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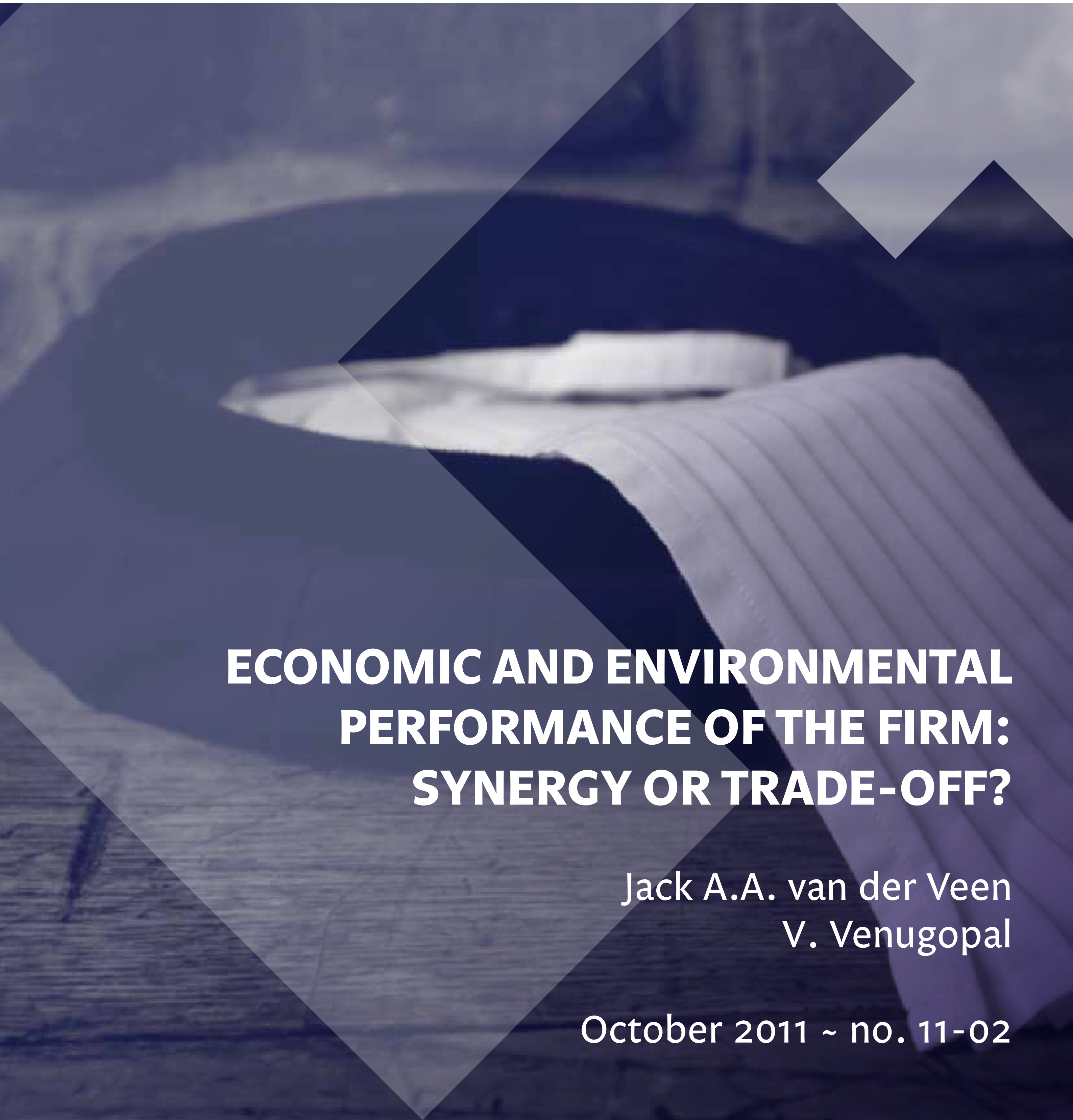

ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF THE FIRM: SYNERGY OR TRADE-OFF?

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ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF THE FIRM: SYNERGY OR TRADE-OFF? INSIGHTS FROM THE EOQ MODEL

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Abstract
Over the last decades, corporations are increasingly expected to fulfill the written and unwritten laws of doing business in a sustainable way. They are implicitly expected to perform well on the so-called triple bottom line; People, Planet and Profit. However, both in academia and in practice, there is no consensus on the feasibility of doing good (for society and environment) and doing well (economically) simultaneously. The traditional view is that there is an unavoidable trade-off between the social & environmental performance of an organization and its profitability. The other school of thought has challenged this view and claimed that doing good and doing well simultaneously, i.e., breaking the trade-off and creating a synergy, is not only desired but actually feasible.
In this paper, the validity of both views (trade-off and synergy) is tested within the context of green sourcing, using a multi-objective approach to a variant of the well- known Economic Order Quantity (EOQ) model. It is demonstrated that both views are not contradictory but valid under different conditions and strategic focus. As such this paper helps to reach a better understanding of the factors and conditions that drive trade-offs and synergy behavior of the triple bottom line measures within the chosen problem setting.

Keywords
Sustainability, Efficiency, Economic Order Quantity, Energy, Management

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1. Introduction

Traditionally, profitability has been the primary objective organizations have focused on. However, under the term *corporate social responsibility* (CSR)*,* over the last decades many organizations have expanded the spectrum of their criteria for measuring success towards the so-called *triple bottom line*: People, Planet and Profit. Besides the usual financial measures such as cost and profitability, nowadays organizations are expected to report on ecological and societal dimensions too. *Environmental sustainability* (the Planet dimension) relates to various aspects such as energy usage, carbon footprint, pollution, biodiversity, deforestation, overfishing et cetera. *Social sustainability* (the People dimension) relates to issues in, e.g., fair trade, child labor, human & labor rights and quality of life.

