). However, a relevant work to the paper is that of El Saadany *et al.* (2011) who attempted at developing a method to quantify the quality of the environmental performance of a supply chain. El Saadany *et al.* (2011) proposed an aggregated quality function that captures a list of quantitative and qualitative elements (whose quality is measured on a scale 0-1 with associated weights) that are product, manufacturing, usage, operations, and customer/user based. The demand function, borrowed from Vörös (2002), was price and quality dependent and was investigated in a two-level supply chain. However, the model of El Saadany *et al.* (2011) does not explicitly treat CO_2 emissions and/or scrap, or provide a sustainability indicator as this paper does. Furthermore, their modelling approach is totally different from that of the paper. Another stream of research that is relevant to our paper studied the production of defective items and the generation of scrap (or non-reparable items) in lot size models. The reader is referred to the following works for further reference (Lee and Rosenblatt, 1987; Khan *et al.*, 2011; Glock and Jaber, in press a).

The results of the paper are especially important for companies operating in markets where customers perceive the sustainability of a product as a quality criterion. The paper shows that by controlling price and quality (sustainability) of a product, companies can stimulate demand and increase profit, which may result in a competitive advantage. The remainder of the paper is structured as follows: The next section introduces the model and Section 3 presents numerical results. The last section concludes the paper and provides suggestions for future research.

2. Model development

2.1 Problem description

This paper illustrates how a price-quality dependent demand function affects inventory policies in a supply chain. Product quality is used as a measure of sustainability in this paper, which is measured in terms of the levels of scrap and greenhouse gas emissions generated from all the production processes in a supply chain. For simplicity and illustrative purposes, the paper considers a supply chain with a single supplier and a single manufacturer (two players). The supplier produces a component which is transformed into a final product by the manufacturer. The demand on the side of the manufacturer is sensitive to both price and quality. The production processes for the supplier and the manufacturer are assumed to generate defective items and greenhouse gas emissions. The supplier and the manufacturer may be able to reduce the percentage of defective items by investing in their processes, while greenhouse gas emissions may be influenced by varying the production rate. Thus, the supplier and the manufacturer may control the degree to which their production processes impact the environment by altering their production policy. Assuming that end customers consider sustainable production as a quality criterion of the product they purchase, the supplier and the manufacturer can stimulate demand by either reducing the product price or by increasing the sustainability (quality) of the product, or both as an aggressive policy.

2.2 Assumptions and definitions

The following terminology is used throughout the paper:

- i is a subscript that is either s or m, where s is the supplier and m the manufacturer;
- a maximum demand in case quality equals zero (units/year);
- b elasticity of demand in price (units/dollars);
- γ_i parameter of the investment function of player *I;*
- c elasticity of demand in quality (units);

$D(p,q)$ demand as a function of price and quality (units/year);
d_i parameter of player i's emissions function (tonne · year^2/unit^3);
$E(P_i)$ level of emissions generated by player i (tonne/unit);
$E_{0,i}$ minimum emission level at player i (tonne/unit);
e_i parameter of player i's emissions function (tonne · year/unit^2);
Em level of emission avoidance;
f_i parameter of player i's emissions function (tonne/unit);
h_i holding cost for player i (dollars/unit/year);
I_i investment amount for player i (dollars);
P_i production rate for player i (unit/year);
$P_{\max,i}$ maximum production rate for player i (unit/year);
$P_{0,i}$ production rate that minimises emissions for player i (unit/year);
p_i price player i charges for the component/end product (dollars);
q product quality index;
K_s setup cost of the supplier (dollars);
Sc level of scrap avoidance;
$S_{0,i}$ minimum level of scrap attainable at player i (units); and
$S(I_i)$ level of scrap generated by player i with investment I_i (units).

Apart from the assumptions already stated, we assume the following hereafter:

(1) The supplier and the manufacturer have implemented a so-called lot-for-lot policy, where the supplier in every cycle produces, stores and ships to the manufacturer the exact quantity requested by the second (see e.g. Banerjee, 1986). For the case of an integer ratio policy, which is not considered in this paper, where the supplier may aggregate several orders of the buyer in a single production lot, the reader is referred to Goyal (1988), among others.

(2) End customer demand follows a linear function of price and quality (see Banker *et al.*, 1998):

$$D(p,q) = a - bp + cq, \tag{1}$$

where $D(p,q) > 0 \ \forall \ p > p_{\min}$ and $q \in [0,1]$.

(3) The environmental impact of the production process is treated as a quality characteristic in this paper, and it is assumed that the customers attribute a higher quality to products that have a minimal effect on the environment. To capture this attribute, we introduce a sustainability indicator SI to measure product quality, which accounts for two types of pollutants, namely emissions and scrap, and it is postulated as:

$$q = SI = Em \cdot Sc \tag{2}$$

(4) The percentage of defective items in a lot at the supplier (manufacturer) is a function of the investment I_s (I_m) chosen by the supplier (manufacturer). We assume that the following logarithmic investment function is valid:

$$S(I_i) = \begin{cases} S_{0,i} & \text{when } I_i = 0 \\ S_{0,i}(1 + I_i^{-\gamma_i}) & \text{when } I_i > 0 \end{cases} \tag{3}$$

with $0 < S(I_i) \leqslant 1 \ i = s, m$

(5) The level of scrap avoidance is defined as:

$$Sc = \frac{S_{0,s} + S_{0,m}}{S(I_s) + S(I_m)} \tag{4}$$

It is clear that $0 < Sc \leqslant 1$ and that the customers prefer high levels of Sc. It is consequently assumed that scrap is independent of either lot size or the production time. Models that consider a lot size-dependent or production time-dependent scrap rate are found in Lee and Rosenblatt (1987), Jaber and Khan (2010) and Glock and Jaber (in press b), among others.

