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Models for Operation Management under Carbon Policies – A Review

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In the last 10 years, more than 300 academic papers have been published on the topic of operation management (especially on the supply chain) under carbon policies. We gather and analyze various research information based on the correlation between carbon emission and operation management (i.e. production and distribution, inventory control and supply chain management). Several models like e.g. EOQ, Newsvendor, Lot-sizing are considered in three main carbon policies (carbon cap, carbon tax, cap and trade). This paper summarizes research on 4 mainly models and methodologies employed for forward operation management and thereby contributes to the further study of this field. The aim of this paper is to report and review several models and methods available on operation management field, help readers appreciate various mechanisms for operation management considering carbon emission and lay some foundation work for future research.

1. Introduction

In recent years, the degradation of the ecological environment caused by climate change not only has had a profound and lasting effect on the sustainable development of the world economy but also has affected human society and the quality of daily life for everyone. In practice, to solve the environmental problems, various actions contributed to control carbon emissions have been taken. Meanwhile, operation management has evolved very rapidly and the case study integrated in carbon polices in different areas attract more attention. In order to reduce carbon emission effectively, entrepreneurs have focused on reducing emissions due to the physical processes involved production, inventory, transportation, etc. Meanwhile, many scholars have found a potentially significant influence which business decisions and operation rules have upon carbon emissions.

Carbon emission regulations place a request on operation management to achieve beyond merely economic issues like e.g. environmental friendly production and optimize cost and margin. This raises attention in its interaction with sustainable and economical development. Scholars and entrepreneurs of all sizes have also come to realize its importance and have been constantly engaged in operation management under carbon emissions. Meanwhile a lot of researchers have been devoted themselves into examination of carbon-footprint supply chain and the influence on operation management.

The aim of this paper is to make general and broad statement by inferring from existing research on operation management under carbon policies (carbon cap, carbon tax, cap and trade) for further study, especially summarize several basic models (EOQ, Newsvendor) to set an important foundation on the theory building. The organization of this paper is as follows: since this study deals with the relevant literature, we derive a structure for our systematic literature by summarizing the content analysis model and method applied in three aspects: production and distribution, inventory control and supply chain management. Next, we summarize five relatively simple and widely used models and corresponding transformation form on the three aspects considering carbon emissions. Furthermore, we also list other mixed models appeared in several literature. And then, we also make the discussion of the literatures, and come to a brief conclusion and finally propose an orientation for future research.

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2. Describing the structure for the literature review

Carbon emission regulations inevitably lead to a substantially increase in emission related cost, which persuades carbon sensitive entrepreneurs to take emission related costs into account, and which certainly catch the scholars' attention. In recent years, the study on carbon emission regulation has drawn extensive attentions both in empirical and theoretical research.

In the presence of the fact, this study forms a wild literature review at the interaction between carbon policies and operation management. The method and models applied have already appeared and described in detail in the literatures about supply chain management (e.g. production, distribution and inventory control). Related papers are identified by the constituted keyword "operation", "carbon", "model" and "regulations". We can easily get related literature by searching major databases and publisher websites such as INFORMS. In detail, literatures are selected in a two-step process. First, as there were models and analysis methods in these papers, we select them for further analysis. Second, these collected literatures are conformity allocated to carbon emission policies, where three main regulations are applied: carbon cap, carbon tax, carbon cap and trade. Eventually, we get a list of papers on operation management involved in carbon policies and models.

Above all, we set several models used by the scholars to examine the operation management problem under these regulations. For the analysis itself, we sort a set of norm at first for describing the matter. Firstly, we consider the basic inventory control theory under carbon emission regulations containing EOQ, Newsvendor and Lot-sizing model. Furthermore, we start with the distribution problem, integrating the production and inventory into the supply chain management. Now, we begin with inventory control theory.

3. Inventory Control Theory

There are several recent papers studying the inventory problems considering environmental condition. Accordingly traditional inventory theory is developed under the operation management considering carbon emissions. As we all know, the lot-sizing, newsvendor and EOQ model are popularly used in production and inventory. Especially considering the carbon emissions, the entrepreneurs are devoted to minimizing cost and maximizing profit under the emission policies, what's more, many experts have succeeded in their research.