In a nutshell, the triple bottom line is all about doing good (for society and the environment) while doing well (economically) at the same time. There is a growing recognition within the business community that transformational effort is required to change the way organizations design, source, manufacture, distribute, recycle and reuse their products to achieve this mission. Hence, business leaders are taking sustainable supply chain approach to achieve this mission (see, e.g., [1]-[2]). At the same time, sustainability has received a lot of attention in the academic literature in the fields of purchasing, operations, logistics and supply chain management (see, e.g., [3]-[5]).

There is a long standing debate regarding how a firm's sustainability and economic measures are related to each other. The traditional view is that there is an unavoidable trade-off between the sustainability and profitability, so that when an organization decides to put more emphasis on sustainability objectives, this inevitably will result in increased cost and reduced profit (see, e.g., [6]-[7]). However, this view has been challenged by many (e.g., [8]-[9]). For example, the claim "lean is green" is motivated by observing that when energy usage would be lowered, both sustainability measures and cost performance could be improved simultaneously. Within this line of thinking, the traditional trade-off is broken and synergy is created as sustainability and profitability can be improved simultaneously.

Many researchers have studied the sustainability versus financial performance issue (see e.g., [10]-[13]). It is fair to say that so far the debate has not reached a satisfactory level of consensus and the discussion is far from settled. The objective of this paper is to test both views within a specific setting using a quantitative model. Formal (quantitative) models are especially suited for this purpose because clear definitions can be used and unambiguous results can be derived. This in contrast to the everyday discussions on the topic, where frequently there is a lot of difference in interpretations of the various terms, concepts and results. As such this paper is aimed to help reaching a better understanding of the factors and conditions that drive trade-offs and synergy behavior of the triple bottom line measures.

In this paper, a multi-objective approach to a variant of the well-known Economic Order Quantity (EOQ) model is used. The EOQ model is fairly straightforward and one of the most frequently cited models within the field of Operations, Logistics and Supply Chain Management and therefore perfectly fitting for our purposes. To keep the model as simple as possible, the focus will be limited to the environmental component of sustainability (viz., green sourcing) and more specifically on one of the measures in this category, viz., "energy usage". This is motivated by the fact that energy consumption reduction initiatives has recently received a lot of attention in practice within operations settings as it goes hand-in-hand with managing greenhouse gas emissions and the organization's carbon footprint.

The remainder of this paper is organized as follows. In the next section, the EOQ model, the key definitions and concepts are introduced. In Section 3 the main results of the analysis are given, which is followed by a discussion of managerial implications in Section 4. The paper is closed in Section 5 with conclusions and pointers for further research.

2. EOQ model with cost and sustainability dimensions

Consider the well-known model for determining the EOQ. When sourcing an item from an external supplier, an organization is facing a stable demand rate where the yearly demand is given by D. For deciding its optimal order quantity, the organization has two types of relevant costs, namely inventory holding costs and ordering costs. The inventory holding cost per unit per year is given by C_H and the fixed cost per order is denoted by C_O. The organization wants to source a fixed amount (given as Q) from the supplier. Within this model, the total annual average relevant cost as function of the order size is given by

$$TC(Q) = \tfrac{1}{2} Q C_H + \left(\frac{D}{Q}\right) C_O . \tag{1}$$

The order size that minimizes the above total annual average cost (i.e., the EOQ) is given by

$$Q_C^* = \sqrt{2D\left(\frac{C_O}{C_H}\right)} . \tag{2}$$

Now consider a situation where both the ordering cost and the holding costs are partly determined by the use of energy. Fixed ordering costs can include energy costs for instance when there are costs of transportation from the supplier to the organization and the truck's fuel usage depends on the truck size and the distance travelled rather than on the amount ordered. Within this setting, let the ordering cost per order be

$$C_O = \gamma_O + c_e E_O , \tag{3}$$

where c_e (>0) is the cost per unit of energy, E_O (>0) is the (fixed) energy usage per order and γ_O is the (fixed) cost per order not related to the use of energy, such as administrative handling costs. Similarly, assume that also the inventory holding cost is partly determined by energy costs

$$C_H = \gamma_H + c_e E_H , \tag{4}$$

where E_H (>0) is the energy usage per unit of inventory per year and γ_H is the per unit annual inventory holding cost not related to the use of energy. The energy costs can for example be related to the energy usage for material handling or the use of energy for maintaining climate conditions at the warehouse where the inventory is stocked. The non-energy cost can, for example, be related to working capital or obsolescence risks.

Note that it is assumed that the required energy usage depends linearly on the number of orders and the inventory size. Clearly, in real life this need not be the case; the energy usage frequently has other shapes like, e.g., a threshold function. However, the model is kept as simple as possible in order to avoid mathematical complexity that can obscure the key issues studied.

A similar model set-up has been discussed in [14-15]. In [14], within an EOQ model setting, it is shown how additional environmental and societal criteria can be appended to traditional cost accounting in order to address sustainability in supply chain management context and a number of insights for managers and policy makers are given. In [15], various environmentally responsible inventory models and policies and the ways in which these may reassure decision makers with environmental concerns are discussed. This paper is, to the best of our knowledge, the first to use a formal (EOQ inventory) model to study the synergy versus trade-off issue.

