Environmental performance measures for supply chains

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Abstract

Purpose – The paper seeks to develop an analytical decision model that is used to investigate the performance of a supply chain when product, process, and environmental quality characteristics are considered.

Design/methodology/approach – Environmental performance measures and methods to quantify quality are reviewed and then used to develop a method to measure environmental quality and its associated costs. This was translated into a two-level supply chain coordination model that captures most aspects of green supply chains. Numerical examples are provided and solved using Excel Solver enhanced with VBA codes.

Findings – The results confirmed some findings in the literature that investing to reduce environmental costs improves environmental performance and increases total profits.

Research limitations/implications – The environmental quality cost function that was used was of a form that guarantees a global optimal solution. A limitation is that the function may take more complex forms where different analytical and solution methods would be needed.

Originality/value – The model fills a gap in the literature where there is a lack of models to help managers implement environmentally acceptable coordinated two-level supply chains.

Keywords Green supply chain, Environment, Quality, Quantitative models, Supply chain management, Sustainable development

Paper type Research paper

1. Supply chain and the environment

Supply chain management (SCM) integrates business processes to provide products, services, and information with an added value for customers and other stakeholders. It also ensures that customers demand is fulfilled through the integration of distribution channels and stages in a supply chain (Lambert, 2008; Chopra and Meindl, 2001). Competitive markets and the introduction of new technologies (e.g. the internet) changed business-to-business connectivity into SCM, where rapid transmission of upstream information along the stages of the chain speeds up the delivery of the desired products to customers. Excessive consumption behaviour depletes natural resources and generates waste at faster rates with severe environmental and social implications (Packard, 1960; Beamon, 1999) and could not continue at the current rates.

The authors thank the Social Sciences and Humanities Research Council of Canada (SSHRC) – Canadian Environmental Issues – for their financial support.

Management Research Review
Vol. 34 No. 11, 2011
pp. 1202-1221

2040-8269
DOI 10.1108/01409171111178756

Recycling has been a human practice for hundreds of years and it has numerous environmental and economic benefits (Van Hoel, 1978). The importance of recycling and similar activities (e.g. remanufacturing, repair, reuse, refurbishing) has been growing since the 1960s, and was reflected in research. Reverse logistics manages the upstream flow of collected used or returned products in a supply chain for the purpose of recovery to reduce the harmful effects of consumerism. The interest in reverse logistics grew with the growing popularity of SCM.

Public awareness accompanied with governmental legislation led manufacturing firms to consider integrating environmental solutions into their SCM practices (Walton *et al.*, 1998; Fleischmann *et al.*, 1997). Consumer awareness and governmental legislation play a major role in implementing green practices and product recovery programs (De Clercq, 1996; Irland, 2007). For example, the Belgian ecotax law improved public environmental awareness. However, Syring (1976) found that inappropriate tax legislation was partly responsible for reducing recovery rates and recycling activities in the 1970s, and the author recommended revising governmental procurement policies to amend the situation.

Supply chains can be greened by reducing energy and virgin raw material usage and waste generation, and increasing product recovery options. The size of reverse logistics was estimated to be about $56 billion in 2007 in the USA alone and growing (Beltran, 2002; Lambert, 2008), which implies a positive relationship between green practices and the economic competitiveness of a company (Hart and Ahuja, 1996). Although the term “green supply chains” has much in common with the term “reverse logistics”, there is a major difference between the two. While reverse logistics is based on collecting used items from the market to recapture value, greening usually refers to the forward supply chain functions such as production, purchasing, materials management, warehousing and inventory control, distribution, shipping, and transport logistics. Benefits and challenges of green supply chains have been discussed in several studies (Willits and Giuntini, 1994; Van Hoek, 1999; Marsillac, 2008).

Our literature review found no studies that quantify the quality of the environmental performance of a supply chain. This paper develops a mathematical model that can be used as a managerial tool to reduce environmental costs and improve a system’s environmental performance. The developed model is used later to investigate a two-level (vendor-buyer) supply chain to determine the impact of its greenness on the supply chain profit.

The remainder of this paper is organized as follows: Section 2 briefly surveys of the work that has investigated lot-sizing policies in forward and reverse logistics. Section 3 surveys the most accepted environmental performance measures. Section 4 surveys some works that investigate how a firm’s activities affect its environmental and financial performance. The mathematical modelling of Section 5 consists of three sub-sections. The first models a supply chain profit function where demand is price and quality dependent. The second provides the mathematics for the aggregate environmental effects, which is incorporated into the supply chain profit function: the third provides numerical examples and discusses the results. Section 6 is a summary and conclusion.