(6) Emissions caused by the supplier and the manufacturer are assumed to depend on the production rates of the players, P_i, $i = s$, m, and to occur according to a quadratic function of the form $E(P_i) = d_i P_i^2 - e_i P_i + f_i$, (see e.g. Bogaschewsky, 1995; Jaber *et al.*, in press). Intuitively, a production rate P_0 which minimises emissions and which leads to a minimum emission level $E_{0,i}$ exists at $P_{0,i}$, with $P_{0,i} = e_i/2d_i$ and $E_{0,i} = f_i - (e_i^2/4d_i)$. The level of emission avoidance is defined as:

$$Em = \frac{E_{0,s} + E_{0,m}}{E(P_s) + E(P_m)} \tag{5}$$

(7) It is clear that $0 < Em \leqslant 1$ and that customers prefer a value of Em close to 1. Further, it follows that $0 < SI \leqslant 1$. In addition, it becomes obvious from Equations (4) and (5) that one company alone can only partially influence product quality; if the supplier, for example, reduces the level of scrap generated, but the manufacturer produces with a high fraction of defectives, the sustainability index will be low and customer demand will decrease. From Equations (2), (4) and (5), it follows that:

$$q = \frac{E_{0,s} + E_{0,m}}{E(P_s) + E(P_m)} \cdot \frac{S_{0,s} + S_{0,m}}{S(I_s) + S(I_m)} \tag{6}$$

(8) The paper concentrates on studying greenhouse gas emissions and scrap as sustainability indicators. The rationale for considering these two measures is that emissions and scrap are the main contributors to sustainability that production planners can influence. Other indicators of sustainability, such as fresh water consumption or the use of ecologically harmful substances in the production process, are often determined by a technical process which is not under control of production planning, but rather of the design department. Thus, the production planner can only influence indicators to a very limited extent once the design process has been finished. Therefore, we decided to exclude such indicators from our analysis. However, additional measures to the two used here could be considered in a future work.

(9) Production costs that vary with the production rate and that may be attributed to changes in energy consumption, for example, are not considered in this paper. The reader is referred to Glock (2010, 2011) for a discussion of

lot sizing problems with variable production rates and rate-dependent production costs.

(10) This paper aims to study how cooperative and non-cooperative behaviour between players (e.g. a supplier and a manufacturer) in a two-level supply-chain impact the level of sustainability of the product and the total costs of both players. In case of no cooperation between the supplier and the manufacturer, we assume that the manufacturer is the dominant party in the supply chain and may dictate its order quantity Q_m.

(11) To avoid planned shortages at the side of the manufacturer, it is assumed that the time required to produce a single lot of the supplier/manufacturer is shorter than the time required to consume the supplied lot by the end customer, i.e. $Q_s/P_s \geqslant (1-S(I_m))Q_m/D(p,q)$ and $Q_m/P_m \geqslant (1-S(I_m))Q_m/D(p,q)$.

2.3 The model

Figure 1 illustrates the behaviour of inventory over time for the supplier and the manufacturer. As can be seen, the supplier produces a lot of size Q_s in Q_s/P_s units of time and scraps $S(I_s)Q_s$ units after its production process has been completed. The reduced lot of size $(1-S(I_s))Q_s$ units is forwarded (delivered) to the manufacturer for the purpose of producing the final product. The manufacturer, in turn, produces a lot of size Q_m in Q_m/P_m units of time and scraps $S(I_m)Q_m$ units after the lot has been produced/delivered. If we assume that one unit of the supplier's product is required to produce one unit of output at the manufacturer, then $Q_m = (1-S(I_s))Q_s$ and the lot which is sold to the end customers is of size $(1-S(I_s))(1-S(I_m))Q_s$.