Next to minimizing costs, the organization might be interested in minimizing energy usage for environmental (i.e., sustainability) reasons. Within the setting of the model, the annual average total energy usage as a function of the order size is given by

$$TE(Q) = \tfrac{1}{2} Q E_H + \left(\frac{D}{Q}\right) E_O . \tag{5}$$

The order size that minimizes overall energy usage is

$$Q_E^* = \sqrt{2D\left(\frac{E_O}{E_H}\right)} . \tag{6}$$

In the remainder of this paper, minimizing TC and TE is referred to as the *cost objective* and *sustainability objective* respectively. Similarly, Q_C^* and Q_E^* are referred to as the *optimal cost order size* and *optimal energy order size* respectively.

Now assume that the firm wants to take account of both objectives simultaneously. Within the field of multi-criteria decision making, there are various ways to handle multiple objectives. One approach is to optimize a weighted objective function. Within the given setting, assume that α denotes the relative weight the organization assigned to the cost objective ($0 \le \alpha \le 1$) when compared to the sustainability objective. The weighted objective function is then given by

$$TW(Q) = \alpha\left(\tfrac{1}{2} Q C_H + \left(\frac{D}{Q}\right) C_O\right) + (1-\alpha) c_e \left(\tfrac{1}{2} Q E_H + \left(\frac{D}{Q}\right) E_O\right). \tag{7}$$

Note that in order to ensure a single unit of measurement, the second term is a cost term too, i.e., TW is a weighted cost function.

For convenience of notation, define $B_O = \alpha\gamma_O + c_e E_O$ and $B_H = \alpha\gamma_H + c_e E_H$. The optimal order size with respect to the weighted objective function is given by

$$Q_W^* = \sqrt{2D\left(\frac{B_O}{B_H}\right)}. \tag{8}$$

Define

$$\Delta = \gamma_0 E_H - \gamma_H E_O. \tag{9}$$

It is easy to see that $Q_C^* < Q_W^* < Q_E^*$ when $\Delta < 0$ and $Q_E^* < Q_W^* < Q_C^*$ when $\Delta > 0$.

To ensure a meaningful discussion, in the remainder of this paper, it will be assumed that the that $\Delta \neq 0$ (i.e., the various optimal order sizes are not the same) and that only nontrivial cases are considered, i.e., $0 < \alpha < 1$.

The purpose of this paper is to study the effect of the various parameters on total annual cost and energy usage. The total annual cost at the optimal solution with respect to the weighted objective function is given by

$$TC(Q_W^*) = \left(\sqrt{\tfrac{1}{2}D}\right)\cdot\left(C_H\sqrt{\frac{B_O}{B_H}} + C_O\sqrt{\frac{B_H}{B_O}}\right), \tag{10}$$

and the total annual energy cost by

$$TE(Q_W^*) = \left(\sqrt{\tfrac{1}{2}D}\right)\cdot\left(E_H\sqrt{\frac{B_O}{B_H}} + E_O\sqrt{\frac{B_H}{B_O}}\right). \tag{11}$$

Numerical example

Let D = 12,000; E_O = 245; c_e = 2; γ_O = 410; E_H = 12 and γ_H = 36 (i.e., $\Delta = -3900 < 0$), C_O = 900 and C_H = 60. It follows that Q_C^* = 600; TC(600) = 36,000; TE(600) = 8,500, and Q_E^* = 700; TC(700) = 36,429; TE(700) = 8,400.

Let α = 0.3. Note that $Q_W^*(0.3)$ = 650; TC(650) = 36,116 > 36,000 = TC(700) and TE(650) = 8,423 < 8,500 = TE(700). The results are summarized in Figure 1. □

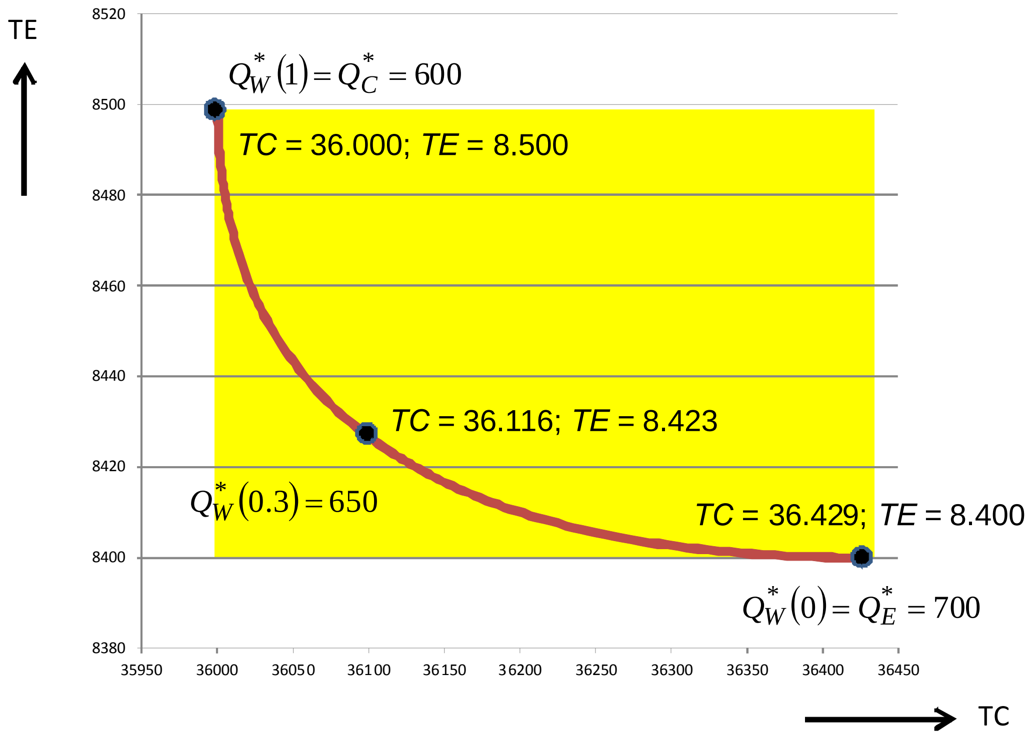

Figure 1: Efficient frontier (using the data from the numerical example).