2. Inventory management in forward and reverse supply chains

Joint inventory replenishment problems for a vendor and a buyer first appeared with the work of Goyal (1977). This concept evolved into what is now known as supply chain coordination where different players at different levels coordinate their order policies to minimize their collective cost and share savings/profits according to some scheme (Jaber and Zolfaghari, 2008).

Lot-sizing policies and coordination benefits are also very valuable when SCM involves recycling/recovery objectives. Reverse logistics, based on recovery processes (i.e. repair, remanufacturing, refurbishing, cannibalization, etc.) has several economical and environmental benefits but collecting disposed products for recovery makes managing inventory in the reverse flow as challenging to that in the forward. The earliest reverse logistics work is believed to be that of Schrady (1967), which regained attention with the work of Richter (1996). Other recent investigations along the lines of Schrady (1967) and Richter (1996) and his later work include, but are not limited to, Jaber and Rosen (2008) and El Saadany and Jaber (2010).

Optimizing inventory in a supply chain, while taking environmental factors into consideration, is a vital research area. The following section explores and defines environmental performance measures. Although, reverse logistics is important too, it is left for the future to extend the model to a closed-loop supply chain.

3. Environmental performance measures of supply chains

How green is a supply chain? Developing performance measures to measure the "greenness" of each supply chain function is a challenge and a research quest. Practitioners have noted that environmental concerns have been examined and treated separately in supply chain functions and there is as yet no integrative approach or mechanism that measures, controls, and improves the environmental aspects of an entire supply chain; a limitation that does not facilitate optimizing the green performance of a supply chain (McIntyre *et al.*, 1998).

The absence of a global performance measure of a green and effective supply chain is echoed in many organisations. Companies that have metrics to measure the performance of some supply chain functions often do not monitor their values on a regular basis, or their metrics do not relate directly to customer satisfaction (Lee and Billington, 1992). In their study of the furniture industry, Walton *et al.* (1998) showed that integrating suppliers into the green supply chain is essential but not easy, facing suppliers' resistance from one side and changing government regulations from the other. In their study of Chinese car manufacturers, Zhu *et al.* (2007) found that the capability to monitor and measure the overall performance of a supply chain and tying it to environmental practices in the supply chain functions is difficult. Input-output analysis (IOA), a framework or a methodology that measures the environmental outcomes of activities or practices performed in supply chains that act on the inputs, is not adequately presented in the literature and is very limited. This research gap may have several causes that include geographical and cultural differences, differences between organizations and industries, and the lack of agreed metrics (Hervani *et al.*, 2005).

Manufacturing performance is usually assessed in terms of cost, quality, delivery, and flexibility, whereas environmental performance commonly measures the amounts of pollutants released into the air from industrial plants and hazardous substances transferred from and to other plants/markets that probably end-up as landfill affecting soil and water quality. Some researchers have suggested that in addition to the social costs and the direct cost of greening an organization, environmental performance measures should be able to measure the tangible and intangible outputs of a system as well as the partial outputs at different level of the organization (Hervani *et al.*, 2005). Rosen *et al.* (2000) laid a conceptual foundation to the structure of interactions between firms in order to improve their joint environmental performance. In their study of the computer industry, the authors suggested that there are difficulties for a firm to switch its relationships with its suppliers from traditional to environmentally conscious ones.

Measuring the greenness of a system in general or a supply chain in specific should be flexible to allow changing priorities with changing industries or products. For example, high environmental performance indicators for a petroleum firm may be treated with scepticism in the financial markets, while those of some other cleaner industries may not. This scepticism is usually translated into financial indicators that once they are made public, negatively affect the price per share, and subsequently the firm's market value (Klassen and McLaughlin, 1996). A recent example is the oil spill in the Gulf of Mexico (April, 2010) and how that put BP in a critical financial position because of the enormous cleanup costs and damage to wild life. King and Lenox (2001) suggested measuring the environmental performance using indicators such as: capital expenditures on pollution control technology, emissions of toxic chemicals, spills and other plant accidents, lawsuits concerning improper disposal of hazardous waste, rewards or other recognition for superior environmental performance, and participation in environmental management standards.

Pollution can take many forms including the emission of toxic fumes to the air, and the disposal of solid, liquid, chemical, and hazardous materials as waste in landfills. Cleanup or waste treatment costs are aggregated costs including, but not limited to, costs for treatment and disposal of solid and chemical waste, costs to treat air and water pollution, costs of purchasing green materials and equipment, and associated energy, training, and recycling costs (Humphreys *et al.*, 2003).

