A Sustainable EOQ Model: theoretical formulation and applications

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Abstract

Traditional inventory models involve different decisions that attempt to optimize material lot sizes by minimizing total annual supply chain costs by an economic point of view.

However, the increasing concern on the environmental problems stresses the need to treat inventory management decisions as a whole by integrating economic and environmental objectives. Recent studies have underlined the need to incorporate additional criteria in traditional inventory models in order to design "responsible inventory systems". This paper explores the integration of factors affecting the environmental impact within the traditional EOQ model and proposes a "Sustainable EOQ Model". All sustainability factors linked to the material purchasing lot size are here analyzed from the beginning of the purchasing order to the end of its life inside the buyer plant. Thus, the environmental impact of transportation and inventory is incorporated in the model and investigated by an economic point of view. In particular internal and external transportation costs, the vendor and supplier location and the different freight vehicle utilization ratio are considered in order to provide an easy-to-use methodology. The optimization approach is applied to representative data from industrial problems to assess the impact of sustainability considerations on purchasing decisions if compared with the traditional approaches. Finally, an illustration of the effect of using the new "Sustainable EOQ model" is presented and discussed.

Keywords: EOQ, environmental sustainability, purchasing strategy, transportation costs, Inventory Management.

1. Introduction

Lot sizing problem is a critical issue since the lot sizing selection directly impacts the economic efficiency of purchasing and production activities.

There are various lot sizing approaches in literature, most of them consider the same cost factors in different ways and have specific advantages and disadvantages.

The "Economic Order Quantity" (EOQ) developed by Harris and generally referred to as the basic model, as well as a similar approach developed by Andler are allocated in literature to "traditional" static methods. Static methods are then converted in dynamic lot sizing approaches thanks to relevant and well-known contributions (Wagner and Whitin, 1958, Silver and Meal, 1973, De Matteis and Mendoza, 1968, Gahse, S, 1965, Trux, 1966/2). By a practical point of view, for enterprise practitioners it is not so critical which method they select for determining the lot size as much as it is that they implement a method aimed at optimization. This is the reason for which the Harris' basic model is always attractive due to its simplicity and the minimal amount of data needed. Moreover, the increasing concern on the environmental problems stresses the need to treat inventory management decisions as a whole by integrating economic and environmental objectives (i.e. Bonney and Jaber, 2011; Wahab et al, 2011). Firms worldwide are called today to incorporate carbon footprint management into their business decision. In this context, the environmental suitability of currently known lot sizing methods is debated. Considering the material purchasing, environmental cost factors usually rise majorly with increasing vehicle transportations. In this work the authors explore the economic lot sizing problem in materials purchasing when environmental concerns are considered. This paper propose a new easy-to-use theoretical model to calculate a sustainable economic order quantity, called from here S-EOQ, and then it compares its application with the traditional approach (simply called EOQ) and discusses results and cost factors with particular regards to the transportation mode selection.

2. Literature review

A few works have been published in the last years with the aim of incorporating sustainability issue in EOQ theory. In particular, there are 4 recent studies closely related to our work. Turkay (2008) revised the standard EOQ model to incorporate sustainability considerations that include environmental criteria. The method is based on revising the standard EOQ model with additional objectives and constraints, proposing different approaches: the Direct Accounting, the Carbon Tax, the Direct Cap, the Cap & Trade and the Carbon Offsets. Numerical applications are missed. Hua et al. (2010) studied this problem under the cap-and-trade mechanism, comparing the classical EOQ model with a new one. They examined the impact on order size of carbon cap and carbon price. The cap and trade mechanism induces the retailer to reduce carbon emissions, thus it results in an increase in the total cost. Moreover, the authors finally underline to have missed the examination of transportation mode decisions. Bonney and Jaber (2011) discuss in depth how to design responsible inventory systems and finally propose a simplistic model that extend the EOQ to include some environmental costs. Anyway they don't provide numerical applications in order to understand how to compute the social cost from vehicle emission and the effect of transportation mode selection and emissions generated in inventory holding are not considered. Under these hypothesis, they conclude that the refined EOQ is always larger than the usual EOQ. Finally, Wahab et al. (2011), develop environmental considerations in lot sizing and focus their attention on reducing CO_2 emission in transporting inventory. They categorized the CO_2 emission cost into fixed and variable, but economic values used for fixed and variable emission costs are not justified.