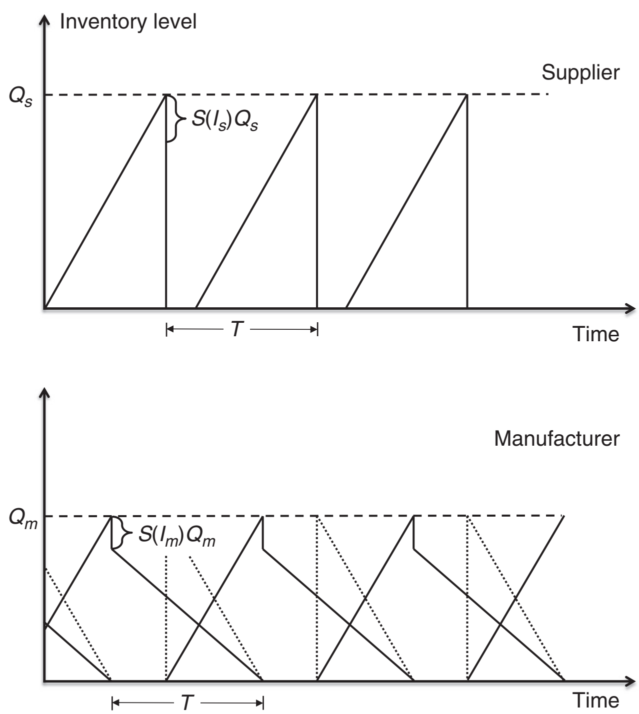

Figure 1.
Inventory time plot

For a given demand rate $D(p_m,q(I_s,I_m,P_s,P_m))$, the supplier's inventory carrying cost per unit of time is calculated as:

$$IC_s = \frac{Q_s h_s}{2P_s} \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m))} \tag{7}$$

We also assume that the supplier incurs investment and setup costs per unit of time, which is calculated as:

$$SC_s = \frac{(K_s + I_s) D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m)) Q_s} \tag{8}$$

The total cost per unit of time of the supplier, TC_s, is the sum of Equations (7) and (8) and is given as:

$$TC_s = \left(\frac{Q_s^2 h_s}{2P_s} + K_s + I_s \right) \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m)) Q_s} \tag{9}$$

In the following, we assume that the supplier sells the component at a net price p_s to the manufacturer. Considering Equation (9), the profit of the supplier can thus be calculated as (revenue minus total cost):

$$\begin{aligned} \Pi_s &= p_s Q_m \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m)) Q_s} - TC_s \\ &= \left(p_s (1 - S(I_s)) Q_s - \frac{Q_s^2 h_s}{2P_s} - K_s - I_s \right) \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m)) Q_s} \end{aligned} \tag{10}$$

Assuming that the inventory carrying charges are the same for semi-finished and finished products at the manufacturer, the inventory carrying cost at the manufacturer can be calculated as (from Figure 1):

$$\begin{aligned} IC_m = {} & \frac{(1 - S(I_s))^2 Q_s h_m}{2} \left(\frac{1}{P_m} + \frac{(1 - S(I_m))^2}{D(p_m, q(I_s, I_m, P_s, P_m))} \right) \\ & \times \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m))} \end{aligned} \tag{11}$$

Apart from the inventory carrying cost, the manufacturer incurs investment and ordering costs, which amount to:

$$SC_m = \frac{(K_m + I_m) D(p_m, q(I_s, I_m, P_s, P_m))}{(1 - S(I_s))(1 - S(I_m)) Q_s} \tag{12}$$

The total cost of the manufacturer, TC_m, which is the sum of Equations (11) and (12), is given as:

$$TC_m = \left(\frac{((1-S(I_s))Q_s)^2}{2} \left(\frac{1}{P_m} + \frac{(1-S(I_m))^2}{D(p_m, q(I_s, I_m, P_s, P_m))} \right) h_m + K_m + I_m \right) \times \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1-S(I_s))(1-S(I_m))Q_s} \tag{13}$$

Similar to the supplier, the manufacturer sells the product at a net price p_m to the end customer with $p_m > p_s$. Considering Equation (13) and the purchase price for the semi-finished product, the profit of the manufacturer can be calculated as (revenue minus total cost):

$$\begin{aligned} \Pi_m &= D(p_m, q(I_s, I_m, P_s, P_m))p_m - TC_m - p_s Q_m \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1-S(I_s))(1-S(I_m))Q_s} \\ &= D(p_m, q(I_s, I_m, P_s, P_m))p_m - \left(\frac{((1-S(I_s))Q_s)^2}{2} \left(\frac{1}{p_m} \right.\right. \\ &\quad \left.\left. + \frac{(1-S(I_m))^2}{D(p_m, q(I_s, I_m, P_s, P_m))} \right) h_m + K_m + I_m + p_s(1-S(I_s))Q_s \right) \\ &\quad \times \frac{D(p_m, q(I_s, I_m, P_s, P_m))}{(1-S(I_s))(1-S(I_m))Q_s} \end{aligned} \tag{14}$$

It is clear from Equations (7) and (11) that the players can minimise their inventory carrying costs during the production phase by choosing to produce at maximum capacity, $P_{\max,i}$. Adopting a higher production rate than $P_{0,i}$, however, increases greenhouse gas emissions of the production process and consequently reduces the demand rate D. For a given lot size, this leads to higher inventory carrying costs in the consumption phase of the lot and lower revenues from sales. Producing at a rate lower than $P_{0,i}$ is not beneficial for the manufacturer as it will lead to higher inventory carrying cost and lower customer demand. The optimisation problem of the supplier is to find values for P_s, p_s, and I_s that maximise its profit given in Equation (10), while the optimisation problem of the manufacturer is to find values for Q_m, P_m, p_m, and I_m that maximise its profit given in Equation (14). In the non-cooperative case, we assume that the manufacturer acts as the Stackelberg leader and the supplier as the follower, while in the cooperative case, the total profit function of the system, which is given as the sum of Equations (10) and (14), is optimised for all decision variables simultaneously.