Single, or standalone, business entities are almost nonexistent today; more commonly they belong to a network of entities at different stages in a supply chain. The output of one stage is the input to another and so the environmental decisions made at one stage are affected by those made at prior stages and will affect those made in subsequent stages. To design a green supply chain also requires designing a system of operational and environmental performance measures to help identify the green and non-green practices. It is inadequate to use a single performance measure (e.g. cost) as it ignores the interactions among important supply chain characteristics and organizational strategic goals (e.g. resources, output, and flexibility) of the supply chain (Beamon, 1999). So, a system of performance measures will most likely include quantitative and qualitative indicators both financial and non-financial. Some studies considered measuring the environmental performance of a supply chain using qualitative (e.g. management involvement, marketing and green image, accidents or spills, lawsuits, quality awards, etc.) and quantitative (e.g. energy, waste, transportation, etc.) measures. Table I summarises the measures used.

This paper tries to bridge the gap between operations management activities and environmental initiatives that are not yet translated into practice. The model will be based on the qualitative and quantitative measures listed in Table I. An

Table I.
Environmental (env.) factors of supply chains

Measure	Irland (2007)	Humphreys *et al.* (2003)	King and Lenox (2001)	Faruk *et al.* (2001)	Author Rosen *et al.* (2000)	Mulder (1998)	Hart and Ahuja (1996)	Klassen and McLaughlin (1996)	Hoel (1978)
Qualitative									
Management involvement		×							
Marketing and green image	×	×					×	×	
Disposal method		×		×		×		×	
Env. policies and audits	×	×		×	×			×	
Quality system (e.g. ISO 14000)		×		×	×			×	
Accidents or spills			×	×				×	×
Law suits			×						
Reward or certifications	×		×					×	
Training		×						×	
Ranking in env. performance			×						
Env. data collection systems				×					
Process innovation					×	×	×	×	×
Product design for remanufacturing		×		×	×	×		×	
Supply redundancy	×				×				
Buying env. friendly materials		×	×	×	×	×		×	
Buying env. friendly technology		×	×	×	×		×	×	

(*continued*)

Measure	Irland (2007)	Humphreys *et al.* (2003)	King and Lenox (2001)	Faruk *et al.* (2001)	Author Rosen *et al.* (2000)	Mulder (1998)	Hart and Ahuja (1996)	Klassen and McLaughlin (1996)	Hoel (1978)
Interaction with suppliers				×	×				
Transportation modes				×					
Packaging				×		×			
Stimulating recovery policy						×			
Quantitative									
Pollution effect									
Solid waste		×		×		×	×		
Air emission		×	×	×	×	×	×	×	×
Water waste		×		×					
Chemical waste (e.g. lead)		×	×	×	×	×			×
Energy used		×		×		×		×	×
Thermal pollution						×			×
Financial									
Recovery cost (+/−)		×		×		×		×	
Market share gain (demand)		×						×	
Stock price								×	
Transport distance				×					

Table I.

environmentally sound product is a quality one (Porter and van der Linde, 1995). Accordingly, the model depends on treating environmental measures as quality measures in a function-based approach where a weight of preference is assigned to each measure, with certain flexibility in order to tailor the model to specific products and industries. The developed model will also include some operational factors, in order to present to supply chain professionals an integral tool that optimizes their operations while taking into consideration environmental aspects. In the following section, a survey of the methods used to quantify quality is presented.

4. Environmental quality and cost

Quality may be defined in many ways. It is value, excellence, conformance to specifications, or meeting and exceeding customers' expectations (Reeves and Bednar, 1994). Quality is an intangible measure; yet, different methods and techniques are used to quantify it. Several works have discussed the quality of supply chains (Robinson and Malhotra, 2005; Lin *et al.*, 2005; Kuei *et al.*, 2008). Supply chain environmental performance is also a measure of quality (McIntyre *et al.*, 1998). Although several qualitative studies provide tools to measure the green performance of supply chains, quantitative studies are limited to those that measure the "green health quality" of supply chains. This section presents environmental quality as a performance measure and examines its relation with other performance measures, including cost.

A supply chain is a complex network involving many stakeholders. Coordinating the levels (suppliers, manufacturers, distributors, etc.) of a supply chain is necessary to deliver products and/or services to customers that conform to their requirements (including the environmental ones). As societies become more conscientious about the environment, it becomes more pressing to develop appropriate environmental measures that assist managers to plan, monitor, control, and improve the environmental performance of the activities in the chain.

A company's environmental performance can affect its financial performance. King and Lenox (2001) found evidence of a real association between lower pollution levels and higher financial performance. This finding makes it reasonable to link environmental quality (non-financial) and costs to develop appropriate performance measures for the activities and operations of a supply chain.