All these approaches provide a great knowledge to the existing literature. Anyway they considers order and inventory cost by an environmental and economic point of view, ignoring material handling and transportation modality constraints (in size and capacity for example). In practice, the EOQ is strongly affected by material handling equipment, transportation flow path and transportation mode technical constraints (Tersine, 1994 and Choi and Noble, 2000). Finally, today fewer numerical applications of the models discussed before are available in the literature.

3. Life Cycle Assessment of a material order quantity

The holistic perspective offered by Life Cycle Assessment (LCA) can help to identify all environmental impacts arising during the life time of a purchasing order quantity. Currently in literature, low interest is devoted to this kind of analysis and all environmental impacts are discussed and treated with the same importance. However, a low resolution analysis reveals that only transportation and handling activities have a great impact on emissions generated, while other process such as ordering, warehousing and disposing of waste have often a minimum incidence. A generalized outline of a life cycle assessment of a material purchasing order is presented in Fig. 1, in which the system boundaries are depicted by dotted lines and main inputs and outputs flows are represented by black arrows. The life of a purchasing order quantity is here supposed to start with the handling and transportation phase and to finish with the selling of the last order unit to the subsequent customer (since the ordering phase has no impact on the environment). Environmental inputs (material and energy) and outputs (air, water and solid emissions) at each stage of the order quantity life cycle need to be accurately computed in order to apply environmental principles to the EOQ theory.

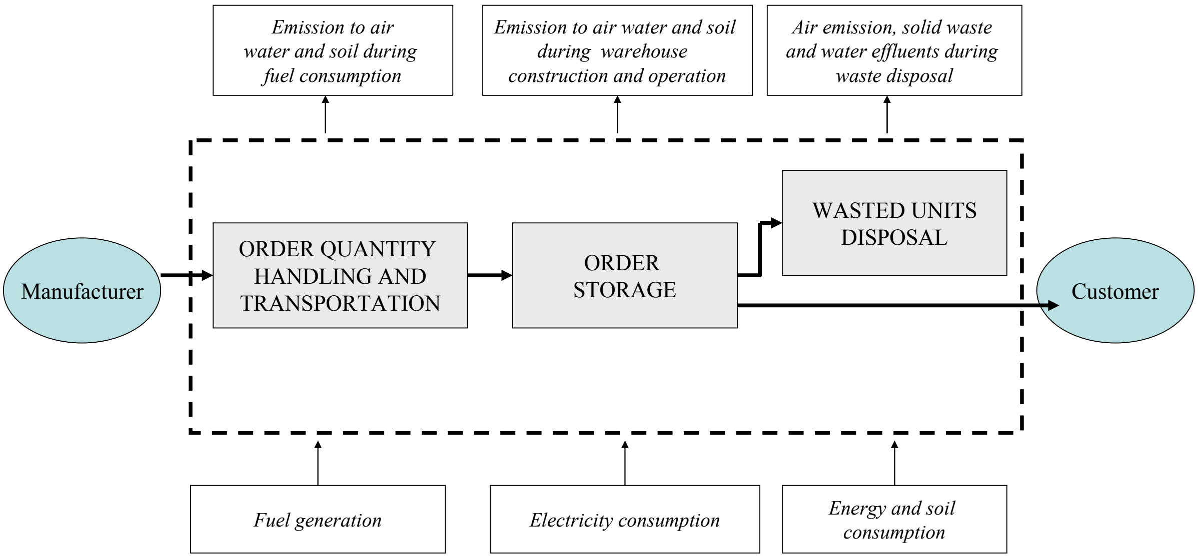

Figure 1. LCA general scheme of a material purchasing order

Of course this is the most difficult issue to solve. Anyway literature is now rich of contributes regarding the modelling of emission across the supply chain. In the following of this research, we will apply the conversion from CO_{2eq} generated during one if the three step in figure 1 into monetary expenses, supporting all assumptions and data with previous literature in the field. In particular, for measuring the environmental impact of transportation through external costs computation we remind to Litman (2009); Ortolani et al. (2009 and 2011), Sahin et al (2009); for warehousing carbon emissions computation to Rai et al (2009) and Fieldson and Siantonas (2008) and finally for carbon emissions costs computation in waste recycling and disposal process to the software WARM developed by EPA (http://www.epa.gov).

4. Theoretical formulation

The mathematical formulation that follows tries to capture economic and environmental trade-offs of lot sizing in material purchasing, according to the scheme reported in figure 1.