Due to the complexity of the objective functions given by Equations (10) and (14), it is very difficult to prove concavity in any of the decision variables (e.g. (10) depends on the lot size decision of the manufacturer, which in turn depends on the demand rate, which is a function of the manufacturer's and the supplier's price). To calculate a good solution for the optimisation problem, we used the NMaximize-function of the Software-Package Mathematica 7.0 by Wolframs Research Inc, a function that contains several methods for solving constrained and unconstrained global optimisation problems, such as genetic algorithms, simulated annealing, or the Simplex method. Numerical examples are illustrated in the following section.

3. Numerical studies

To illustrate the behaviour of the model developed above, we consider the following input parameters: $a = 1{,}000$ (units/year), $b = 0.75$ (units/dollars), $c = 100$ (units), $d_s = 0.01$ (tonne · year^2/unit^3), $d_m = 0.012$ (tonne · year^2/units^3), $e_s = 10$ (tonne · year/unit^2), $e_m = 9.8$ (tonne · year/unit^2), $f_s = 12{,}500$ (tonne/unit), $f_m = 12{,}200$ (tonne/unit), $h_s = 4$ (dollars/unit/year), $h_m = 6$ (dollars/unit/year), $K_s = 250$ (dollars), $K_m = 80$ (dollars), $P_{\max,s} = 1{,}000$ (unit/year), $P_{\max,m} = 800$ (unit/year), $S_{0,s} = 0.1$ (unit), $S_{0,m} = 0.08$ (unit), $\gamma_s = 0.1$, and $\gamma_m = 0.12$ (cf. example No. 1 in Table I). If the supplier and the manufacturer do not cooperate, then, for this set of parameters, the manufacturer orders a quantity of $Q_s{*} = 337.71$ units and produces at a rate of $P_m{*} = 452.52$ units/year. The supplier selects a production rate of $P_s{*} = 518.79$ units/year, and both players invest $I_s{*} = 883.18$ and $I_m{*} = 1{,}194.72$ dollars to reduce the fraction of defectives. The price of the supplier equals $p_s{*} = 627.79$ dollars, while the manufacturer charges $p_m{*} = 1{,}069.84$ dollars from the end customers. This leads to an end customer demand of 265.47 units/year. The profits of the supplier and the manufacturer are $\Pi_s = 186{,}500.10$ and $\Pi_m = 93{,}205.06$ dollars, and the profit of the system equals $\Pi = 279{,}705.16$ dollars. In contrast, if the supplier and the manufacturer cooperate, the optimal order quantity $Q_s{*} = 353.24$ units, which is produced/processed at production rates of $P_s{*} = 700.08$ and $P_m{*} = 592.17$ units/year and with investments in the amounts of $I_s{*} = 462.81$ and $I_m{*} = 414.51$ dollars, respectively. The manufacturer chooses a final

No.	c	b	e_s	f_s	h_s	$S_{0,s}$	γ_s
1	100	0.75	10	12,500	4	0.1	0.1
2	50	0.75	10	12,500	4	0.1	0.1
3	10	0.75	10	12,500	4	0.1	0.1
4	0	0.75	10	12,500	4	0.1	0.1
5	150	0.75	10	12,500	4	0.1	0.1
6	200	0.75	10	12,500	4	0.1	0.1
7	100	0.50	10	12,500	4	0.1	0.1
8	100	0.25	10	12,500	4	0.1	0.1
9	100	1.00	10	12,500	4	0.1	0.1
10	100	1.25	10	12,500	4	0.1	0.1
11	100	0.75	12	12,500	4	0.1	0.1
12	100	0.75	14	12,500	4	0.1	0.1
13	100	0.75	16	12,500	4	0.1	0.1
14	100	0.75	10	7,500	4	0.1	0.1
15	100	0.75	10	5,000	4	0.1	0.1
16	100	0.75	10	2,500	4	0.1	0.1
17	100	0.75	10	12,500	2	0.1	0.1
18	100	0.75	10	12,500	1	0.1	0.1
19	100	0.75	10	12,500	8	0.1	0.1
20	100	0.75	10	12,500	16	0.1	0.1
21	100	0.75	10	12,500	4	0.2	0.1
22	100	0.75	10	12,500	4	0.4	0.1
23	100	0.75	10	12,500	4	0.1	0.5
24	100	0.75	10	12,500	4	0.1	1.0
25	100	0.75	10	12,500	4	0.1	2.0

Table I. Sample data sets used for numerical experimentation price $p_m{}^* = 722.14$, which leads to a demand that equals 521.82 units/year. The profit of the supply chain will be 372,035.81 dollars (note that the supplier's selling price is irrelevant from the system's perspective, since it only serves the purpose of allocating the supply-chain profit on the supply-chain partners. Since p_s is not included in the optimisation problem that results from adding Equations (10) and (14), the supplier's price and profit were neglected in Table III).

