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The Economic Order Quantity model revisited: an Extended Exergy Accounting approach

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ABSTRACT

The Economic Order Quantity, *EOQ*, model has been popular among academicians and practitioners for decades. Despite the many variants of the *EOQ* that have appeared in the literature to fine-tune it to reality, it still has limitations. A major one is that it does not take into account the hidden costs inherent in inventory systems. Some of these costs relate to sustainability issues including environmental, social labor, and economic effects.

This paper considers some of these costs, referred to as the exergetic costs, and estimates them using the Extended Exergy Accounting, *EEA*, approach. Extended Exergy Accounting assigns equivalent exergetic values to capital, labor and environmental remediation costs of a system. The analysis combines the classical exergy analysis with the sustainability factors, which are the labor, capital and environment. The paper uses an exergetic model to determine the EOQ inventory policies for three firms operating in the USA, Germany and China. The results show that the *EOQ* is different for the three firms because the equivalent exergy of capital, labor and environment remediation costs is different in each country.

1. Introduction

The classic Economic Order Quantity (*EOQ*) minimizes the sum of two conflicting inventory costs: ordering (setup) and holding costs. The EOQ model of Harris (1990); a reprint of the 1913 paper) was the first scientific treatment of inventory systems. Thus, it is considered to be a fundamental model of inventory and logistics management. Since its inception, the EOQ model has undergone extensive investigation and development to fit various requirements (e.g., Schwaller, 1988; Drezner et al., 1995; Chen and Min, 1991). The applicability of the *EOQ* model has been queried despite its wide use. Woolsey (1990) criticized the classical *EOQ* model and recommended business firms to think more before using it. He totally disagreed with the *EOQ* assumptions (see Section 3) regarding constant price, demand and average quantity in stock. Selen and Wood (1987) stated that the EOQ model produces poor results because of poor definition and estimation of its input parameters. They noted that the difficulty in calculating the variable set-up and holding costs was because the financial accounting rules were not examined. Zangwill (1987) showed that the *EOQ* with zero inventory (*ZI*) can be mistaken in its assertion that inventory reduces when set-up time and/or cost reduces.

The classical *EOQ* model also has other limitations. It neglects some aspects of practical situations. For instance, it assumes that all units of a specific product or the material used in producing it are of perfect quality with steady demand (Khan and Jaber, 2011). Salameh and Jaber (2000) modified the classical *EOQ* model to consider the imperfect quality of products. They showed that the size of the *EOQ* increases as the average percentage of imperfect quality items increases. Readings on inventory and quality are found in Wright and Mehrez (1998) and Khan et al. (2011).

Facing pressures from governments, customers and other stakeholders, business firms have realized that there is a need to adopt better strategies and tools to minimize the negative environmental and social effects that their operations produce, while seeking economic profitability. Bonney and Jaber (2011) presented a detailed discussion and analysis of the need to design responsible inventory systems. They examined the importance of inventory planning to the environment. For illustrative purposes, they developed an analytical inventory model, a variation of the *EOQ*, and concluded that items should be ordered in larger quantities less frequently than the classical *EOQ* model recommends in order to reduce the transportation cost and, consequently, CO_2 emissions.

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The novel idea of presenting an analogy between the behavior of production and thermal systems has encouraged some researchers to merge the concepts of the first and second laws of thermodynamics with inventory management. Thermodynamics is a discipline that deals with the conversion of matter and energy from one state to another. It illustrates that increasing energy and matter resource-flows into a given system, results in a depletion of these resources, which increases the disorder (entropy) of the system (Norde, 1997). This suggests that thermodynamics could be used as a tool to protect global resources and achieve more sustainable systems.

Entropy is defined as the degree of disorder in a process or a system that illustrates the amount of unused energy. It “frequently manifests itself as a queue; for example, materials may wait to be processed or a plant is not fully utilized as it waits for materials; machines wait for service or maintenance men wait to service machines; finished goods wait for customers' orders or customers wait for goods, etc.” (Drechsler, 1968).

To reduce the effects of entropy, Jaber et al. (2004) suggested adding a third cost component (entropy) when analyzing production and inventory policies. They found that using the entropy cost approach recommends ordering in larger quantities less frequently, which leads to higher profits than the classical *EOQ* model suggests. Their results also showed that reducing the lot size without considering entropy cost would reduce profits. A review of the works that deal with this line of research are found in Jaber (2009). Thermodynamically, entropy is related to exergy. Exergy is defined as the useful amount of energy available. Losses relating to exergy and entropy in a thermodynamic system are described by their source, location and cause. It is believed that exergy provides a more transparent view of an energy system. Generally, entropy production is proportional to exergy consumption (Rosen and Scott, 2003). As an indicator, exergy can be considered as a good measure of sustainability for each material used. “Exergy indicators” are based on the exergy content of a resource and the rate of losing that exergy to the environment. These indicators can assist in selecting energy and resources that minimize the environmental impact in the long term (Koroneos et al., 2012).