For this reason, the authors apply (in accordance with Harris et al., 2011) a "prudent approach" by modeling the environmental issues linked with logistics and warehousing activities as part of the design objectives rather then as constraints. This way, more information is available to help balancing cost versus environmental impact (Current et al., 1990). We consider the single-product replenishment problem based on the traditional EOQ model and applying a direct accounting approach (Bonney and Jaber, 2010; Aslon and Turkey, 2011). We suppose that the product demand is deterministic, the product price is exogenous and the buyer decides only the order size. The process of delivering and storing a purchasing lot of materials (from the beginning to the end of the order life) consume an amount of energy for the transportation and warehouse operations and produce an amount of emissions, as previously discussed in paragraph 3. In addition to these environmental factors, the new formulation should consider also that the material order life cycle imposes costs on society: social impacts are majorly linked to delivery and waste disposal operations. To this purpose, we will apply the concept of "external costs" (Ortolani et al., 2011) in order to consider jointly environmental and social dimensions in delivery operation (i.e. external cost of congestion, accidents, roadway facility costs ..), warehousing and waste disposal.

First, we introduce the notations used in the paper as follows:

D annual demand [units/year]

Q_s decision variable with sustainability considerations [units/purchasing order]

Q decision variable without sustainability consideration [units/purchasing order]

$C(Q_s)$ total average annual cost of replenishment with sustainability considerations [€/year]

$C(Q)$ total average annual cost of replenishment without sustainability considerations [€/year]

S-EOQ optimal sustainable order quantity [units/purchasing order]

EOQ optimal order quantity without sustainability consideration [units/purchasing order]

O fixed ordering cost per order [€/order]

h holding cost [€/unit]

p unit purchase cost [€/unit]

d distance travelled from the origin (supplier) to the destination (buyer) [km]

b space occupied by a product unit [m^3/unit]

β average inventory obsolescence annual rate [%]

a weight of an obsolete unit stored in the warehouse [ton/unit]

S freight vehicle utilization ratio in %

y full load-vehicle/container capacity [units or m^3]

$c_{\text{int} f}$ fixed internal cost coefficient [€/km]

$c_{\text{int} v}$ variable internal cost coefficient [€/km m^3]

c_{extf} fixed external cost coefficient [€/km]

c_{extv} variable external cost coefficient [€/km m^3]

C_{eh} total annual carbon emissions cost for holding [€/unit]

c_{eh} average carbon emission cost coefficient of a warehouse [€/m^3]

C_{eo} total annual carbon emission costs for inventory waste collection and recycling [€/ton]

c_{eo} average carbon emission cost coefficient of inventory waste for collection and recycling [€/ton]

Unlike prior models (see paragraph 2), transportation and obsolescence cost are here considered explicitly and treated by a sustainability point of view. The full average annual cost of replenishment (without sustainability considerations) is here expressed by the simply sum of 5 terms: the variable cost of purchasing D units in one year, the ordering cost (which not includes the cost of transportation), the cost of transportation C_t , the holding cost C_h and the cost of inventory obsolescence C_{obs}.

$$C(Q) = c \cdot D + C_o(Q) + C_t(Q) + C_h(Q) + C_{obs}(Q) \qquad (1)$$

A Sustainable EOQ total cost function can be expressed by the sum of the same 5 terms. This time, by a sustainable point of view, the last 3 terms must consider also external costs and their quantifications.

$$C(Q_s) = c \cdot D + C_o(Q_s) + C_t^*(Q_s) + C_h^*(Q_s) + C_{obs}^*(Q_s) \tag{2}$$

Following we will discuss each of the 5 terms in formula (2). The ordering cost are associated only to the buyer fixed cost of processing the order, according to traditional models:

$$C_o(Q_s) = \frac{D}{Q_s} \cdot O \tag{3}$$

Transportation cost with sustainability considerations are here the sum of two terms: internal transportation costs and external transportation costs.

$$C_t^*(Q_s) = C_{t-\text{int}}(Q_s, d, S) + C_{t-ext}(Q_s, d, S) \tag{4}$$

In a real logistic system, internal and external transportation costs include both fixed and variable costs (Zhao et al, 2004; Birbil et al., 2009) and the two final function present Discontinuity Points (DP) when the vehicle capacity is saturated. Thus, we introduce a fixed internal cost coefficient and a variable internal cost coefficient, which depends on the quantity transported and on the vehicle saturation *S:*

$$C_{t-\text{int}}(Q_s) = \left[c_{\text{int} f} \cdot d + (c_{\text{int} v} \cdot d) \cdot \frac{Q_s}{S} \right] \cdot \frac{D}{Q_s} \tag{5}$$

Vehicle saturation depend on the quantity transported, on the vehicle capacity and on the number of vehicle used in the order cycle.