By comparing the results, it becomes clear that in case of cooperation, the profit of the system is higher than in the case of non-cooperation. This has two reasons: first, this is a result of the well-known double marginalisation problem, which occurs when the supplier and the buyer both calculate their prices by adding a profit margin to their respective total costs (see e.g. Spengler, 1950). Vertical integration is one possibility to avoid the double marginalisation phenomenon, which is the underlying assumption of the cooperative case. Second, the manufacturer does not consider the supplier's cost function when deciding on the order quantity, which increases in the supplier's total cost (note that although the order frequency is lower in the uncoordinated case than in the case of coordination, the supplier would still prefer a lower order frequency due to $K_s > K_m$). Cooperation is again a suitable measure to balance the supplier's and the manufacturer's inventory and setup/ordering costs and to increase the system profit. Finally, it can be seen that in case of non-cooperation, product quality, as measured by the sustainability index given in Equation (2), is higher than in the cooperative case. This is a result of the high-price level under individual optimisation, which induces the supply-chain partners to increase product quality to attract additional customers. In contrast, the price level is lower in the coordinated case, wherefore buyer and supplier do not have to increase the sustainability index to balance the loss of price-oriented customers. Clearly, lower sustainability levels in the coordinated case are bad for the environment; however, since increasing sustainability is usually associated with high costs, the buyer and the supplier can maximise their profits by choosing not to reduce emissions and scrap to minimum levels if it is not necessary to do so (or if customers can be satisfied by other measures as well, for example by a reduction in the end price).

To gain further insights into the behaviour of the model, we varied several of the model parameters and studied their impact on the decision variables and the profit of the manufacturer. The data sets can be found in Table I, and the results are summarised in Tables II and III.

It is also clear that a variation in the elasticity of demand in quality, c, influences the importance of product quality from the end customer's perspective. If c is reduced, customers would be less interested in the sustainability of the manufacturer's production process and attribute a relatively higher importance to the price of the product. Consequently, the supplier and the manufacturer have a poor incentive to produce with minimum emissions and scrap, wherefore both react with a reduction in the investment to lower investment costs (cf. example Nos 1-4). By comparing the results in Tables II and III, it can further be observed that in case of individual optimisation, the investment levels are higher for $c > 0$ than in case of joint optimisation. One reason for this tendency is that the supplier may influence the production cycle by investing in product quality, since a higher proportion of good items in a lot increases the time between two setups and consequently reduces setup costs. A second reason is that the price in the case of individual optimisation is much higher than in the case of joint optimisation, wherefore both players have to increase product quality to attract additional customers. In case $c = 0$, the players have no

Table II. Results of the numerical study (individual optimisation)