There are conflicting opinions when it comes to identifying the relation between output quality and unit production cost. Wagner (1994) found that the relationship between the cost of an activity and the quality produced is neither explicable nor simple. This finding was confirmed by Phillips *et al.* (1983), who showed that achieving higher quality or lower costs are two different goals that require different courses of action. Some researchers considered that costs increase as quality increases (Vörös, 2002; El Saadany and Jaber, 2010), while some management approaches advocate that higher quality is accompanied by lower costs. In practice, a company may develop a quality-cost relationship that is more descriptive of their operations and activities. For example, Sony promotes a procurement policy that is based on quality, cost, delivery, service, and the environment, while Intel started detailing their "total cost" models to consider the disposal cost of its products (Handfield *et al.*, 2005). Earlier to this study, Klassen and Whybark (1999) compared the effect of proactive environmental management policies with the effect of reactive or compliance policies and controls on the manufacturing performance of a firm. They found that adopting pollution prevention technologies improves manufacturing performance, whereas in contrast, performance worsens as the pollution reactive technologies are considered.

There has been increasing attention given to non-financial performance measures alongside the financial measures. The complexity in supply chains design and partnership makes it unrealistic to resort to financial measures only. In their review, Gunasekaran *et al.* (2001) listed several financial and non-financial measures (e.g. customer service, asset utilization, environmental quality) and concluded that cost accounting methods should consider not only the cost of an activity, but also how the activity effects other activities. Phillips *et al.* (1983) showed that increasing product quality increases market share and reduces direct costs. Hendricks and Singhal (1997) examined the operating performance of 400 publicly traded firms who won their first quality awards as a result of implementing TQM programs. Their study found strong evidence that implementing a successful quality system results in increasing sales and operating income; however, the evidence was weak that firms that improved their quality were able to control the costs of such improvements. Banker *et al.* (1998) modelled a duopoly (i.e. a market condition when there are only two sellers) competition with demand as a linear function of price and quality with cost being directly proportional to the quality index. Faruk *et al.* (2001) presented a life cycle assessment-based tool to analyze and map the environmental impacts of supply chains. Their tool, using a matrix with scoring parameters, assesses 30 categories of environmental impact and evaluates the environmental burdens on a supply chain in order to target the most effective supply chain-related actions in mitigating environmental damage.

Assessing a life cycle of a product can face the challenge of contradicting objectives; for example, a lightweight toxic material may use less energy than a less toxic heavier material. Therefore, it is beneficial to develop an approach that considers more than one alternative and to reach a solution based on life cycle cost estimations (Quella and Schmidt, 2003). Lamming and Hampson (1996) suggested linking the environmental policy of a company with the activities of the purchasing function as acquiring green raw material and/or products affect the performance of the company and the supply chain as a whole. Another example of linking price/cost to quality is the work of Milgrom and Roberts (1986), who described sales revenue as a function of price and quality of the product. In their model, the quality of a product has two measures, the conformance of the product to the company's quality measures and how its quality is perceived by customers. They suggested that production costs are linearly proportional to the quality measure used.

At any given time, a product lies within one of four life-cycle stages: introduction, growth, maturity, and decline (Cox, 1967; Asiedu and Gu, 1998). Decisions made at the introduction phase are responsible for 85 percent of life cycle costs (Sroufe *et al.*, 2000). Accordingly, designing products while considering protecting the environment and maintaining a sustainable environment, led to the popularity of a new approach, design for environment (DfE). In the DfE approach, products are designed while considering several factors, including: product life extension, energy consumption reduction during product usage, and risk analysis against toxic exposure (Fiksel, 1993).

The environmental quality measures are summarized and categorized in Table II. These measures may provide a definition of quality; however, each company may not adopt all of these requirements as some of them may not be suitable for their strategic plan, product, and target market. For example, a soup company will be focused on

	Measure q_i
Product-based elements	
Performance (compared to other products for the same market target)	[0,1]
Features	[0,1]
Manufacturing-based elements	
Reliability	[0,1]
Conformance	[0,1]
Durability	[0,1]
Serviceability	[0,1]
Less pollution content (less content → higher quality)	[0,1]
Solid waste	
Chemical waste	
Air emissions	
Thermal pollution	
Less energy used (less energy → higher quality)	[0,1]
Environmental policies certifications and audits (e.g. ISO 14000)	[0,1]
Training	[0,1]
Process innovation and product design for remanufacturing	[0,1]
Buying environmentally friendly materials and technology	[0,1]
Packaging (environmentally friendly)	[0,1]
Usage measures	
Life extension	[0,1]
Possibility of reuse/refurbish/remanufacture	[0,1]
Less material use during life	[0,1]
Less energy impact during life	[0,1]
Less toxicity	[0,1]
Operations-based elements	
Transport distance (less distance → higher quality)	[0,1]
Greener transportation modes	[0,1]
Env. data collection systems	[0,1]
Supply redundancy	[0,1]
User-based measures	
Product perceived quality and brand image	[0,1]
Product advertising	[0,1]
Green image advertising	[0,1]
Management involvement	[0,1]
Green disposal method	[0,1]
No accidents or spills or law suits	[0,1]
Ranking in env. performance	[0,1]
Stimulating recovery policy	[0,1]
Market share	[0,1]

Table II.
Quality environmental measures of a supply chain

meeting demand with least cost, while a winter sport's company will be less focused on cost than on flexible and timely response to market demand (Brewer and Speh, 2000).