3.1 Economic Order Quantity (EOQ)

The "Economic Order Quantity" (EOQ) model was first developed by Harris and generally referred to as the basic model. Without losing generality, we assumed a constant and continuous demand, zero lead-time and without shortage cost. The average total cost per time unit has the following expression:

$$Z(Q) = \frac{AD}{Q} + \frac{hQ}{2} + cD \tag{1}$$

With Q= order quantity

c =fixed purchased or produced cost per unit

D= constant demand per unit time

h= holding cost per unit at unit time kept in inventory

A= fixed cost per order

Under EOQ model, the target of the entrepreneur is to minimize its cost by choosing an optimum order quantity Q at per unit time. While considering the carbon emissions during the process. Emissions are associated with ordering, production/purchasing, and inventory holding are substituted by A^, h^ and c^.

Under carbon cap regulation, X. Chen et al. consider the amount of carbon produced is defined to be a carton cap C, the problem then can be formally described as follows:

$$\text{Min} \quad Z(Q) = \frac{AD}{Q} + \frac{hQ}{2} + cD \tag{2}$$

$$\text{s.t.} \quad \frac{\hat{A}D}{Q} + \frac{\hat{h}Q}{2} + \hat{c}D \le C \tag{3}$$

Under the framework of the economic order quantity (EOQ) model, Xi et al. perfect the model under carbon cap. They provide analytical support for numerical and discuss the extensive suitability of these results to other operation management models. For further study, Xi et al. move forward to discuss the applicability of the model to the operation management under a variety of environmental regulations (Xi et al., 2013). We select the model under carbon tax as below. Carbon tax is a simple mechanism which imposing a financial penalty t for per unit of carbon emitted. Then the total cost incurred can be expressed as below. Finally, they discuss the special case in which carbon tax is similar to carbon cap and trade.

$$Z(Q) = \frac{AD}{Q} + \frac{hQ}{2} + cD + t\left(\frac{\hat{A}D}{Q} + \frac{\hat{h}Q}{2} + \hat{c}D\right) \tag{4}$$

Furthermore, Ping et al. examine the production lot-sizing issues of an entrepreneur under cap & trade and carbon tax using EOQ model. Under cap and trade, the entrepreneur can buy (sell) carbon quota at per unit price *b* (*s*) if its carbon emissions level is higher (lower) than the carbon cap. And *E* to be the carbon emission entrepreneur produced. They revised the EOQ model under cap and trade and get the cost formulation model:

$$Z\ (Q) = \frac{AD}{Q} + \frac{hQ}{2} + cD + b(E - C)^{+} - s(C - E)^{+} \tag{5}$$

In their study, the entrepreneur's decisions of the optimal production and carbon emissions are determined by the differentiated permits trading prices under the cap & trade regulation. Above all equations are the transformation of the basic EOQ considering environment impact and carbon emission policies (Ping et al., 2015). Guo-Wei et al. extended the EOQ model and investigated how entrepreneurs react in inventory management under cap and trade regulation based the model. They derive the optimal order quantities and check the impacts of parameters on the optimal decisions and carbon emissions (Guo-Wei et al., 2011).
What's more, Dinçer further researched the inventory and transportation problem under various carbon emissions regulations and considered the effects of regulations on transportation costs and carbon mitigation (Dinçer, 2014a). In another paper, Dinçer et al. revised the model under carbon tax, cap and trade policies with LTC and TL carrier. In their analysis, they assumed that the market price (selling or buying) per unit carbon emissions is fixed at a unit (Dinçer et al., 2014b).
Similarly, Daria et al. explore the integration of factors affecting the environmental impact within the traditional EOQ model and put forward a "Sustainable EOQ Model". All sustainability factors linked to the process of operation management such as the environment impact of transportation and inventory are incorporated in the model (Daria et al., 2013). Unlike above models, the cost regarding transportation and obsolescence is considered definitely and treated in a developmental point. In the numerical analysis, the results offer some insight into the future carbon policies aimed at reducing carbon emission. Anyway, Sustainable-EOQ under the carbon cap, carbon tax should be further study point.

