Chapter 1
Open problems in green supply chain modeling and optimization with carbon emission targets

Konstantina Skouri, Angelo Sifaleras, and Ioannis Konstantaras

Abstract Research on pollutant emissions management is developing into a very essential part of the green supply chain landscape as more industries try to make it part of their strategy among pressure from customers, competitors and regulatory agencies. This has resulted in an increased tendency to not only focus on financial costs in the production process, but also on its impact on society. This public impact comprises, for instance, environmental implications, such as the emission of pollutants during production. The carbon tax and emissions trading mechanisms are the most effective market-based choices used to lower carbon emissions. These mechanisms are incorporated into the development inventory lot sizing models, the results of which could improve the effectiveness of carbon management in the supply chain. The paper presents some open problems associated with the lot sizing problem under emissions constraints.

1.1 Introduction

Emissions of the anthropogenic greenhouse gases (GHG) that drive climate change and their impact around the world are increasing. In a recent estimate by the Committee on Climate Change [7], the cumulative emission of greenhouse gases needs to be reduced by about 60% (below 1990 levels) by the year 2030. The European Com-

Konstantina Skouri
Department of Mathematics, University of Ioannina, Ioannina 45110, Greece, e-mail: kskouri@uoi.gr

Angelo Sifaleras
Department of Applied Informatics, School of Information Sciences, University of Macedonia, 156 Egnatia Str., Thessaloniki 54636, Greece, e-mail: sifalera@uom.gr

Ioannis Konstantaras
Department of Business Administration, School of Business Administration, University of Macedonia, 156 Egnatia Str., Thessaloniki 54636, Greece, e-mail: ikonst@uom.gr

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mission (EU) is looking at cost-efficient ways to make the European economy more climate-friendly. Its low-carbon economy roadmap suggests that by 2050, the EU should cut emissions to 80% below 1990 levels. To this end, 40% emissions should cut by 2030 and 60% by 2040 (http://ec.europa.eu/clima/policies/strategies). Consequently, many countries endeavor to reduce these greenhouse gases, as formalized in treaties, such as the Kyoto Protocol (United Nations, [17]), as well as in legislation, such as the European Union Emissions Trading System (European Commission 2010) (Helmrich et al. [12]). When discussing emissions, most companies and people automatically start looking at electricity and other operational emission sources. However, emissions in the supply chain are a substantial part of a company's footprint, and should not be ignored just because they are outside of direct operational control. When analyzing the emission inventories over 4000 companies, upstream emissions are on average over twice that of the operational emissions of a company (CDP Report, December 2015, `https://www.cdp.net/CDPResults/committing-to-climate-action-in-the-supply-chain.pdf`). In other words, the majority of the companies are focused on the physical processes for reducing emissions and not on the operational practices and policies, such as production, transportation, inventory, etc. (Benjaafar et al. [6]).

Given now the potential impact of operational decisions on carbon emissions, there is a need for extensive model-based research that incorporates carbon emission targets. The traditional quantitative models on Operations Management, that are focused on either minimizing costs or maximizing profits, have to be extended to incorporate the carbon footprint [10]. After that, these models can be utilized to see how carbon emissions may influence operational choices and to especially inform operations managers on how basic policies, such as mandatory emission caps, taxes on carbon emissions, and emission cap and trade, affect decision-making.

So, starting with the existing inventory lot sizing problems under carbon emissions constraints, the purpose of this chapter is to present some open problems.

1.2 Open Problems: Formulation and Optimization Issues

In the following section we shall present some open problems with lot sizing under carbon emissions constraints.

Before that, we have to recall the basic dynamic lot sizing model given by Wagner and Within [18], which will be denoted as problem P_1:

$$\min \sum_{t=1}^{T} (K_t y_t + p_t x_t + h_t I_t), \tag{1.1}$$

s.t.

$$I_t = I_{t-1} + x_t - d_t, t = 1, \ldots, T, \tag{1.2}$$

$$x_t \leq y_t \sum_{s=t}^{T} d_s, t = 1, \ldots, T, \tag{1.3}$$

$$I_0 = 0, \tag{1.4}$$

$$x_t, I_t \geq 0, t = 1, \ldots, T, \tag{1.5}$$

$$y_t \in 0, 1, t = 1, \ldots, T, \tag{1.6}$$

where

T : is the planning horizon,
x_t : the quantity produced in period t,
I_t : the inventory at the end of period t,
y_t : a binary variable indicating a set-up in period t,
d_t : the demand in period t,
K_t : the set-up cost in period t,
p_t : production cost in period t,
h_t : holding cost in period t,

It should be noted that, the constraints (1.3) ensure that production can only take place if there is a set-up in that period.