Accordingly, an environmental quality model is presented in the next section that aggregates all of the quantitative and qualitative performance measures surveyed by introducing a weight to each of them. This can help a company calibrate its own performance measures while taking Six Sigma concepts into consideration. The proposed model is a simple two-level supply chain in which demand depends on the environmental quality of the system and the associated costs.

5. The model

The model presented is a two-level supply chain coordinated to optimize inventory costs that takes into consideration various environmental factors. Some factors are measured quantitatively and others are measured qualitatively through questionnaires or interviews (Cronin and Taylor, 1992; Parasuraman *et al.*, 1985; Saraph *et al.*, 1989; Lin *et al.*, 2005). These measures reflect the various environmental dimensions of a supply chain and are incorporated into a mathematical relationship that is translated into a single measure of quality.

5.1 The two-level supply chain model

The model considers a two-level supply chain system with total costs optimized by coordinating the lot sizes shipped from the vendor (manufacturer) to the buyer (retailer). There are two inventory stocks; one at the manufacturer's with a setup cost, and one at the buyer's with a fixed ordering cost. Demand is assumed to be a function of the product's quality and price. The demand function, adopted from Vörös (2002), is comprised of two parts: a demand-price function and a demand-quality function, where demand increases (decreases) as quality (price) increases at fixed price (quality). Quality herein is a combination of product, process, and environmental quality.

Notations

d_{max}	upper bound of demand rate
P	product selling price
q	aggregate quality measure for n product, process and environmental quality characteristics
q_i	quality measure for product characteristic i, where $i \in [1, n]$
λ	coordination multiplier
S_r	retailer's ordering cost
S_m	manufacturing setup cost
h_r	retailer's holding cost
h_m	manufacturer's holding cost
P_m	manufacturer's production rate
a, θ	price factor adjustors, $0 < a < 1$, $\theta > 0$
b, φ	quality factor adjustors, $0 < b < 1$, $\varphi > 0$
$C(q)$	aggregated quality cost function
$Z(P, q, \lambda)$	supply chain profit function

Considering the demand function from Vörös (2002), equation (1) represents demand as a function of price and quality. The price factor of the demand function, $ae^{-\theta P}$ presents the relation between price and demand at fixed quality: as price increases, demand decreases, where a and θ are used as price function adjustors. Similarly, the quality factor of the demand function $(1 - be^{-\phi q})$, presents the relation between quality and demand at fixed price: as quality increases, demand increases, where b and φ are used as quality function adjustors. The demand upper bound, $d_{\max}$, represents the demand's maximum forecasted value, when price is very affordable and quality is supreme, without considering profitability, i.e. an unrealistic non-practical maximum demand. Actual demand as a function of price and quality is presented as the multiplication of both factors and the upper bound of demand rate, as follows:

$$d = d_{\max} a e^{-\theta P}(1 - be^{-\phi q}) \tag{1}$$

Meanwhile, a supply chain is optimized when the operations of the manufacturer and retailers are coordinated. El Saadany and Jaber (2008) presented a two-level supply chain inventory coordination model that optimized total supply chain costs. A simplified form of their model (no imperfect production and process restorations) is adopted, where λ is the manufacturer lot-size multiplier (positive integer) of the retailer's order quantity in a manufacturer's cycle inventory, i.e. the manufacturer delivers to the retailer its order in λ shipments for each manufacturing cycle, as shown in Figure 1.

The two-level supply chain cost is given as:

$$SC = \sqrt{2(S_m + \lambda S_r)\left(h_m\left(1 - \frac{d}{P_m} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right)d} \tag{2}$$

The above equation is derived in the Appendix. The profit Z, of a two-level supply chain is maximized with demand being dependent on price and quality as shown in equation (1). The profit is computed by subtracting equation (2) from the total net revenue, as:

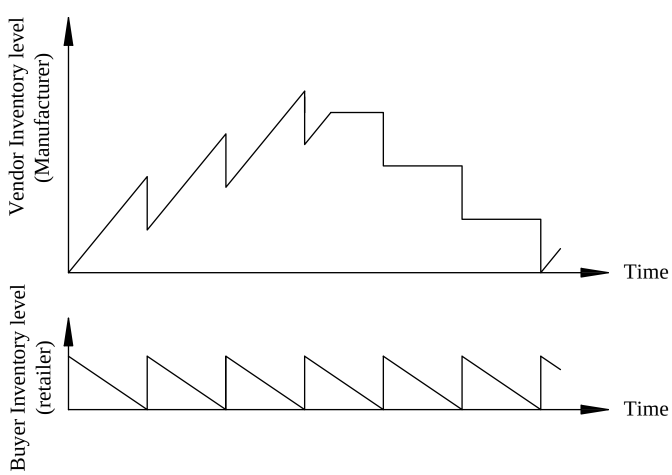

Figure 1.
A two-level supply chain

$$\begin{aligned}
\mathrm{Max}Z &= Z(P,q,\lambda) = \text{net revenue} - \text{cost} \\
&= (P - C(q))d - \sqrt{2(S_m + \lambda S_r)\left(h_m\left(1 - \frac{d}{P_m} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right)d} \\
&= (P - C(q))d_{\max} ae^{-\theta P}(1 - be^{-\phi q}) \\
&\quad - \sqrt{2(S_m + \lambda S_r)\left(h_m\left(1 - \frac{d_{\max}\cdot ae^{-\theta P}\cdot(1 - be^{-\phi q})}{P_m} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right)d_{\max} ae^{-\theta P}(1 - be^{-\phi q})}
\end{aligned} \tag{3}$$

5.2 The quality function

The model depends on an environmental quality cost function $C(q)$, which is an aggregated quality measure of all the measures listed in Table II. Cost measures can be a constant term, a linear function of quality, or a non-linear function of quality, or a combination of all of them. The proposed environmental quality cost function takes the following form:

$$C(q) = \alpha_1 c(q_1) + \alpha_2 c(q_2) + \alpha_3 c(q_3) + \cdots + \alpha_i c(q_i) + \cdots + \alpha_n c(q_n) \tag{4}$$

where $c(q_i)$, which can take any form, is the associated cost required for the product quality measure q_i to reach its maximum attainable value 1 (i.e. 100 percent quality). Associated costs can either be negative or positive according to whether improving a specific quality measure may results in savings (− ve) or additional costs (+ ve) to the supply chain. For example, increasing a machine's power output may be associated with additional costs; however, increasing reliability may be associated with a reduction in costs. Each $c(q_i)$ is assigned a weight, α_i, which are set by the decision maker(s) to fine-tune the supply chain performance to match the firm's strategic goals, where the sum of the weights should equal 1. Assigning weights is a challenging task by itself. It is assumed here that the weights are given a priori according to some method, e.g. analytical hierarchy process (Saaty, 1980). Accordingly:

$$\alpha_1 + \alpha_2 + \cdots + \alpha_n = 1 \tag{5}$$

$$0 \leq \alpha_1, \alpha_2, \ldots, \alpha_n, \ldots, q_1, q_2, \ldots, q_n \leq 1 \tag{6}$$

$$q = \alpha_1 q_1 + \alpha_2 q_2 + \cdots + \alpha_n q_n, \quad 0 \leq q \leq 1 \tag{7}$$

where equation (7) represents the product's total environmental quality. In this approach, quality is considered as an input parameter (initial state of quality), and also as a decision variable (desired output quality). Accordingly, the following approach should be considered when measuring and optimizing the environmental quality of a system:

- Determine the essential quality measures of the company or organization in order to improve both product and environmental quality.
- Assign weights to each measure relevant to its importance.
- Determine maximum expectations for each quality measure and associated costs (either + ve or − ve) to reach this maximum.
- Determine the final quality function, $C(q)$.
- Apply $C(q)$ in an operations decision-making process.

- Optimize for optimum quality q^* and other optimal operational decision variables.
- Set and plan for new optimal environmental quality targets.
- Apply the DMAIC methodology (www.dmaictools.com/) to bridge gaps and improve performance towards the optimal environmental targets.

5.3 Numerical example

The model is investigated by a numerical example. A company defined the important product, process, and environmental quality measures, and listed them with weights and corresponding costs, as shown in Table III. The following values of the input