3.2 Newsvendor

Jing-Pu et al. research the classical single-period (newsvendor) problem under carbon emissions policies including carbon cap, carbon tax, and cap and trade system (Jing-Pu et al., 2012). For the classical single-period problem, let x denote the aggregate demand which is assumed to be a random variable with the probability density function f(x) and the cumulative distribution function F(x), and the entrepreneur faced the unit selling price p; salvage value v; acquisition cost c; shortage costs; order quantity Q. So the entrepreneur's expected profit function as,

$$J(Q) = (p - v)\int_0^Q xf(x)dx + (p + s - c)\int_Q^\infty Qf(x)dx - s\int_Q^\infty xf(x)dx - (c - v)\int_0^Q Qf(x)dx \tag{6}$$

Under carbon cap constraint, Song set Qc to be the mandatory capacity. For carbon tax, we can deduce the entrepreneur's total tax cost as tQ,
Under cap and trade, the entrepreneur's expected profit can be written as,

$$J(Q) = (p - v)\int_0^Q xf(x)dx + (p + s - c - t)\int_Q^\infty Qf(x)dx - s\int_Q^\infty xf(x)dx - (c + t - v)\int_0^Q Qf(x)dx \tag{7}$$

$$\begin{aligned} J(Q) = {} & (p - v)\int_0^Q xf(x)dx + (p + s - c)\int_Q^\infty Qf(x)dx - s\int_Q^\infty xf(x)dx \\ & - (c - v)\int_0^Q Qf(x)dx + b(Q - Q_c)^{+} + s(Q_c - Q)^{+} \end{aligned} \tag{8}$$

The classical newsvendor problem with single sourcing is also studied by Emel and Werner, they considered the dual sourcing model under three different scenarios and get the similar inventory model (Emel et al., 2014). In contrast to Jing-Pu et al.'s work, Heidrun et al. analyze a stochastic, single-period dual sourcing model with respect to economic and environmental performance and carbon emission regulations concerning transportation (Heidrun et al., 2013).
Besides, Bin et al. summarize the multi-item operation management with carbon cap and trade mechanism, revised the single period newsvendor model and present the optimization model for the multi-item production planning (Bin et al. 2013). Hoen et al. study the impact of carbon emission regulation on various transport modes selection, they use the regulation and the single-period Newsboy problem to make choice among the various transport modes and ensure an optimum cost (Hoen et al., 2014).

3.3 Lot sizing model

For the lot-sizing model, we use cost parameters f_t, c_t, h_t, and b_t denoting the fixed cost per order, the variable cost per unit, the inventory cost per unit carried from period t to t+1, and the backordered cost per unit in each period t. On account of carbon emission, Saif et al. introduced corresponding carbon emission parameters $\hat{f}_t$, $\hat{c}_t$ and $\hat{h}_t$. All entrepreneurs must take carbon cap into consideration, thus restrict the emission on a fixed cap C over the entire program horizon, they provide the revised model respecting single and multiple entrepreneurs based on classic lot-sizing models (Saif et al. 2013).

Min $$\sum_{t=1}^{T}(f_t y_t + c_t q_t + h_t I_t + b_t B_t) \quad (9)$$

s.t. $$I_t - B_t = I_{t-1} - B_{t-1} + q_t - d_t \quad (10)$$

$$\sum_{t=1}^{T}(\hat{f}_t y_t + \hat{c}_t q_t + \hat{h} I_t) \le C \quad (11)$$

$$q_t \le \left(\sum_{t'=1} d_{t'}\right) y_t \quad (12)$$

$$I_t \;\; B_t \;\; q_t \ge 0 \quad (13)$$

$$y_t \in \{01\} \qquad t=1,\ldots,T \quad (14)$$

Let t denote the financial penalty for per unit of carbon emitted, then

Min $$\sum_{t=1}^{T}(f_t y_t + c_t q_t + h_t I_t + b_t B_t) + t \sum_{t=1}^{T}(\hat{f}_t y_t + \hat{c}_t q_t + \hat{h} I_t) \quad (15)$$

Subject to 9; 11; 12 and 13.

Similarly, under cap and trade, the lot-sizing model can be transformed as follow:

Min $$\sum_{t=1}^{T}(f_t y_t + c_t q_t + h_t I_t + b_t B_t) + P(e_t^+ - e_t^-) \quad (16)$$

s.t. $$\sum_{t=1}^{T}(\hat{f}_t y_t + \hat{c}_t q_t + \hat{h} I_t + e_t^-) \le C + \sum_{t=1}^{T} e_t^+ \quad (17)$$

$$e_t^+, e_t^- \ge 0 \qquad t = 1,\ldots,T \quad (18)$$

and 10; 12; 13; 14.

For the lot-sizing problem, Mathijn-J et al. consider the emission capacity constraint like Saif does. In their model, besides the usual financial costs, they also associated emissions with production and inventory. Furthermore, they present a fully polynomial time approximation scheme (FPTAS) for such carbon emissions and entrepreneur's cost. It leads to a better performance in terms of their analysis on that problem, and assists entrepreneurs to make good choices (Mathijn-J et al.2015). Nabil et al. further analyzes the incapacitated multi-sourcing lot-sizing problem with four types of carbon emission constraints (periodic, cumulative, global and rolling carbon emission constraint) using a polynomial dynamic programming algorithm (Nabil et al. 2013).