Starting with this model, Absi et al. [1] proposed a multi–sourcing lot sizing problem with carbon emission constraints, which aims at limiting carbon emissions per unit of product supplied with different modes. One mode corresponds to the combination of a production facility and a transportation mode and is characterized by its economical costs and its unitary carbon emissions. This problem (thereafter called P_2) is modeled by Absi et al. [1] as:

$$\min \sum_{m=1}^{M} \sum_{t=1}^{T} (K_t^m y_t^m + p_t^m x_t^m) + \sum_{t=1}^{T} h_t I_t, \tag{1.7}$$

s.t.

$$I_t = I_{t-1} + \sum_{m=1}^{M} x_t^m - d_t, t = 1, \ldots, T, \tag{1.8}$$

$$x_t^m \leq y_t^m \sum_{s=t}^{T} d_s, t = 1, \ldots, T, m = 1, \ldots, M \tag{1.9}$$

$$I_0 = 0, \tag{1.10}$$

$$x_t^m, I_t \geq 0, t = 1, \ldots, T, m = 1, \ldots, M \tag{1.11}$$

$$y_t^m \in 0,1, t = 1,\dots,T, \tag{1.12}$$

$$\sum_{m=1}^{M}\sum_{t=1}^{T}(e_t^m - E^{max})x_t^m \leq 0 \tag{1.13}$$

where

m : a specific production mode (i.e., a specific supplier)
e_t^m : carbon emission related to supplying one unit using supplier m in period t,
E^{max} : maximum unitary environmental impact allowed in period t.

Relation (1.13) represents that the unitary carbon emission over the whole planning horizon cannot be larger than the maximum unitary environmental impact allowed.
The above problem P_2 is NP-complete as it has been proved by Absi et al. [1].

Based on the Absi et al. [1] basic model, the following open problems are possible:

Problem A.1. The above problem can be extended in an integrated supply chain framework in order to jointly optimize supplier and retailer costs. To this end, a kind of cooperation between suppliers could be adopted regarding their carbon emissions–for example, by transferring unused quantities of carbon units between suppliers.

Problem A.2. An inventory routing coordination scheme that takes carbon emissions from warehouse activities into consideration, could be of interest. So, P_2 could be extended by assuming that a fleet of vehicles transport different products from multiple suppliers to multiple retailers under emission constraints and objectives.

Problem A.3. The demand per period could be a stochastic variable (see Parsopoulos et al. [14])

Problem A.4. For firms dealing with both manufacturing and remanufacturing activities, decisions on managing the new and remanufactured products should be made under the consideration of carbon emissions. This leads to interesting research questions such as: How will carbon emission constraints influence production and remanufacturing decisions? Can the regulations lead to carbon emission reduction and urge the manufacturer to choose lower carbon remanufacturing technology?

For the above extensions, the derivation of theoretical results could be useful for their optimization, and heuristics or meta-heuristics could be proposed or modified for their solution as well.

Recently, Hong et al. [13] proposed a modification of the problem from Absi et al. [1] by assuming emission limitations in each period and considering $M = 2$ where 1 is used for regular and 2 is used for green mode. So, the resulting problem (hereinafter called P_3) is modeled as:

$$\min \sum_{m=1}^{2} \sum_{t=1}^{T} (K_t^m y_t^m + p_t^m x_t^m) + \sum_{t=1}^{T} h_t I_t, \tag{1.14}$$

s.t.

$$I_t = I_{t-1} + \sum_{m=1}^{2} x_t^m - d_t, t = 1, \ldots, T, \tag{1.15}$$

$$x_t^m \leq y_t^m \sum_{s=t}^{T} d_s, t = 1, \ldots, T, m = 1, 2 \tag{1.16}$$

$$I_0 = 0, \tag{1.17}$$

$$x_t^m, I_t \geq 0, t = 1, \ldots, T, m = 1, 2 \tag{1.18}$$

$$y_t^m \in 0, 1, t = 1, \ldots, T, \tag{1.19}$$

$$\sum_{m=1}^{2} e_t^m x_t^m \leq E^{max}, t = 1, \ldots, T, \tag{1.20}$$

Based on the Hong et al. [13] model, the following open problems are possible:

Problem B.1. In the above problem, the emissions constraint can be modified once the emissions both from inventory holding and production activities are taken into account.