Table III. Numerical example

Description and classification of quality characteristics	$c(q_i)$ (\$/unit)	α_i	$\alpha_i.\ c(q_i)$	q_i	Env. cost
Product-based elements					
Performance (compared to other products for same market target)	$20 - 5q_i + 30q_i^2$	0.14	$2.8 - 0.7q_i + 4.2q_i^2$	0.5	3.5
Features	$15 + 7q_i + 8q_i^2$	0.1	$1.5 + 0.7q_i + 0.8q_i^2$	0.2	1.672
Manufacturing-based elements					
Reliability	$-q_i$	0.07	$-0.07q_i$	0.2	−0.014
Less pollution content (less content → higher quality)					
Solid waste					
Chemical waste					
Air emissions					
Thermal pollution	q_i	0.05	$0.05q_i$	0.1	0.005
Less energy used (less energy → higher quality)	$-2q_i$	0.04	$-0.08q_i$	0.3	−0.024
Environmental policies certifications and audits (e.g. ISO 14000)	q_i	0.05	$0.05q_i$	0.4	0.02
Buying environmentally friendly materials and technology	$0.4q_i$	0.03	$0.012q_i$	0.1	0.0012
Packaging (environmentally friendly)	$3q_i$	0.04	$0.12q_i$	0.1	0.012
Working life of the product					
Life extension	$2q_i$	0.05	$0.1q_i$	0.5	0.05
Possibility of reuse/refurbish/remanufacture	q_i	0.02	$0.02q_i$	0.1	0.002
Less material use during life	$-0.1q_i$	0.05	$-0.005q_i$	0.2	−0.0001
Less energy impact during life	$-4q_i$	0.03	$-0.12q_i$	0.2	−0.024
Less toxicity	q_i	0.02	$0.02q_i$	0.5	0.01
Operations-based elements					
Transport distance (less distance → higher quality)	$-0.1q_i$	0.02	$-0.002q_i$	0.1	−0.0002
Greener transportation modes	$0.3q_i$	0.02	$0.006q_i$	0.1	0.0006
Green image and perceived quality					
Product perceived quality and brand image	$0.1q_i$	0.1	$0.01q_i$	0.5	0.005
Green image advertising	$3q_i$	0.05	$0.15q_i$	0.1	0.015
Green disposal method	$4q_i$	0.05	$0.2q_i$	0.3	0.06
Stimulating recovery policy	$-0.1q_i$	0.05	$-0.005q_i$	0.2	−0.0001
Market share	$-4q_i$	0.02	$-0.08q_i$	0.3	−0.024
Total		$\Sigma = 1$			5.2646

parameters are assumed: $d_{max} = 10{,}000$ units/year (demand when price is lowest and quality is highest), $\theta = 0.15$, $a = 0.8$, $\varphi = 2$, $b = 0.7$, $h_m = 4$ \$/unit/year, $h_r = 2$ \$/unit/year, $S_m = 100$ \$, $S_r = 50$ \$, and $P_m = 3{,}000$ unit/year.

From the given data, summing all the quality measures, including the environmental ones:

$$C(q) = \sum \alpha_i c_i(q_i) = 4.3 + 0.376q + 5q^2,$$

with total quality is at level $q = \sum \alpha_i q_i = 0.291$. The cost function is substituted in equation (3), and optimized to derive the optimum P^*, q^*, and λ^*. The optimal solution was found at $P^* = 12.92$ \$/unit, $q^* = 0.468$ and $\lambda^* = 2$, with optimal demand $= 835$ units/year, total supply chain cost at 1,403 \$/year and total profits $= 4{,}738$ \$/year. These values were determined using Excel Solver enhanced with visual basic code. Note that the $c(q_i)$ functions were assumed to be such that $C(q)$ could handled by the optimization tool used. However, using this tool when more complex forms of $C(q)$ are assumed may not guarantee a global optimal solution. This is a limitation to the tool presented. Therefore, a new total quality level of 0.468 is required to optimize, not only quality, but also total system performance. The model was investigated for varying values of $q \in (0, 1)$, while optimizing for total profits, and the results are shown in Figure 2.

As shown in Figure 2, an optimal maximum quality level is found to correspond to maximum demand, but does not correspond to minimum price. To analyze the proposed model further, a slight reduction in the main quality cost function (through an improved environmental performance) is considered:

$$C(q) = \sum c_i \alpha_i(q_i) = 4.3 + 0.1q + 5q^2.$$

The cost function is substituted in equation (3), and is optimized to produce the optimum P^*, q^*, and λ^*. The optimal solution was found at $P^* = 12.83$ \$/unit, $\lambda^* = 2$, and $q^* = 0.48$. Therefore, a new total quality level at 48 percent is required to increase total

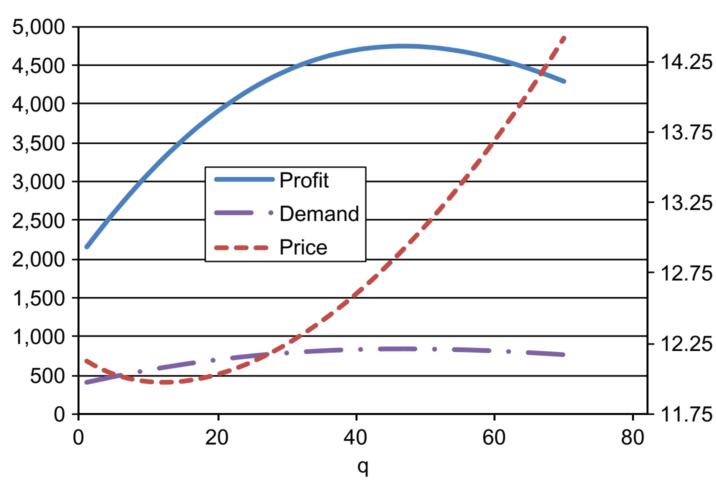

Figure 2.
The behaviour of the total profit, price, demand for varying q

profits to 4,850 \$/year. As environmental costs decrease, total profits increase, which emphasises the importance of reducing environmental costs. The model was optimized for total profits using varying values of $q \in (0, 1)$. The results are shown in Figure 3.