In Figure 1 the so-called *efficient frontier* is given, i.e., the combination of values of $TC\left(Q_W^*(\alpha)\right)$ and $TE\left(Q_W^*(\alpha)\right)$ for all values of the relative weight parameter α. The efficient frontier forms the collection of all Pareto optimal solutions and is sometimes referred to as situations of *operational efficiency*. In other words, within the framework of the model, operational efficiency refers to the situation where, given the exogenous parameters of the model, the optimal order size is used.

It is important to distinguish between the different roles the various parameters and the decision variable have within the model (see Figure 2). First of all, the weight α is a parameter that represents the strategic choice on how much importance the firm puts to the cost objective when compared to the sustainability objective. Second, the decision variable Q relates to the operational efficiency of the organization. As mentioned, choosing the optimal value for the decision variable is considered as being equal to achieving operational efficiency. Finally, the parameters D, c_e, E_H, E_O, γ_O and γ_H are considered as being exogenous data, i.e., are determined outside the model. However, this does not necessarily imply that these parameters cannot be influenced by the organization. Therefore, also these parameters will be included in the analysis below.

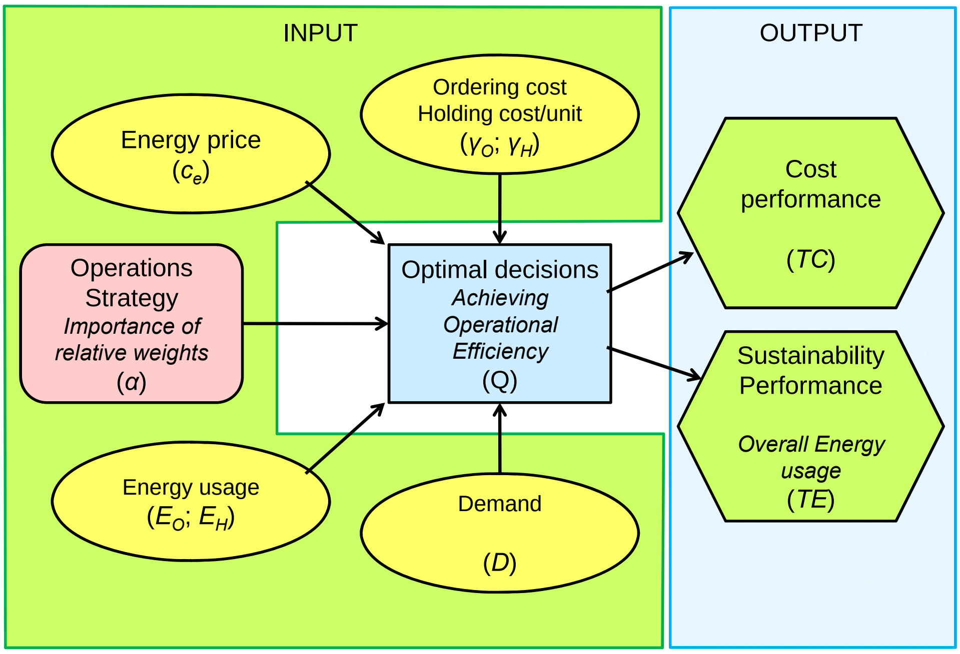

Figure 2: Role and relations between the various parameters in the model.

As mentioned in the outset, the objective of this paper is to get an insight on when the Sustainability and Cost objectives are aligned or conflicting. Objectives are said to be *aligned* (thus leading to synergy), when changing a parameter will result in improvement (or worsening) of both objectives simultaneously and *conflicting* (leading to trade-offs) when this will result in improved performance on one objective and at the same time a worsened performance on the other objective. Note that this definition is related to parameters α, E_O, E_H, γ_O, γ_H, D *and* c_e, i.e., it is quite possible that the objectives can be aligned with respect to one parameter, while at the same time being conflicting with respect to another parameter. It is also important to note that the definition assumes incremental parameter changes; starting from a given set of parameter values, in what direction (increase or decrease) would the Cost and Sustainability objective develop at a small change of one of the parameters. The exact mathematical definition is given in the appendix.

3. Cost and sustainability performance: aligned or conflicting?

Note that

$$TW(Q_W^*) = \sqrt{\tfrac{1}{2} D B_O B_H} \; . \qquad (12)$$

It follows that lowering any of the parameters α, γ_O, γ_H, E_O, E_H, c_e *and* D would result in improved overall weighted performance of the firm (lower *TW*). However, it is less straightforward how changes in these parameters impact the individual Cost and Sustainability performance measures respectively. In this section, such impacts will be analyzed. More specifically, five observations will be made on whether the economic objective (cost, as given by the $TC(Q_W^*)$ function) and sustainability objective (in terms of energy usage as given by the $TE(Q_W^*)$ function) are aligned or conflicting with respect to each of the parameters.

Observation 1

$TC(Q_W^*)$ *is a decreasing function of* α *and* $TE(Q_W^*)$ *is an increasing function of* α*, i.e. the cost and sustainability objectives are conflicting with respect to the relative weight parameter* α.