For simplicity, if we consider to use only one vehicle type with a certain capacity y, we can assume that $S = \frac{Q_s}{n \cdot y}$ is the vehicle saturation, where $n = \left\lceil \frac{Q_s}{y} \right\rceil$ is the number of vehicle used in a order cycle. Thus, formula (5) becomes:

$$C_{t-\text{int}}(Q_s) = \left[c_{\text{int} f} + (c_{\text{int} v}) \cdot y \cdot n \right] \cdot d \cdot \frac{D}{Q_s} \tag{6}$$

As discussed in previous works (Zhao et al, 2004 and Birbil et al., 2009) and highlighted in fig. 2, the previous is not a continuous function and it cannot be differentiated during the whole interval. Moreover, the value *n* depends on the number of different vehicle type used in the transportation (for example different containers with different capacities). Normally, in practice more type of vehicle are available with different capacity and different costs. Thus it's necessary to evaluate all discontinuity points and ranges between them accurately and then apply a step by step approach, previously adopted in literature. To simplify the problem, when DP_i is the Discontinuity Point *i*, obtained after the accurate evaluation of all capacity saturation ranges when different kind of vehicle (*j*) are applied in the same purchasing cycle, we can write that in general:

$$C_{t-\text{int}}(Q_s) = \left[c_{\text{int}\,f} \cdot d + (c_{\text{int}\,v} \cdot d) \cdot DP_i\right] \cdot \frac{D}{Q_s} \tag{7}$$

Where *j=1,…,J* are different kind of vehicle available for transportation and discontinuity points are:

$$DP_i = \sum_j y_j \cdot n_j \tag{8}$$

Then follows:

$$\frac{dC_{t-\text{int}}(Q_s)}{dQ_s} = -\left[c_{\text{int}\,f} \cdot d + (c_{\text{int}\,v} \cdot d) \cdot DP_i\right] \cdot \frac{D}{Q_s^{\,2}} \tag{9}$$

Defined only when:

$$DP_{i-1} < Q_s < DP_i \tag{10}$$

In the same way and under the same conditions, also external transportation costs presents the same discontinuity points and are formulated in the same way, obtaining the following:

$$C_{t-ext}(Q_s) = \left[c_{extf} \cdot d + (c_{extv} \cdot d) \cdot DP_i\right] \cdot \frac{D}{Q_s} \tag{11}$$

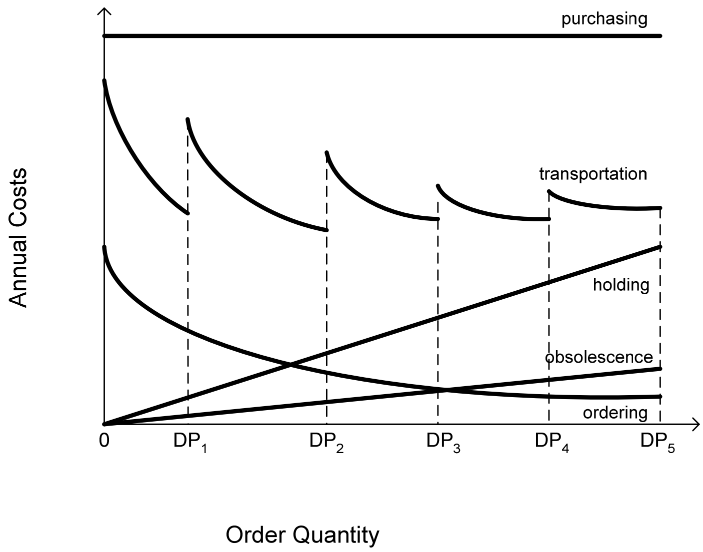

Figure 2. Cost functions in a purchasing order cycle

Holding cost now considers both the traditional holding cost of carrying inventory and the cost associated to carbon emissions generated by warehousing:

$$C_h^*(Q) = \frac{Q}{2}h + C_{eh}(Q) \tag{12}$$

where

$$C_{eh}(Q) = c_{eh}\left(\frac{Q}{2} \cdot b\right) \tag{13}$$

c_{eh} is the average emission cost coefficient of a warehouse expressed in € per cube meter of warehouse space occupied by inventory, and b measures the cube meters occupied by a product unit stored in the warehouse (considering also packaging materials).