The increasing concerns of human societies about sustainable development have encouraged many parties to study and develop better techniques to improve the usage of energy and natural resources. Exergy analysis is a powerful technique that has been used to minimize energy usage and depletion of natural resources. It helps to improve the efficiency of a system by analyzing its input and output flows along with the destroyed and wasted exergy. Performing an exergy analysis makes the comparison, modification and development of a product, process or a system easier (Dincer, 2002). Exergy analysis addresses and solves energy problems that relate to sustainable development and the environment, where exergy is the confluence of energy, environmental and sustainable development (Rosen and Dincer, 2001).

Exergy analysis can help to identify a system's imperfections (Koroneos and Tsarouhis, 2012). It has been widely used by many industrial and production firms, e.g. aluminum (Balomenos et al., 2011), food (Apaiah et al., 2006), cement (Madlool et al., 2012), manufacturing (Gutowski et al., 2009), metal recycling (Amini et al., 2007) and waste management (Gaudreau et al., 2009).

Ayres et al. (1998) addressed three potential advantages of using exergy in the life cycle assessment (LCA) of a system. These advantages are: (1) it estimates the exergetic efficiency of a system, (2) it helps to compare the impact that different systems (processes) have on the environment, and (3) it provides a single performance measure that captures the environmental performance of complex systems. Szargut et al. (1988) presented the concepts of Cumulative Exergy Consumption (*CExC*), which measures the required amount of exergy embodied in raw material and energy used to produce a product. *CExC* computes the total exergy from consuming different resources at each stage of a system and quantifying them against a single resource accounting scale (Moya et al., 2013).

Bösch et al. (2007) modified some of the concepts of *CExC* and introduced a new index, the Cumulative Exergy Demand (*CExD*), to assess the demand of energy and natural resource from an energetic quality point-of-view. By using the *CExD* index they were able to calculate the exergy indices for a large number of energy carriers and non-energetic material, which were entered into the Ecoinvent database (http://www.ecoinvent.org/database/) available to be used by any interested party.

In economics, the cost of a commodity (c) is generally expressed by a “production function”, which is an aggregation of material (M), energy (E), labor (L), capital (K) and environment remediation (O) costs; i.e., $c = f(M, E, L, K, O)$ (Sciubba, 2009). To bridge the gap with the classical *CExC* analysis method, Sciubba (2001) introduced “Extended Exergy Accounting (*EEA*)” to highlight other non-energetic production factors, including labor, capital, and environmental remediation costs in the *CExC* analysis. *EEA* uses equivalent exergetic values assigned to capital, labor and environment remediation costs of a system. EEA uses exergy as a direct measure of the impact activities of a system have on the environment and to compute the environmental exergetic costs associated with a type of flow; the cost of bringing a discharged stream into equilibrium with its surroundings (environment) is proportional to the exergetic content of the flow (Sciubba, 1999).

Over the last decade, *EEA* has been applied to a number of countries, regions and specific sectors, including the UK (Gasparatos et al., 2009), Norway (Ertesvåg, 2005), China (Chen and Chen, 2009), the province of Nova Scotia in Canada (Bligh and Ismet Ugursal, 2012), and the Turkish transportation sector (Seckin et al., 2013) to measure their exergetic performance. *EEA* provides an engineering tool that helps an industry achieve environmental compatibility (Creyts and Carey, 1999). It also measures the environmental performance of a system by assigning an extended exergy content to the inputs of the system needed to produce a product and reduce the exergy of unwanted outputs (e.g., waste, CO_2 emissions) to zero (Simpson and Edwards, 2011).

Recently, Jaber et al. (2011) modified the *EOQ* model and used it to investigate a simple reverse logistic model in the presence of the “exergy cost”. They used exergy to measure the cost of lost potential to produce/recover new/used items because of entropy effects. Their results showed that an integrated policy of production and recovery is profitable, a result that may encourage firms to implement green inventory management practices. To our knowledge, there is no available study in the open literature that combines the environmental, social and economic aspects in the *EOQ* model and there is no research that uses *EEA* to analyze inventory systems. The aim of this paper is to develop a new *EOQ* model based on *EEA*, and to calculate the total exergetic cost associated with the inventories of a product for firms located in the economies of the USA, Germany and China.

The paper is organized as follows. Section 2 presents a brief background to the concept of exergy and exergy analysis. Section 3 introduces the concept of exergetic cost of inventory and illustrates how to introduce the *CExC* and *EEA* principles into inventory modeling. Sections 4, 5 and 6, respectively present numerical analysis, results and discussion, and conclusions.

2. A brief introduction to Exergy

Exergy is defined as the maximum useful work that can be obtained when a system is brought into equilibrium with its