Intuitively, the rationale behind Observation 1 is easy to understand: as more weight is put on sustainability, Q_W^* moves closer to Q_E^* along the efficient frontier and further away from Q_C^* (and the other way around). The formal proof of this observation (and for all other observations) is given in the appendix.

Note that Observation 1 supports the traditional view on sustainability objectives and economic performance objectives: there is an unavoidable trade-off between the sustainability and cost. If a change in α is made, this is to be considered as a strategic repositioning of the firm, which can be visualized by a repositioning towards the preferred position on the efficient frontier. In other words, in determining its strategy, the organization must choose in which of the two performance measures it wants to excel and to which extent; you cannot have it both ways.

Example (continued).

Assume that an organization strategically decides to decrease the value of α from 0.3 to 0.1 (i.e., the relative importance of the sustainability objective is increased). Note that $Q_W^*(0.1) =$ 680; *TC*(680) = 36,279 > 36,116 and *TE*(680) = 8,404, i.e., *TC* has increased and *TE* has decreased. □

For the next observation two conditions are used, namely

$$E_O > \frac{\gamma_O}{c_e}\left(\frac{(1-\alpha)B_H}{C_H + B_H} - \alpha\right), \tag{13}$$

and

$$E_H > \frac{\gamma_H}{c_e}\left(\frac{(1-\alpha)B_O}{C_O + B_O} - \alpha\right). \tag{14}$$

Observation 2

(i) *If condition (13) applies, then both $TC(Q_W^*)$ and $TE(Q_W^*)$ are increasing functions of E_O, i.e., the cost and sustainability objectives are aligned with respect to the per order energy usage E_O.*

(ii) *If the reverse of condition (13) applies, then $TC(Q_W^*)$ is a decreasing and $TE(Q_W^*)$ is an increasing functions of E_O, i.e., the cost and sustainability objectives are conflicting with respect to the per order energy usage E_O.*

(iii) *If condition (14) applies, then both $TC(Q_W^*)$ and $TE(Q_W^*)$ are increasing functions of E_H, i.e., the cost and sustainability objectives are aligned with respect to the per unit holding energy usage E_H.*

(iv) *If the reverse of condition (14) applies, then $TC(Q_W^*)$ is a decreasing and $TE(Q_W^*)$ is an increasing functions of E_H, i.e., the cost and sustainability objectives are conflicting with respect to the per unit holding energy usage E_H.*

Intuitively, one would expect that if the energy usage is reduced, this would have a positive effect on both the total annual cost and the total annual energy usage (both would be reduced), i.e., that the two objectives are aligned and there is a synergy with respect to the per unit energy usage. By Observation 2, this precisely is the case, but only if conditions (13) and (14) are fulfilled.

To understand the reason for existence of conditions (13)-(14), it is important to note that a decrease in the per unit energy usage has two effects; (a) on the optimal order size Q_W^*; and (b) on the *TC* and *TE* functions itself (other than through the order size). Clearly, the *TC* and *TE* functions are, apart from the influence of the order size, increasing functions in E_H and E_O. However, if the energy usage is reduced, this also causes a change in the optimal order size. As demonstrated in Observation 2, the net effect of (a) and (b) together can be that under certain circumstances a decrease of the energy usage leads to increased total costs. Note that conditions (13)-(14) indicate that such "unexpected' behavior can only happen if the energy usage is relatively small.

Example (continued)

Assume that the per order energy usage becomes E_O = 215 (i.e., is reduced by 30). Note that the right hand side of (13) is -8.82, so that condition (13) is fulfilled. The new optimal order size is Q_W^* = 618; TC(618) = 34,849 < 36,116 and TE(680) = 7,883 < 8,423, i.e., both TC and TE have decreased and the objectives are aligned.

Next assume that E_H = 10 (reduced by 2) and E_O is reset at 245. Note that the right hand side of (14) is -0.3, hence condition (14) is fulfilled The new optimal order size is Q_W^* = 691; TC(691) = 34,978 < 36,116 and TE(691) = 7,710 < 8,423, i.e., both TC and TE have decreased and the objectives are aligned. □

Observation 3

(i) *If $\Delta>0$, then both $TC(Q_W^*)$ and $TE(Q_W^*)$ are increasing functions of γ_O, i.e., the cost and sustainability objectives are aligned with respect to the fixed cost per order not related to the use of energy γ_O.*

(ii) *If $\Delta<0$, then $TC(Q_W^*)$ is an increasing and $TE(Q_W^*)$ is a decreasing function of γ_O, i.e., the cost and sustainability objectives are conflicting with respect to the fixed cost per order not related to the use of energy γ_O.*

(iii) *If $\Delta<0$, then both $TC(Q_W^*)$ and $TE(Q_W^*)$ are increasing functions of γ_H, i.e., the cost and sustainability objectives are aligned with respect to the per unit holding cost not related to the use of energy γ_H.*

(iv) *If $\Delta>0$, then $TC(Q_W^*)$ is an increasing and $TE(Q_W^*)$ is a decreasing function of γ_H, i.e., the cost and sustainability objectives are conflicting with respect to the per unit holding cost not related to the use of energy γ_H.*

At first glance it might look somewhat surprising that the parameters γ_O and γ_H, do impact the sustainability objective as these are not a direct part of the energy usage function TE. However, obviously a change in these two parameters does have an impact on the optimal order size Q_W^*, hence also influences $TE(Q_W^*)$. Clearly, whether TE and TC are aligned or conflicting depends on whether Q_W^* will move closer either to Q_C^* or to Q_E^*; it is therefore no surprise that this is determined by the sign of Δ.