The inventory stored in the warehouse present a risk of obsolescence at the end of the year, expressed by the obsolescence annual risk rate β. Obsolescence goods at the end of the year are sold by the buyer to a specific waste treatment company for recycling at the disposal price *p'*, lower then *p*. Anyway, by a sustainability point of view, the waste recycling process consume energy and increase carbon emissions. Therefore:

$$C^*_{obs}(Q) = \frac{Q}{2}(p - p') \cdot \beta + C_{eo}(Q) \tag{14}$$

$$C_{eo}(Q) = \frac{Q}{2} \cdot \beta \cdot a \cdot c_{eo} \tag{15}$$

c_{eo} is the carbon emission cost coefficient for obsolete inventory waste collection and recycling, expressed in €/ton and a is the weight of an obsolete unit stored in the warehouse in tons/unit. Finally, due to the reasons described above and to the discontinuity nature of the transportation cost function, in order to minimize *C(Q)* and $C(Q_s)$ we will adopt the easy-to use approach of comparing total cost functions *C(Q)* and $C(Q_s)$ at each Discontinuity Point quantity DP_i and then find the optimal purchasing lot size, *EOQ* and *S-EOQ*.

In the next paragraph real applications are presented and compared in order to discuss the effect of applying a sustainability oriented full cost formula in purchasing decision.

5. Applications

In this section we present a numerical examples, directly derived by a real industrial case, to illustrate the above analytical model and provide some interesting observations. Let consider three different purchasing possibilities for a product *X*, which in the following example can be assimilated to a DVD lector. The model is applied to a buyer company located in the North-East part of Italy and closed to intermodal terminals, making use of company's and literature data (as previously discussed at the end of paragraph 3). Internal transportation costs are derived from the Italian Ministry of Transport report (2011) and from the company's data. Let consider the possibility to purchase del product in analysis from two different vendors: one located 600 km distance from the buyer (using a road or a road-rail intermodal transportation), the other located overseas by adopting a road-ship intermodal transport. The product unitary purchasing price is kept constant in order to better comprehend the differences. All input parameters used are summed up in table 1. For each purchasing case all cost function reported in formula (1) and (2) are computed in relation to the set of discontinuity points DP_i identified according to the different handling units used (container 1: ISO 20 feet and container 2: ISO 40 feet). An example of the application of formula (2) for case 3 is reported in Table 2 and results depicted in Figure 2.

The final results for the three cases are shown in Table 3, Figure 3, Figure 4 and Figure 5. The results reported in table 3 verify the difference between full annual cost without sustainability considerations *C(EOQ)* and the full annual cost with sustainability considerations *C(S-EOQ),* which of course assumes higher relevance in case of a mono-modal road transportation.

Input Data	*case1: road*	*case2: road-rail*	*case3: road-ship*
D	40,000	40,000	40,000
O [€/order]	400	400	400
p [€/unit]	10	10	10
p' [€/unit]	5	5	5
h [€/unit]	2.5	2.5	2.5
d [km on road]	600	100	100
d [km by train]	0	500	0
d [km by ship]	0	0	14,000
y_1 *[units/contanier 1]*	1,700	1,700	1,700
y_2 *[units/container 2]*	3,400	3,400	3,400
β [%]	10%	10%	10%
a [tons/unit]	0.0020	0.0020	0.0020
b [m^3/unit]	0.0170	0.0170	0.0170
c_{intf} *[€/km]*	0.8000	0.6000	0.0480
c_{intv} *[€/km*m^3]*	0.0100	0.0070	0.0030
c_{extf} *[€/km]*	0.2000	0.0066	0.0044
c_{extv} *[€/km*m^3]*	0.02	0.00	0.00
c_{eh} *[€/m^3]*	0.55	0.55	0.55
c_{eo} *[€/ton]*	13	13	13