No.	Q_s	P_s	P_m	I_s	I_m	p_s	p_m	$E(P_s)$	$E(P_m)$	$S(I_s)$	$S(I_m)$	q	$D(p,q)$	Π_s	Π_m	Π
1	337.71	518.79	452.52	883.18	1,194.72	627.79	1,069.84	10,003.5	10,222.6	0.1507	0.1142	0.6785	265.47	186,500.10	93,205.06	279,705.16
2	297.02	532.32	479.13	402.85	889.78	606.64	1,034.75	10,010.4	10,259.3	0.1549	0.1154	0.6636	257.12	175,186.88	87,477.84	262,664.72
3	285.26	625.66	626.25	83.82	723.50	590.28	1,007.33	10,157.9	10,769.0	0.1642	0.1163	0.6193	250.69	166,748.79	83,164.66	249,913.45
4	301.65	1000.0	800.00	4.60	714.09	586.53	1,000.90	12,500.0	12,040.0	0.1858	0.1164	0.4903	249.33	164,992.20	82,232.52	247,224.72
5	383.65	514.23	442.83	1,471.72	1,562.97	649.21	1,105.57	10,002.0	10,213.4	0.1482	0.1131	0.6883	274.06	198,440.86	99,274.45	297,715.31
6	432.18	511.98	437.84	2,174.31	1,990.76	670.90	1,141.85	10,001.4	10,209.6	0.1464	0.1122	0.6958	282.78	210,958.00	105,635.66	316,593.66
7	456.94	516.58	448.09	1,760.63	2,286.92	945.87	1,606.67	10,002.7	10,218.1	0.1474	0.1116	0.6943	266.09	281,144.39	140,571.04	421,715.43
8	788.02	513.76	442.29	5,856.07	7,112.15	1,905.82	3,220.45	10,001.9	10,213.0	0.1420	0.1076	0.7206	266.95	566,323.08	283,233.96	849,557.04
9	276.05	520.78	456.44	547.60	762.51	469.36	801.77	10,004.3	10,226.9	0.1532	0.1161	0.6673	264.96	139,294.81	69,584.15	208,878.96
10	238.50	522.67	460.11	381.54	543.22	374.58	641.09	10,005.1	10,231.3	0.1552	0.1176	0.6587	264.51	111,017.38	55,438.18	166,455.56
11	337.15	612.71	450.42	881.49	1,192.80	627.68	1,069.79	8,901.6	10,220.4	0.1508	0.1142	0.6786	265.52	186,570.55	93,237.78	279,808.33
12	336.46	708.83	447.91	879.54	1,190.51	627.59	1,069.75	7,600.8	10,218.0	0.1508	0.1142	0.6786	265.55	186,621.55	93,262.89	279,884.44
13	335.64	806.24	444.97	877.08	1,187.70	627.43	1,069.66	6,100.3	10,215.3	0.1508	0.1142	0.6786	265.61	186,659.29	93,307.89	279,967.18
14	335.02	514.27	442.77	876.55	1,186.12	627.77	1,069.86	5,002.0	10,213.4	0.1508	0.1142	0.6785	265.46	186,487.69	93,201.43	279,689.12
15	333.57	511.98	437.66	872.92	1,181.47	627.73	1,069.85	2,501.4	10,209.5	0.1508	0.1142	0.6785	265.46	186,481.18	93,208.25	279,689.43
16	332.05	509.66	432.35	869.22	1,176.64	627.73	1,069.87	0.9	10,206.1	0.1508	0.1142	0.6785	265.45	186,474.45	93,202.89	279,677.34
17	337.72	509.73	452.51	882.10	1,194.33	627.43	1,069.64	10,000.9	10,022.6	0.1508	0.1142	0.6786	265.63	186,728.89	93,315.49	280,044.38
18	337.72	504.96	452.51	881.48	1,194.09	627.23	1,069.53	10,000.2	10,022.6	0.1508	0.1142	0.6786	265.71	186,845.65	93,375.98	280,221.63
19	337.69	535.33	452.55	884.86	1,195.26	628.41	1,070.17	10,012.5	10,022.5	0.1507	0.1142	0.6783	265.20	186,058.85	93,009.60	279,068.45
20	337.59	563.88	452.64	887.30	1,195.86	629.51	1,070.73	10,040.8	10,022.4	0.1507	0.1142	0.6773	264.68	185,227.98	92,648.38	277,876.36
21	376.71	525.05	449.77	1,027.35	999.68	627.44	1,069.36	10,006.3	10,025.2	0.3000	0.1149	0.6740	265.38	186,062.05	93,200.40	279,262.45
22	612.30	562.11	447.69	1,205.05	868.93	628.69	1,069.97	10,038.6	10,027.4	0.5968	0.1155	0.6720	264.72	184,780.94	92,779.82	277,560.76
23	356.53	515.55	449.24	591.25	1,496.17	637.14	1,085.06	10,002.4	10,025.8	0.1041	0.1133	0.8271	268.92	191,958.23	95,572.34	287,530.57
24	358.89	515.32	449.02	173.35	1,528.96	637.86	1,086.40	10,002.3	10,026.0	0.1006	0.1132	0.8411	269.31	192,838.31	95,844.83	288,683.14
25	359.25	515.29	448.99	39.25	1,533.80	637.91	1,086.57	10,002.3	10,026.0	0.1001	0.1132	0.8432	269.39	193,035.67	95,902.19	288,937.86

Table III.
Results of the numerical study (joint optimisation)

No.	Q_s	P_s	P_m	I_s	I_m	p_m	$E(P_s)$	$E(P_m)$	$S(I_s)$	$S(I_m)$	q	$D(p,q)$	Π
1	353.24	700.08	592.17	462.81	414.51	722.14	10,400.3	10,604.7	0.1541	0.1188	0.6342	521.82	372,035.81
2	261.38	692.87	582.23	174.39	159.27	693.81	10,372.0	10,562.0	0.1597	0.1235	0.6132	510.30	350,536.06
3	202.53	698.39	597.29	28.00	27.25	672.75	10,358.7	10,627.6	0.1717	0.1338	0.5662	501.10	334,457.83
4	214.70	1,000	800	2.12	3.92	668.50	12,500.0	12,040.0	0.1928	0.1479	0.4349	498.63	331,061.57
5	456.53	709.89	602.88	883.74	782.74	751.96	10,440.5	10,653.3	0.1507	0.1160	0.6463	532.97	394,564.15
6	566.93	720.37	613.53	1,443.64	1,268.85	782.97	10,487.9	10,704.4	0.1483	0.1139	0.6543	543.63	417,911.83
7	449.46	696.39	591.37	871.83	770.75	1,084.35	10,385.7	10,601.2	0.1508	0.1160	0.6492	522.75	560,730.70
8	751.89	690.08	589.90	2,831.22	2,445.20	2,173.70	10,361.3	10,594.8	0.1452	0.1114	0.6763	524.21	1,129,177.63
9	307.61	702.58	592.66	304.59	275.25	541.32	10,410.4	10,606.9	0.1564	0.1208	0.6240	521.09	277,917.27
10	281.42	704.41	592.97	224.11	203.92	432.95	10,417.8	10,608.3	0.1582	0.1223	0.6165	520.47	221,541.63
11	353.40	702.62	594.30	460.18	413.84	720.68	9,005.3	10,614.2	0.1542	0.1188	0.6419	523.68	372,617.59
12	353.42	719.46	596.10	453.37	409.69	718.82	7,603.8	10,622.2	0.1542	0.1189	0.6436	525.25	372,800.30
13	362.54	814.31	595.60	463.66	420.27	719.24	6,102.1	10,620.0	0.1541	0.1188	0.6430	524.87	372,789.91
14	352.87	696.60	589.23	462.87	417.95	724.66	5,386.5	10,591.8	0.1541	0.1188	0.6274	519.24	371,495.56
15	352.59	694.02	587.05	462.90	420.49	726.53	2,876.4	10,582.4	0.1541	0.1187	0.6224	517.34	371,087.90
16	352.19	690.45	584.03	462.93	424.00	729.13	362.7	10,569.6	0.1541	0.1187	0.6155	514.70	370,512.48
17	399.17	699.38	592.03	520.80	465.75	722.26	10,397.5	10,604.1	0.1535	0.1183	0.6370	522.01	372,410.88
18	428.15	698.98	591.94	557.18	497.87	722.34	10,395.9	10,603.7	0.1531	0.1180	0.6386	522.11	372,617.51
19	290.92	701.20	592.40	383.61	344.44	721.95	10,404.8	10,605.7	0.1552	0.1197	0.6296	521.50	371,396.60
20	221.44	702.78	592.70	294.48	265.42	721.74	10,411.2	10,607.1	0.1566	0.1209	0.6232	521.01	370,387.73
21	417.73	846.30	587.82	603.99	285.91	725.34	11,199.2	10,585.8	0.3054	0.1206	0.6094	516.94	370,012.75
22	1,621.69	1,000	512.41	9,601.62	1,388.50	897.25	12,500	10,329.2	0.5599	0.1136	0.6306	390.12	336,078.45
23	351.30	668.40	598.01	355.51	616.94	733.54	10,283.6	10,630.9	0.1053	0.1170	0.7820	528.04	382,385.29
24	308.22	666.39	599.15	110.63	568.38	734.43	10,276.9	10,636.1	0.1009	0.1174	0.7965	528.83	384,023.79
25	291.19	666.17	599.47	28.54	542.88	734.49	10,276.1	10,637.6	0.1001	0.1176	0.7986	528.99	384,413.51