Example (continued).

Assume that γ_O = 350 (i.e., is decreased by 60). Note that $\Delta = -4620$, i.e., remains negative. The new optimal order size is Q_W^* = 641; *TC*(641) = 34,9535 < 36,116 and *TE*(641) = 8,433 > 8,423, i.e., *TC* has increased and *TE* has decreased so that the objectives are conflicting.

Next consider the case that γ_O = 410 (reset at the original value) and γ_H = 25 (i.e., is decreased by 11). Note that $\Delta = -1205$, i.e., still negative. The new optimal order size is Q_W^* = 683; *TC*(683) = 32,547 < 36,116 and *TE*(683) = 8,402 < 8,423, i.e., both *TC* and *TE* have decreased and the objectives are aligned. □

Observation 4

(i) *Both $TC(Q_W^*)$ and $TE(Q_W^*)$ are increasing functions of D, i.e., the cost and sustainability objectives are aligned with respect to the demand parameter D.*

(ii) *The cost per unit ($TC(Q_W^*)/D$) and the Energy usage per unit ($TE(Q_W^*)/D$) both are decreasing functions of D, i.e., these two objectives are aligned with respect to the demand parameter D.*

Since within the EOQ model there is no "revenue" associated to increased demand, it is no surprise that both *TC* and *TE* increase at higher demand. Therefore, Observation 4(ii) on the per unit behavior of annual cost and annual energy usage is probably more relevant from a managerial point of view.

Observation 5

(i) *$TC(Q_W^*)$ is an increasing functions of c_e, and $TE(Q_W^*)$ is a decreasing function of c_e, i.e., the cost and sustainability objectives are conflicting with respect to the cost per unit of energy parameter c_e.*

(ii) $\lim_{c_e \to \infty} Q_C^* = Q_E^*$.

Intuitively, Observation 5(i) is easy to understand; obviously higher per unit energy costs would increase total annual costs, and at the same time be a driver to reduce overall annual energy usage. Observation 5(ii) shows that if the per unit energy costs increase, the gap between the optimal energy order size and optimal cost order size is reduced. This can be interpreted as follows: at increasing energy costs, other costs get less relevant in determining the optimal order size and in the ultimate case (extremely high energy costs), the energy usage is all that matters so that the optimal decisions for the two objectives (hence also the weighted objective function) coincide.

Example (continued).

If $c_e = 1$, instead of the original $c_e = 2$, the new optimal order size is $Q_W^* = 622$; $TC(622) = 27{,}566 < 36{,}116$ and $TE(622) = 8{,}458 > 8{,}423$, i.e., *TC* has decreased and *TE* has increased, so that both objectives are conflicting. □

4. Discussion and managerial insights

The five observations in the previous section together constitute the main conclusion of this paper: the trade-off and synergetic views on the economic and environmental objectives are not contradictory but valid under different conditions and strategic focus. In this section, we will discuss the managerial implications of the results derived in the previous section.

To understand the decision processes underlying the approach towards sustainability, it is important to start with the question: why would any firm involve itself in efforts to improve environmental and societal sustainability? Typically, there are three fundamental reasons (see also [16]). The first one is the *altruistic motive*, the deeply felt urge to do good. Undoubtedly, there are many people and organizations who feel that there is more to life than money alone; by the altruistic motive, firms are finding their reward in strong sustainability performance by itself, even if there is no economic benefit. The second reason is the *legitimacy motive*: firms need to (and want to) fulfill the written and unwritten laws of doing business in a sustainable way. Clearly, within the altruistic and legitimacy motives, there is no real need for synergy between the two objectives so that the discussion of trade-off Vs. synergy becomes irrelevant. The third reason for firms getting into sustainability is the *economic motive*: the believe that there are (long term) economic benefits to focusing on environmental and societal performance (see, e.g., Wal-Marts motives in [17]). Clearly, for firms in this category, it is paramount to find synergies between the three bottom line measures.

In the previous section, it has been demonstrated that sustainability and economic benefits do not always go hand-in-hand. However, for firms that operate in a complex environment, the observations made do not always tell the full story. Firms that focus on (environmental and societal) sustainability because of the economic motive, believe that *long term* benefits can come from various sources, including operational cost reductions, attracting new customers by establishing a higher sustainability prestige and reputation, attracting and maintaining highly motivated employees who like working for a social & environmental responsible firm, et cetera.

It is important to note that all observations in the previous section assume a *ceteris paribus condition*, i.e., the impact of a change in one parameter is studied under the assumption that all other parameters remain at their original value. Although from a mathematical point of view this is a convenient assumption, the managerial practice at firms is far more complex.

For firms getting into a strategy of sustainability for economic motives, typically several developments happen in parallel:

(i) More strategic emphasis on sustainability implies that sustainability measures get more weight (within the model setting: α gets smaller). By Observation 1, this might result in decreased cost performance;

(ii) The firm probably expects to attract more (sustainable sensitive) customers which, in turn, creates more revenue (see Arc B in Figure 3). Note that by Observation 4, higher demand (D) might result in higher cost, but at a lower cost per unit;

(iii) It is to be expected that a sustainability focused firm will increase its efforts to reduce energy usage (E_H; E_O). The effect of such efforts on cost performance can be positive or negative, see Observation 2.

Note that the overall net effect of (i)-(iii) on cost performance (represented by Arc A in Figure 3) can be positive or negative depending on several factors such as the setting of the parameters and the extent to which efforts of reducing energy efforts are successful. Also, the elasticity of demand with respect to the strategic sustainable positioning efforts of the firm will largely drive the impact of Arc B in Figure 3. Concluding, whether the firm will be successful in finding a synergy between sustainability and the economy depends on many aspects of which only a few were studied in the model setting discussed in the previous section.