Table 1. Input data

i	*DPi*	*#container 1*	*# container 2*	*# containers per year*	*Orders per year*	*Transportation Cost*	*Order Cost*	*Holding Cost*	*Obsolescence Cost*	*Purchase Cost*	*Total Cost*
1	1400	1	0	28.6	28.6	61,203	11,429	1,757	350	400,000	474,738
2	3400	0	1	11.8	11.8	40,501	4,706	4,266	851	400,000	450,324
3	5100	1	1	15.7	7.8	43,802	3,137	6,399	1,276	400,000	454,614
4	6800	0	2	11.8	5.9	40,501	2,353	8,532	1,701	400,000	453,087
5	8500	1	2	14.1	4.7	42,481	1,882	10,665	2,127	400,000	457,155

Table 2. Case 3: example of the theoretical model application with intermodal road shipping transportation and sustainability considerations.

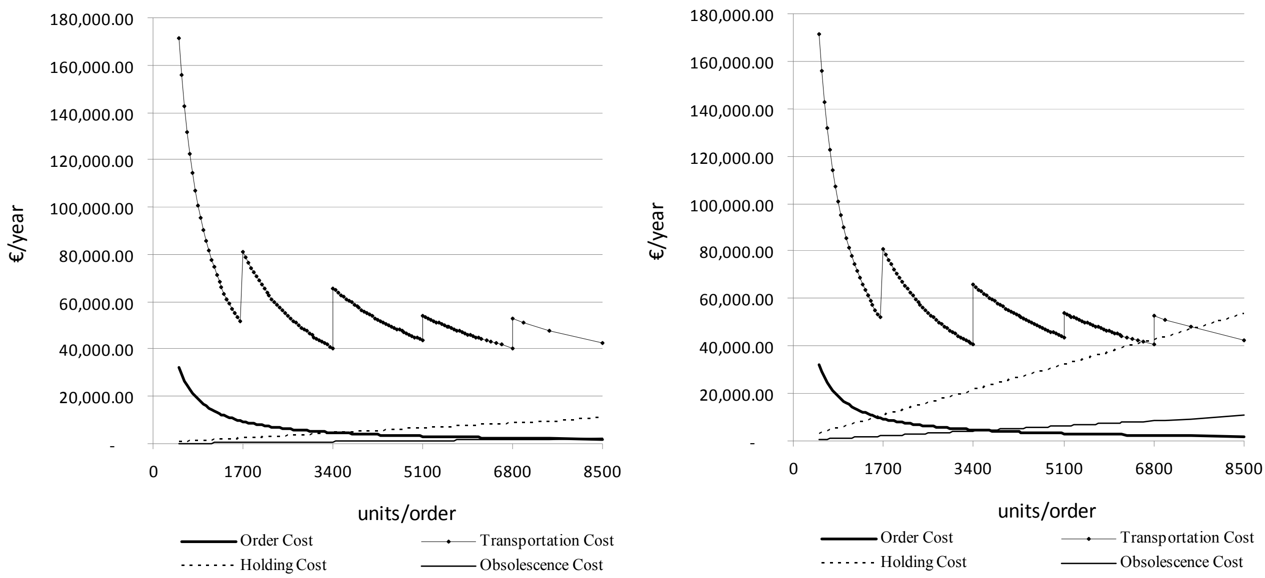

Figure 2. Case 3: dependence of the average transportation, holding, order and obsolescence cost on the purchasing order size (on the left: the product price is 10€/unit, on the right: the product price is 50 €/unit).

Anyway the difference between EOQ and S-EOQ becomes trivial when the purchasing price is low and in this case equal to the second discontinuity point of 3400 units, which saturate one big container. A sensitivity analysis of the difference between the two economic quantities is reported in Figure 3 for case 1: the S-EOQ is maximum higher to the EOQ of about a 20%. Results reported in Figure 4 and 5 reveals that the beneficial effects of the EOQ theory revisited by sustainability considerations is majorly linked to the opportunity to change the transportation modes applied rather then to change the purchasing lot size. According to the results reported in Figure 4 and Figure 5, the convenience to adopt a multimodal road-rail transportation becomes evident when adopting sustainability considerations (formula 2) rather then the traditional cost computation (formula 1).

	EOQ	*S-EOQ*	*C(EOQ)*	*C(S-EOQ)*	*Internal Transportation Costs*	*External Transportation Costs*
case1	3400	3400	419,532.94	429,105.32	9,727.06	9,571.76
case2	3400	3400	419,716.47	421,367.07	9,910.59	1,634.12
case3	3400	3400	447,987.06	450,323.54	38,181.18	2,320.00

Table 3. Economic Order Quantity and Sustainable Economic Order Quantity and related costs computed in the three cases.