incentive to increase product quality. In this case, investments are only made to influence the order and production cycles and to economise on purchasing costs. A last observation is that lower values for c imply that product price becomes the major criterion in the purchasing decision of the customers. Accordingly, the supplier and the manufacturer react by reducing their respective prices to attract further buyers and to compensate for the loss of quality-oriented customers. Although this dampens the decline in demand somewhat, overall customer demand is reduced and the manufacturer's profit declines. In contrast, if the value of c increases, the importance of product quality increases. This entices the supplier and the manufacturer to invest in the production process to reduce the amount of units that need to be scrapped (cf. example Nos 5 and 6).

Similarly, the elasticity of demand in price, b, influences customer demand. Consequently, customers are more sensitive to product price for higher values of b than for lower ones, which leads to high-price levels for low values of b and vice versa (cf. example Nos 7-10). Further, it can be seen that for lower values of b, the supplier and the manufacturer try to attract further customers by increasing product quality, while in the case of highly price-sensitive demand, product quality is reduced. Clearly, there is an interaction between price and product quality: if price has to be reduced, both parties try to stimulate demand by increasing product quality, and if the price can be increased, the parties try to attract some additional quality-oriented customers who then have to pay the high price as well.

In the next step of our analysis, we increase the value of the parameter e_s, which represents the technical characteristics of the production process that relates the variation in the production rate to the amount of greenhouse gas emissions generated in the production process. An increase in e_s reduces the slope of the emission function of the supplier and consequently the impact a variation in P_s has on the level of emissions. Since an increase in e_s further leads to a higher emission-minimal production rate $P_{0,s}$ (see Assumption (6) in Section 2.2), P_s is increased as e_s takes on higher values (cf. example Nos 11-13). It was found that the production rate of the manufacturer is somewhat insensitive to changes in e_s. As product quality remains almost unchanged while the value of e_s varies, the profits of the supplier and the manufacturer increase slightly as e_s increases. A reduction in the parameter f_s, in turn, leads to lower emissions per unit produced for a given value of P_s. Although this is favourable as it less negatively impacts the environment, the supplier faces, as a result, the problem that a variation in the P_s value leads to a relatively higher increase in the greenhouse gas emissions. Consequently, the supplier reacts by reducing P_s as f_s reduces, which reduces the supply chain's total profit (cf. example Nos 14-16). Thus, it is not beneficial from the perspectives of the supplier and the manufacturer to reduce the parameters e_i and f_i and therewith the overall greenhouse gas emissions generated by the supply chain, especially since a reduction in e_i and f_i would be associated with a cost in many practical situations. This is due to the fact that the decision criterion used by the customers in this paper only considers changes in the amount of greenhouse gas emissions generated, but not the overall level of emissions caused, which gives wrong incentives to the supply-chain partners (as seen from an environmental perspective).

Example Nos 17-20 illustrate the effect of a variation in the inventory carrying charges on the supply chain. It can be seen that a decrease in h_s reduces the importance of inventory carrying cost in the model, which leads to a larger lot size and a lower production rate P_s in case of joint optimisation. In case of individual optimisation, the lot size remains relatively constant as it is a decision variable of the manufacturer.