6. Conclusions

Environmental performance measures of supply chains have been widely investigated, but a functional decision analysis tool to convey green concepts into practice has not previously been presented yet. The paper reviewed different environmental performance measures in the literature and organised them into groups. A method to quantify quality was developed that quantifies different environmental quality factors in terms of cost. The problem of coordinating a two-level supply chain model was used to present an innovative tool that optimizes profits while considering green aspects of the supply chain. The developed decision model fills a gap in the literature which until now lacks models to help managers achieve this. This is the main contribution of the paper.

The model can be used as a managerial tool to reduce environmental costs and improve a system's environmental performance while increasing total profits. Preliminary numerical investigation of the developed decision model showed that accounting for hard-to-quantify environmental costs results in a minimum price that does not necessarily correspond to maximum profit. The results from the decision model confirmed some findings in the literature that investing to reduce environmental costs results in improving environmental performance and increasing total profits (Klassen and McLaughlin, 1996; Rao and Holt, 2005; Ambec and Lanoie, 2008). The results also confirmed that conventional cost accounting methods lack the flexibility to consider qualitative environmental measures. Future works should consider investigating IOA to bridge the gap between supply chain environmental inputs and outputs.

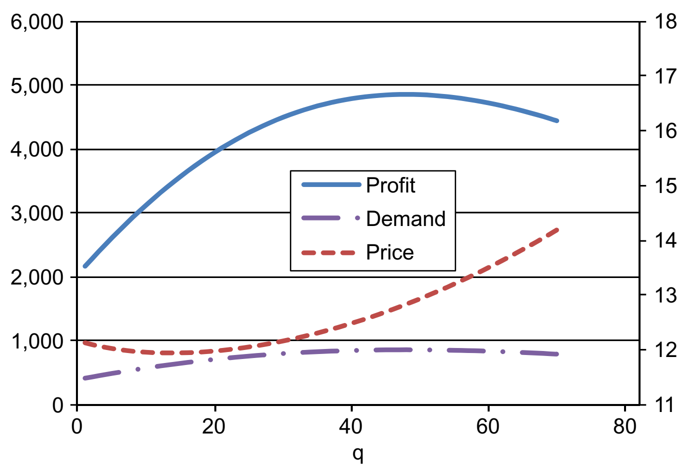

Figure 3.
The behaviour of the total profit, price, demand for varying q

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Appendix

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

$$\psi_m = \frac{S_m d}{\lambda q} + h_m \frac{q}{2}\left[1 + \lambda\left(1 - \frac{d}{P_m}\right)\right] \tag{A1}$$

$$\psi_r = \frac{S_r d}{q} + h_r \frac{q}{2} \tag{A2}$$

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

$$\psi_{sc} = \frac{S_m d}{\lambda q} + h_m \frac{q}{2}\left[1 + \lambda\left(1 - \frac{d}{P_m}\right)\right] + \frac{S_r d}{q} + h_r \frac{q}{2} \tag{A3}$$

ψ_{sc} is convex since $\mathrm{d}^2\psi_{sc}/\mathrm{d}q^2 = 2(S_m + \lambda S_r)/\lambda q > 0 \quad \forall \mathrm{q} > 0$. The minimum of equation (A3) is given by setting its first derivative equal to zero and solving for q. This gives:

$$q = \sqrt{\frac{2d((S_m/\lambda) + S_r)}{h_m[1 + \lambda(1 - (d/P_m))] + h_r}} = \sqrt{\frac{2dS}{H}} \tag{A4}$$

By substituting equation (A4) in equation (A3) gives the minimum supply chain cost as:

$$\begin{aligned}\psi_{sc} &= \frac{Sd}{q} + \frac{H}{2}q = \frac{Sd}{\sqrt{2dS/H}} + \frac{H}{2}\sqrt{\frac{2dS}{H}} = \sqrt{2dSH} \\ &= \sqrt{2d\left(\frac{S_m}{\lambda} + S_r\right)\left[h_m\left(1 + \lambda\left(1 - \frac{d}{P_m}\right)\right) + h_r\right]} \\ &= \sqrt{2d(S_m + \lambda S_r)\left[h_m\left(1 - \frac{d}{P_m} + \frac{1}{\lambda}\right) + \frac{h_r}{\lambda}\right]}\end{aligned} \tag{A6}$$

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