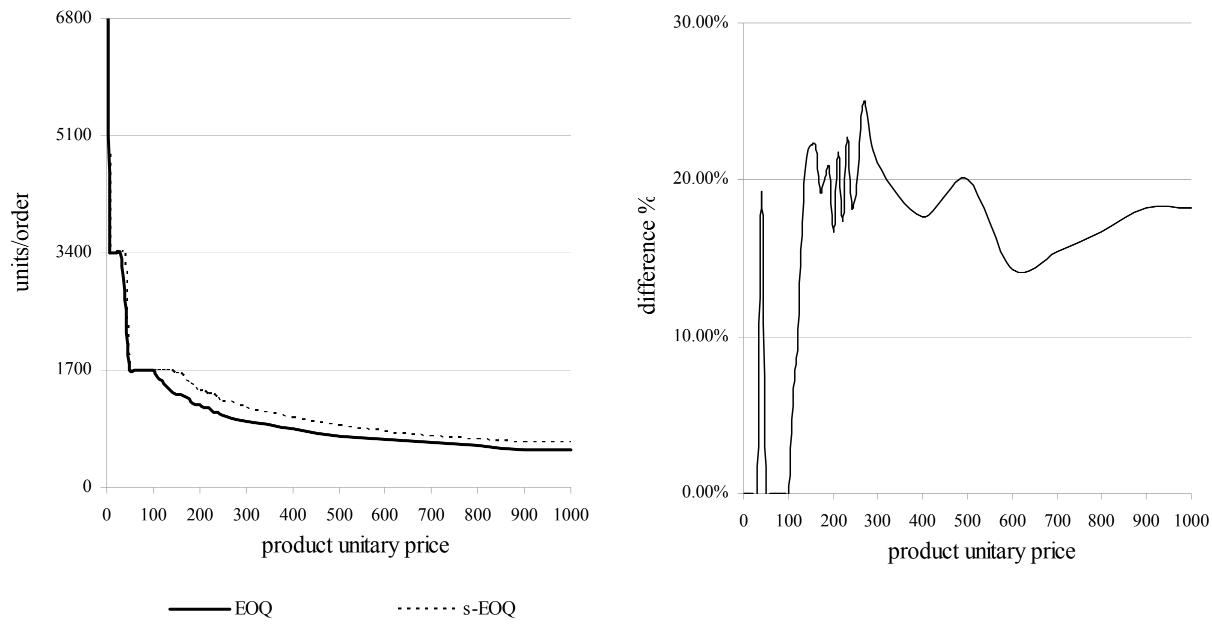

Figure 3. EOQ and S-EOQ according to variance in the purchasing price p (€/unit) on the left and relative difference in % between S-EOQ and EOQ on the right.