4. Supply chain management

For the supply chain management under carbon emission, Gökçe et al. employ mathematical models for operations which integrate decisions upon replenishment and transportation mode selection and analyze the impacts of carbon regulatory mechanisms on replenishment decisions in a bio-fuel supply chain. Here, on the base of the model, we conclude the linear programming formulation under emission regulations which is also represented in other papers. For the variables, f_{it}、c_{it} denoted fixed cost and variable cost for using supplier i in period t. and h_t denoting the cost per unit on an inventory arc(Gökçe et al.2014).

Min $$\sum_{i=1}^{I}\sum_{t=1}^{T}\{f_{it} y_{it} + c_{it} q_{it} + h_t H_t\} \quad (19)$$

s.t. $$\sum_{i=1}^{I} q_{it} + H_{t-1} - d_t = H_t \quad (20)$$

$$H_0 = 0 \quad (21)$$

$$q_{it} \le \left(\sum_{\tau=t}^{T} d_\tau\right) y_{it} \tag{22}$$

$$y_{it} \in \{01\} \qquad \forall i, \quad \forall t \tag{23}$$

$$q_{it}, H_t \ge 0 \qquad \forall i, \quad \forall t \tag{24}$$

Considering a carbon cap mechanism, we get the revised model:

$$\text{Min} \quad \sum_{i=1}^{I}\sum_{t=1}^{T}\{f_{it}y_{it} + c_{it}q_{it} + h_t H_t\} \tag{25}$$

$$\text{s.t.} \quad \sum_{i=1}^{I}\sum_{t=1}^{T}\{\hat{f}_i y_{it} + \hat{c}_i q_{it} + \hat{h}_t H_t\} \le C \tag{26}$$

and 19-23

Under a carbon tax mechanism, we also get the new model:

$$\text{Min} \quad \sum_{i=1}^{I}\sum_{t=1}^{T}\{(f_{it} + \alpha\hat{f}_i)y_{it} + (c_{it} + \alpha\hat{c}_i)q_{it} + (h_t + \alpha\hat{h}_t)H_t\} \tag{27}$$

s.t. 20-24

Li-Ya et al. also present the classical linear programming formulation model under carbon emission policies. In the model, Z denotes the total cost and x_{ij} (i =1, 2, ..., m; j =1, 2, ..., n) is the number of units to be distributed from source i to destination j, in addition, c_{ij} is the unit distribution cost; s_i is the number of units in source i; d_j is the number of units to destination j. By this model, the transportation problem can be included into the operation management, and make entrepreneurs realized the impact of carbon footprint on the process of transportation. It also provides us many ways to redesign the supply chain and reduces carbon emissions (Li-Ya et al., 2014).

Furthermore, Joanna et al. propose an integer programming model to minimize the total emissions and operation cost with a transportation network design(Joanna et al., 2010). Diabat et al. put forward a new supply chain network for green supply chain management that integrates MIP model with carbon emission considerations. According to this model, Supply chain managers should keep a long-term view and take carbon emission decreases into account under a wide range of scenarios(Diabat et al., 2009). Abdallah et al. formulated MIP for the carbon-sensitive supply and performed a life cycle assessment for three different situations. Considering life cycle assessment (LCA) principles and the traditional material balance constraints (Abdallah et al., 2012), Diabat et al. take the operation management (including recycling and disposal) into consideration and formulate the MILP(Diabat et al., 2013).

5. Conclusions

The economic order quantity (EOQ) model, the newsvendor problem, the lot sizing model and the mixed integer linear programming (MILP) are widely used to account for carbon emissions due to production, inventory and transportation in the operation management. In this paper we make a detailed review on operation management under carbon emission regulations including carbon cap, carbon tax, carbon cap and trade. We summarize several relatively simple and widely used models appeared in other professional literatures. With these models and methods, managing an effective operation is not most difficult. Typically, it is observed that the operation management can be described with the models using various variables. On this background, it is essential for the entrepreneurs to make decisions using these models. This paper attempts to deliberate on various theoretical models on OM. Working out an effective approach towards carbon-emission regulated operation management could be a huge challenge which prompts us to put forward and resolve the issues on operation management in future.

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