In this case, the supplier may only influence inventory carrying cost by varying P_s. A reduction in P_s, in turn, increases product quality and customer demand. The profits of the supplier and the manufacturer consequently increase as h_s is reduced and vice versa.

In case the minimum scrap rate of the supplier, $S_{0,s}$, increases, the supplier tends to increase the amount invested, I_s, to bring the level of scrap generated by its manufacturing process closer to an acceptable level. The manufacturer, in turn, increases the order quantity to increase the number of good units per lot that can be sold on the market. This mechanism results in an increase in the production rate of the supplier, which reduces inventory carrying cost. In the case of coordination, the production rate of the supplier reaches the maximum production rate for a high value of $S_{0,s}$ due to the higher demand level, which induces the supplier to increase its investment to reduce the fraction of defectives in a lot. The profits of the supplier and the manufacturer decrease as $S_{0,s}$ increases for both the cases of coordination and non-coordination (cf. example Nos 21-22).

Finally, a variation in the parameter γ_i influences the amount of investment needed by a player to reduce the scrap generated from its production process to a given level. High values of γ_s require less investment to bring the level of scrap close to the minimal and desired level $S_{0,s}$, while the opposite holds when value of γ_s is close to 0. As can be seen from example Nos 23-25, the supplier reduces the scrap rate as γ_s increases. Furthermore, since a low level of scrap avoidance, *Sc*, stimulates the impact of a variation in P_s on product quality due to the multiplicative correlation of *Em* and *Sc* (see Equation (2)), the supplier simultaneously reduces its production rate P_s to lower the greenhouse gas emissions its processes generates. This, ceteris paribus, leads to higher product quality, higher customer demand, and an increase in the supplier's profit. In case of a joint optimisation of the supplier and the manufacturer profit functions, the manufacturer reduces its order quantity as γ_s increases since a higher fraction of good units are contained in the production lot of the supplier. This enables the manufacturer to reduce its investment to reduce the scrap its processes generate. In case of individual optimisation, the order quantity is relatively insensitive, which induces the manufacturer to increase its investment as γ_s increases. The manufacturer, however, also benefits from an increase in γ_s at the supplier and realises higher profits for high values of γ_s.

4. Conclusion

This paper studied a supplier and a manufacturer producing a single product which is sold on a market with price- and quality-sensitive demand. The production processes of the supplier and the manufacturer were assumed to produce emissions and to generate scrap, and it was also assumed that both players can control the emissions and the scrap they generate by varying their respective production rates or by investing in the production processes. It was shown that by controlling scrap and emissions, the supplier and the manufacturer can attract additional customers and increase their profits, which may result in the supply chain having a competitive advantage over its competitors.

The results indicate that the decision criterion used by the customers to evaluate products determines the behaviour of the supplier and the manufacturer. If customers only value changes in the level of sustainability, as was assumed in this paper, the players in the supply chain will solely concentrate on the variations in the levels of greenhouse gas emissions and scrap, which is maximised in case they want to attract further customers or minimised in case they try to conceal lower overall levels of sustainability. In fact, if customers only value changes in the level of sustainability, the supply chain has no incentive to reduce the overall levels of scrap and emissions, which would increase the negative impact of changes in the production rate and would make higher investment levels necessary. This illustrates that more sophisticated decision criteria (or incentive systems) are necessary if customers want to give manufacturers an incentive to increase the sustainability of their production processes. Further, our results showed that the elasticity of demand in price and quality is critical for the amount of greenhouse gas emissions and scrap produced in the supply chain and for the price of the final product. If customers value sustainable products, and if they are willing to pay a premium price for sustainably produced products, then manufacturers have an incentive to reduce greenhouse gas emissions and scrap. If, in contrast, price is the primary decision criterion of the customers' purchase decisions, then manufacturers will try to reduce the price of the product at the expense of lower sustainability levels. This illustrates that besides the technological characteristics of the production process, customer preferences are a major determinant of sustainability in the supply chain.

Another interesting aspect that was found in the numerical studies of this paper is that coordination consistently led to lower quality levels (and consequently less sustainable products) than the case where each party maximises its individual profit. This is a result of the double marginalisation phenomenon: if two players in a supply chain add a profit margin to their respective total costs, this results in a high end customer price which is too high to maximise system profit. An excessive end customer price, in turn, forces the members of the supply chain to increase product quality to attract additional customers, which explains this effect. To gain further insights into this phenomenon, future work could study alternative demand functions to see whether our result remains valid. Further, it would also be interesting to study whether linking sustainability to a monetary component, for example by an emission tax (see e.g. Jaber *et al.*, in press), could be a measure to increase quality in case of cooperation.

Future research could also focus on studying the impact of alternative decision criteria on the behaviour of the supply-chain members to identify market conditions under which the supply chain also reduces the absolute levels of emissions and scrap. In addition, it would be interesting to include additional manufacturers or production stages into the model that compete on price and quality. This would permit analysing how sustainability and pricing strategies of one manufacturer impact the behaviour of other competitors in the market as everyone will compete to increase its market share. Finally, including further sustainability indicators in the model could lead to interesting results.

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