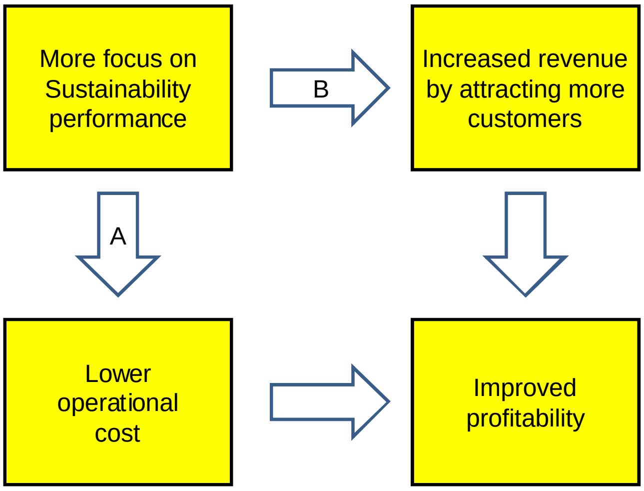

Figure 3: The road from sustainability to profitability.

The final remarks in this section are related to the role of energy prices (c_e in the model). One of the frequently proposed instruments by governments to achieve environmental sustainability is to use energy taxes. One of the reasons behind energy taxes appears to be that higher energy prices would make firms more aware of their energy usage, so that the need for energy usage reductions get higher on the firm's agenda, which in turn would lead to improved sustainability performance.

The model in this paper only partly supports such logic behind energy taxes. The impacts of increasing energy prices are multiple and the various dynamics are to be considered concurrently. First note that within the model, increased energy prices neither have a direct impact on the organization's importance assigned to sustainability objectives (a higher value of c_e does not imply a lower value of α), nor on the efforts to lower energy usage rates (a higher c_e does not imply lower values for E_O and E_H). However, by Observation 5, energy taxes do have the (intended) effect that a firm's annual energy usage is decreased. This effect might be partially offset by a higher energy usage per unit of output when the energy taxes would lead to a higher consumer price hence lower demand, see Observation 4(ii).

When compared to other government instruments to stimulate sustainable behavior, like communication (promoting sustainable behavior of firms and the public through education, promotion and subsidies) and legislation, it is not clear whether introducing energy taxes is the best choice (achieving the most impact on sustainability). The model discussed in this paper seems to indicate that, depending on the parameters, it is possible that the annual energy usage

(TE) is more sensitive to strategy changes (α) when compared to energy cost (c_e). From that perspective, persuading firms to make sustainability as a part of their strategy might be a more important instrument for governments compared to taxing energy.

5. Conclusions

Within the framework of a multi-criteria decision making extension of the EOQ model, in this paper it has been shown that there is no single answer to the issue whether economic and environmental (sustainability) performance are aligned or conflicting. In fact both can be the case, and which one applies is a matter of perspective. Indeed careful analysis is needed in every problem setting to see which of the two situations applies under what conditions.

The results in this paper can be extended in multiple ways. Other models of operations, logistics and supply chain decision making can be reviewed and analyzed in this context (see e.g. [18]). One useful extension could be to incorporate the effect of organization's strategic choice with respect to sustainability on customer demand. Furthermore, besides energy usage, other issues in environmental and social aspects of sustainability could be incorporated in the model. Another interesting line of research could be to consider the sustainability impact of decision making in multi-echelon, multi-decision maker supply chains.

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Appendix

In this appendix the formal proofs of the observations in Section 3 will be given. To do so, the partial derivatives of $TC(Q_W^*)$ and $TE(Q_W^*)$ with respect to the parameter at hand will be determined. Note that when either both partial derivates are positive or both are negative, the two objectives are aligned and if both partial derivatives have opposite signs, the objectives are conflicting. Throughout this appendix, the assumptions $\Delta \neq 0$, $0 < \alpha < 1$, and c_e, γ_H, γ_O, E_O, $E_H >$ 0 will be used.

Proof of Observation 1

Note that

$$\frac{\partial}{\partial\alpha} TC(Q_W^*) = \sqrt{\tfrac{1}{8}}D\left(\frac{C_H}{B_H} - \frac{C_O}{B_O}\right)\left(\frac{\gamma_O\sqrt{B_H}}{\sqrt{B_O}} - \frac{\gamma_H\sqrt{B_O}}{\sqrt{B_H}}\right).$$

It is easy to see that

$$\left(\frac{C_H}{B_H} - \frac{C_O}{B_O}\right) > 0 \text{ iff } (1-\alpha)\Delta < 0,$$

and

$$\left(\frac{\gamma_O\sqrt{B_H}}{\sqrt{B_O}} - \frac{\gamma_H\sqrt{B_O}}{\sqrt{B_H}}\right) > 0 \text{ iff } \Delta > 0.$$

Similarly, note that

$$\frac{\partial}{\partial\alpha} TE(Q_W^*) = \sqrt{\tfrac{1}{8}}D\left(\frac{E_H}{B_H} - \frac{E_O}{B_O}\right)\left(\frac{\gamma_O\sqrt{B_H}}{\sqrt{B_O}} - \frac{\gamma_H\sqrt{B_O}}{\sqrt{B_H}}\right),$$

and

$$\left(\frac{E_H}{B_H} - \frac{E_O}{B_O}\right) > 0 \text{ iff } \alpha\Delta > 0.$$