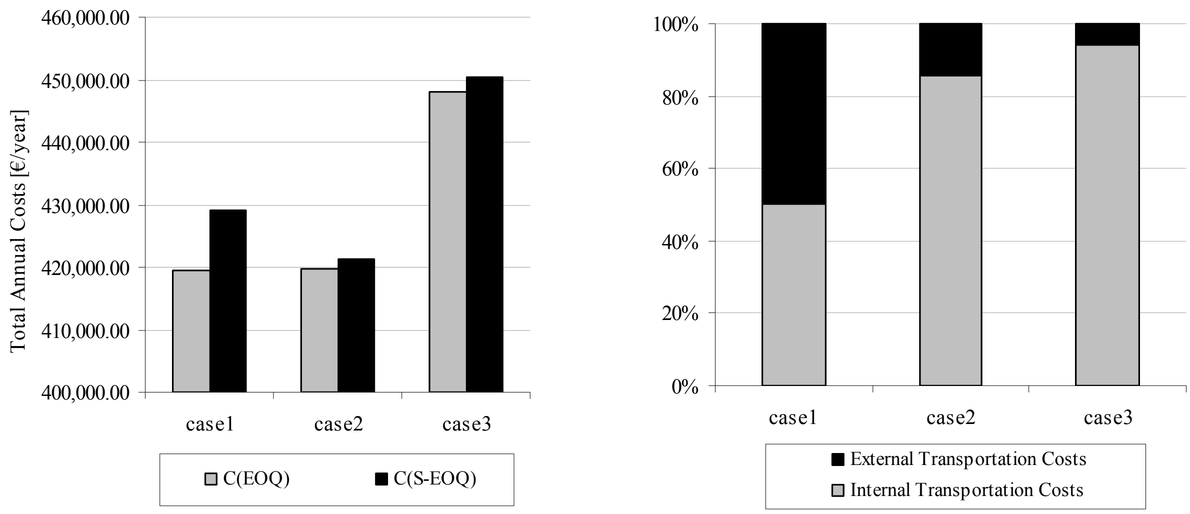

Figure 4. Comparison between full costs (on the left) and internal/external transportation costs (on the right) for EOQ and Sustainable EOQ.

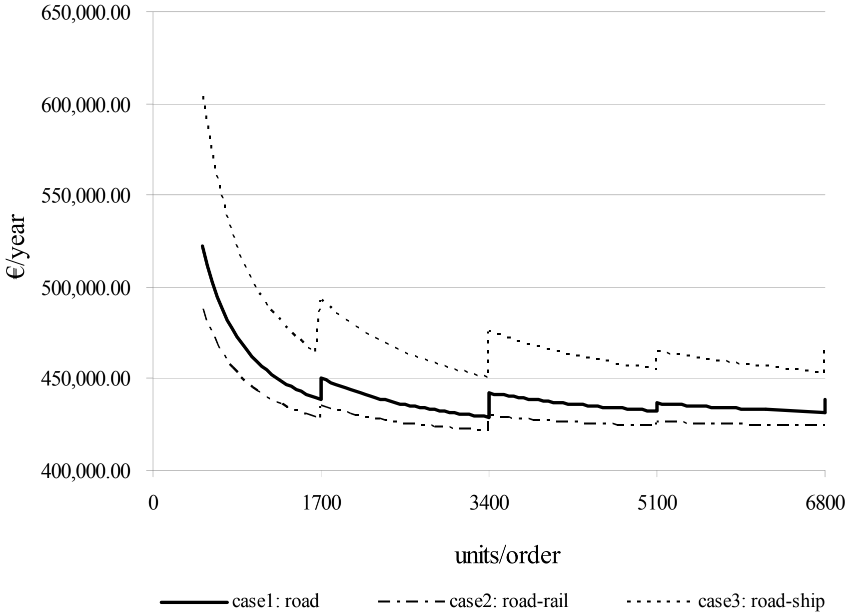

Figure 5. Dependence of the average full costs (with sustainability considerations) of the three purchasing cases considered on the purchasing order size.

6. Conclusions

The paper developed a model for calculating the full costs of a single-product replenishment problem based on the traditional EOQ model and applying a direct accounting approach. The main difference from previous literature in the field relates to transportation costs analysis and quantification and to external costs integration according to an LCA approach. In the numerical applications reported intermodal and road freight transport options are considered for the same product. The model is applied to understand the real effect of sustainability considerations in EOQ theory when a direct accounting method is applied.

The results show that, for the same transportation modality, the difference between EOQ and sustainable-EOQ is low and it increases when the product unitary price increases, varying around the 20% of increment in the purchasing lot size for the mono-modal road transportation. Anyway, when different transportation modes are considered and compared, the inclusion of sustainability considerations in the EOQ theory helps practitioners to change their purchasing strategy and transportation modality more rapidly, with a clear economical convenience in adopting the intermodal case rather than the mono-modal road transportation. Consequently, the costs of both transportation modalities (mono-modal and multi-modal) under sustainability considerations equalized at a break-even point (traditionally represented by the travel distance) shorter respect to a traditional costs computation.

Despite the limits inevitable in such numerical applications, the results offer some insight into the future EU policies aimed at internalizing transport externalities. If *sustainability considerations* and a *direct accounting method* are to be used in the near future, the intermodal transport will becomes of course competitive and beneficial also in the medium-distance markets (600-900 km) and more and more competitive in the long-distance markets (up to 900 km).

Anyway, the limits of a *direct accounting method* when externalities need to be quantified are also evident: the difference in fact between EOQ and Sustainable-EOQ becomes often trivial. This suggests us (as highlighted previously by Turkay, 2008 ad Hua et al., 2010) that a *cap and trade* approach to carbon emissions limitation could be the only one to be effective and forceful in the industrial practice.

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