Problem B.2. A carbon cap can be imposed under a carbon offset mechanism, and a carbon market also exists that allows the purchase of carbon units. Notice that under a carbon offset mechanism, unused carbon units cannot be sold. In this case, the above problem can be modified as:

$$\min \sum_{m=1}^{2} \sum_{t=1}^{T} (K_t^m y_t^m + p_t^m x_t^m) + \sum_{t=1}^{T} h_t I_t + \alpha \sum_{t=1}^{T} e_t^+, \tag{1.21}$$

s.t.

$$I_t = I_{t-1} + \sum_{m=1}^{2} x_t^m - d_t, t = 1, \ldots, T, \tag{1.22}$$

$$x_t^m \leq y_t^m \sum_{s=t}^{T} d_s, t = 1, \ldots, T, m = 1, 2 \tag{1.23}$$

$$I_0 = 0, \tag{1.24}$$

$$x_t^m, I_t \geq 0, t = 1, ..., T, m = 1, 2 \tag{1.25}$$

$$y_t^m \in 0, 1, t = 1, ..., T, \tag{1.26}$$

$$\sum_{m=1}^{2} e_t^m x_t^m \leq E^{max} + e_t^+, t = 1, ..., T, \tag{1.27}$$

where

e_t^+: the quantity of carbon units to buy in period t,
α : the market price of one unit of carbon

Akbalik and Rapine [2] extend P_1 by considering the carbon emissions constraints under the cap–and–trade policy. Besides a limitation on the total carbon emissions over the entire horizon, the cap–and–trade policy allows a firm to buy and to sell carbon units. Therefore, the ensuing problem (hereinafter denoted as P_4) is modeled as:

$$\min \sum_{t=1}^{T} (K_t y_t + p_t x_t + h_t I_t) + \alpha(\sum_{t=1}^{T} e_t^+ - \sum_{t=1}^{T} e_t^-), \tag{1.28}$$

s.t.

$$I_t = I_{t-1} + x_t - d_t, t = 1, ..., T, \tag{1.29}$$

$$x_t \leq y_t \sum_{s=t}^{T} d_s, t = 1, ..., T, \tag{1.30}$$

$$I_0 = 0, \tag{1.31}$$

$$x_t, I_t \geq 0, t = 1, ..., T, \tag{1.32}$$

$$y_t \in 0, 1, t = 1, ..., T, \tag{1.33}$$

$$\sum_{t=1}^{T} \left(\hat{K}_t y_t + \hat{p}_t x_t + \hat{h}_t I_t\right) \leq \hat{C} + \sum_{t=1}^{T} e_t^+ - \sum_{t=1}^{T} e_t^- \tag{1.34}$$

$$\alpha \sum_{t=1}^{T} e_t^+ \leq B \tag{1.35}$$

$$\sum_{t=1}^{T} e_t^+ \geq 0, \sum_{t=1}^{T} e_t^- \geq 0 \tag{1.36}$$

where

e_t^- : the quantity of carbon units to sell in period t,
$\hat{K}_t$: the carbon emission per set up in period t,
$\hat{p}_t$: the carbon emission per produced unit in period t,
$\hat{h}_t$: the carbon emission per stored unit in period t,
C : the global carbon cap (carbon limit) over the entire horizon,
B : the available budget.

Relation (1.34) represents the cap-and-trade constraint while (1.35) represents the budget constraint.

Based on the Akbalik and Rapine [2] model, the following open problems are possible:

Problem C.1. Open problems relating to P_4 could be in the same direction as in P_2 (i.e., Problems A.1-A.4).

Problem C.2. In an integrated supply chain framework, cooperative activities between members of the supply chain in regards to the trade of carbon units could be considered.

Problem C.3. The consideration of the market price of one unit of carbon, α, as a decision-making variable could be another research direction.

1.3 Conclusions

Companies have increased efforts to manage and reduce their carbon footprint. Towards this direction, the carbon management in the supply chain is an essential capability. In this chapter, we have presented some interesting open problems concerning modeling and optimization issues with inventory lot sizing under carbon emissions constraints. There is a growing need for facing such carbon emission reduction problems in the modern supply chain industry. Since, the majority of these problems are NP-hard, further research effort will be required, using either mathematical programming approaches [3, 4, 8, 15] or metaheuristics [9, 16], and exploiting parallel computing techniques [5, 11] in order to tackle such cases.

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