It follows that

$$\frac{\partial}{\partial\alpha} TE(Q_W^*) > 0 \text{ and } \frac{\partial}{\partial\alpha} TC(Q_W^*) < 0$$

for all $0 < \alpha < 1$. ■

Proof of Observation 2

Using

$$\frac{\partial}{\partial E_O} TC(Q_W^*) = c_e \sqrt{\tfrac{1}{8} D} \left(\frac{C_H}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_H}}{\sqrt{B_O}} - \frac{C_O \sqrt{B_H B_O}}{B_O^2} \right),$$

it is easy to verify that this partial derivate is positive iff Condition (13) is fulfilled. Similarly,

$$\frac{\partial}{\partial E_H} TC(Q_W^*) = c_e \sqrt{\tfrac{1}{8} D} \left(\frac{C_O}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_O}}{\sqrt{B_H}} - \frac{C_H \sqrt{B_H B_O}}{B_H^2} \right),$$

which is positive iff condition (14) is fulfilled.

Furthermore,

$$\frac{\partial}{\partial E_O} TE(Q_W^*) = \sqrt{\tfrac{1}{8} D} \left(\frac{c_e E_H}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_H}}{\sqrt{B_O}} - \frac{c_e E_O \sqrt{B_H B_O}}{B_O^2} \right),$$

and

$$\frac{\partial}{\partial E_H} TE(Q_W^*) = \sqrt{\tfrac{1}{8} D} \left(\frac{c_e E_O}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_O}}{\sqrt{B_H}} - \frac{c_e E_H \sqrt{B_H B_O}}{B_H^2} \right).$$

Note that

$$\left(\frac{c_e E_H}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_H}}{\sqrt{B_O}} - \frac{c_e E_O \sqrt{B_H B_O}}{B_O^2} \right) < 0 \text{ iff } E_O < \frac{-\alpha\gamma_O}{c_e} \left(\frac{2B_H + c_e E_H}{B_H + c_e E_H} \right) < 0,$$

and

$$\left(\frac{c_e E_O}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_O}}{\sqrt{B_H}} - \frac{c_e E_H \sqrt{B_H B_O}}{B_H^2} \right) < 0 \text{ iff } E_H < \frac{-\alpha\gamma_H}{c_e} \left(\frac{2B_O + c_e E_O}{B_O + c_e E_O} \right) < 0,$$

from which Observation 2 follows. ■

Proof of Observation 3

Note that

$$\frac{\partial}{\partial \gamma_O} TC(Q_W^*) = \sqrt{\tfrac{1}{8} D} \left(\frac{\alpha C_H}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_H}}{\sqrt{B_O}} - \frac{\alpha C_O \sqrt{B_H B_O}}{B_O^2} \right),$$

which is negative iff

$$\gamma_O < \frac{-c_e E_O \left(\alpha C_H + (2-\alpha) B_H\right)}{\alpha\left(\alpha C_H + B_H\right)} < 0.$$

Similarly,

$$\frac{\partial}{\partial \gamma_H} TC(Q_W^*) = \sqrt{\tfrac{1}{8} D} \left(\frac{\alpha C_O}{\sqrt{B_H B_O}} + 2\frac{\sqrt{B_O}}{\sqrt{B_H}} - \frac{\alpha C_H \sqrt{B_H B_O}}{B_H^2} \right),$$

is negative iff

$$\gamma_H < \frac{-c_e E_H \left(\alpha C_O + (2-\alpha) B_O\right)\big)}{\alpha\left(\alpha C_O + B_O\right)} < 0 .$$

Also,

$$\frac{\partial}{\partial \gamma_O} TE(Q_W^*) = \alpha \sqrt{\tfrac{1}{8} D}\left(\frac{E_H}{\sqrt{B_H B_O}} - \frac{E_O \sqrt{B_H B_O}}{B_O^2} \right),$$

is positive iff $\alpha\Delta > 0$, and

$$\frac{\partial}{\partial \gamma_H} TE(Q_W^*) = \alpha \sqrt{\tfrac{1}{8} D}\left(\frac{E_O}{\sqrt{B_H B_O}} - \frac{E_H \sqrt{B_H B_O}}{B_H^2} \right),$$

is positive iff $\alpha\Delta < 0$. Observation 3 follows immediately. ■

The proofs of Observation 4 and 5(ii) are trivial and will be omitted.

Proof of Observation 5(i)

Note that

$$\frac{\partial}{\partial c_e} TC(Q_W^*) = \sqrt{\tfrac{1}{8} D}\left(\frac{C_0 E_H + C_H E_O}{\sqrt{B_H B_O}} + 2E_O \frac{\sqrt{B_H}}{\sqrt{B_O}} + 2E_H \frac{\sqrt{B_O}}{\sqrt{B_H}} - \frac{C_O E_O \sqrt{B_H B_O}}{B_O^2} - \frac{C_H E_H \sqrt{B_H B_O}}{B_H^2} \right)$$

Careful analysis shows that this is positive iff

$$2 B_O B_H \left(E_O B_H + E_H B_O \right) + \alpha(1-\alpha)\Delta^2 > 0 .$$

Furthermore,

$$\frac{\partial}{\partial c_e} TE(Q_W^*) = \sqrt{\tfrac{1}{8} D}\left(\frac{2 E_H E_O}{\sqrt{B_H B_O}} - \frac{E_O^2 \sqrt{B_H B_O}}{B_O^2} - \frac{E_H^2 \sqrt{B_H B_O}}{B_H^2} \right),$$

Which is negative iff $\alpha^2 \Delta^2 > 0$. Together these results constitute Observation 5(i). ■

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