A Competitive Multi-period Supply Chain Network Model with Freight Carriers and Green Technology Investment Option

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Abstract: This paper presents a multi-period supply chain with freight carriers network model. In this model manufacturers, retailers, and carriers maximize the net present value (NPV) of their investments in ecologically friendly technology. Future production, inventory, transaction, and transportation costs savings are used to help fund investments. The environmental impact of production, inventory, transportation, and consumption of products in the supply chain network are all integrated. The tradeoff between the initial technology investment and its ecological footprint effect are considered for the supply chain planning period. We provide variational inequality formulations of the equilibrium conditions and then propose the modified projection method, along with conditions for convergence. Numerical examples are examined with an analysis of the effects of ecologically friendly technology investments on supply chain network production, transportation, and sales.

Keyword: Supply chain management, game theory, Nash equilibrium, multi-period planning, Net present value, variational inequalities, green supply chain

1. Introduction

Consumer, regulatory, community, competitive, and media pressures have caused firms to raise their environmental awareness and improve their ecological footprint. Firms and their stakeholders have come to realize that the major way to reduce their environmental burdens is through their supply chain networks (Bloemhof-Ruwaard et al. (1995); Hill (1997); Nagurney and Toyasaki (2005); Toyasaki et al. (2014)). Recently and practically, Walmart plans not only to decrease its own

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CO2 emission but also decrease emissions in its extended supply chain. They have encouraged and supported their suppliers’s efforts to reduce emissions by focusing on clean energy efforts in agriculture, waste, packaging, deforestation, and product use and design (SCDigest (2017)). As a result, many organizations have embraced ambitious green practices and programs. One of the major environmental burdens is the focus on global climate change and, thus, their carbon footprints.

Supply chain activities and practices represent the greatest opportunity for carbon footprint reduction (Fahimnia et al. (2015); Wiedmann and Minx (2008)). For example, in 2015 Siemens announced that it would spend nearly $110 million to lower the company’s emissions. Siemens plans to slash its carbon emissions in half by 2020 and to become carbon neutral by 2030. The company insisted that the investment would eventually pay off through savings of between $20 million to $30 million annually. At the same time, Dell announced that it uses packaging material made of wheat straw and suggested that this new material uses 40% less energy to produce, 90% less water, and costs less to make than traditional packaging (Fehrenbacher (2015)). Hence, to reduce their ecological and carbon footprints firms may need to invest in technology while capitalizing on savings achieved through process improvement and the use of environmentally friendly materials.

Wiedmann and Minx (2008) defined carbon footprinting as a methodology that estimates the total greenhouse gas emissions in carbon equivalent units across a product’s lifecycle, including raw material procurement, manufacturing, packaging, logistics, recycling, and waste disposal. The literature and research on carbon emissions management within the supply chain has been growing (Blanco, et al., 2016). Techniques for accounting and measurement of supply chain carbon footprints in itself is an area of research (Sundarakani et al. (2008)). Calculations have also considered specific stages of the supply chain, bounding the accounting, such as energy and carbon emissions associated with the transportation links and warehousing activities (Cholette and Venkat (2009); Sarkar et al. (2016)). IBM provided a carbon heat map to illustrate the degree of carbon impact on the operations of a typical supply chain. Butner et al. (2008) presented a case study of carbon footprint estimation in the supply chain of a leading importer of bananas in the USA. Accenture (2010) argued that shippers and buyers can reduce not only the transport emissions of their product but also the whole lifecycle carbon impact of products through alternative sourcing and production processes.

Nevertheless, most of the literature on sustainable supply chain management has focused on environmental decision making and closed-loop supply chains as in recycling and remanufacturing (Bhattacharjee and Cruz (2015); Wakolbinger et al. (2014)). The literature on managing carbon and ecological footprints in supply chains is only starting to ascend.

To further extend the research and provide additional insights for policy makers and managers from both economic and environmental perspectives, a supply chain network game theoretic model is introduced in this paper. The model considers the environmental impact of production, inventory, transportation, and consumption of products in the supply chain network, and the tradeoff between the initial investment in technology and its ecological footprint effect in the supply chain over a longitudinal planning horizon. NPV is one of the core economic performance evaluation criteria in financial decision making, and has been widely adopted in supply chain management (cf. Dhavale and Sarkis (2015); Liu and Cruz (2012); Sun and Queyranne (2002); Yang et al. (2005)). However, this is the first time that NPV is used to analyze the tradeoff between investment in carbon foot-
print reduction and cost savings in a multiperiod competitive supply chain network with multiple interacting decision makers.

Moreover, the formulation discussed here provides purposeful and detailed representation of each of the key categories of decision makers who influence the demand and supply of products considering both economic and environmental issues. The specific focus of this study is on ecologically and economically balancing and optimizing production flow and its movement across a dynamic multilayered supply chain, when the SC partners are dealing with technology investment strategy and its future effect on production, inventory, shipment, and customers’ demand.

Mainly, this paper extends the literature as follow:

- We explicitly model competition among manufacturing firms, retail stores, and freight carriers in terms products and inventory quantities, product shipping costs, and energy rating levels using initial technology investments. This multi-faceted inclusion of competition from price, quantity, and energy rating level dimensions leads to results that can be used to assess the trade-offs between initial investment and future costs and meeting demands at each supply chain echelon.

- This study is the first that models integrating oligopolistic competition among manufacturers, retail stores, and freight carriers using shipping price, product flow, and environmentally sensitive demand functions with nonlinear cost functions.

- Explicit integration of environmental preferences of retailers and manufacturers in selecting their manufacturers and carriers, to help form a green supply chain network and address global environmental issues is something that other models have not addressed.

- Consumer awareness of green technology and footprint outcomes in spatial price equilibrium conditions are modeled using customers’ demand functions that consider not only the price of product at retail stores but also the retailer energy ratings.

In introducing this work and study, this paper is organized into a number of sections. In Section 2, an overview of the literature is presented to provide support for and positioning of research. In Section 3, the multiperiod competitive supply chain network model is introduced. We derive the supply chain network governing equilibrium conditions and provide the variational inequality formulations in the Appendix. Also, qualitative studies and computational procedure that yields closed form expressions, at each iteration, for the variables are given in the Appendix. In Section 4, we present our numerical examples. We conclude and provide managerial insights in Section 5 and then summarize our paper in Section 6.

2. Background

The research on modeling supply chain decision making and management from operational, tactical, and strategic business, environmental, and social perspectives has seen substantial growth in recent
Researchers have investigated environmental decision making in supply chain management processes and associated optimization from a number of dimensions. Usually, economic decisions have played a significant role. For example, Nagurney et al. (2007) and Cruz (2008) developed supply chain models which included the maximization of revenue and the minimization of environmental emissions. Frota Neto et al. (2008) designed an evaluation of sustainable logistics networks where activities affecting the environment and cost efficiency are considered.

There may be tactical and strategic supply chain network design problems such as joint transportation planning and warehousing decisions (Mallidis et al. (2012)) that have been considered for supply chain carbon emissions planning. The decisions have also been mapped into multiple optimization objectives, usually with some form of tradeoffs. For example, bi-objective models integrating the broader strategic supply chain configuration planning decisions that sought maximization of NPV and minimization of environmental impact have been outlined in the Guillen-Gosalbez and Grossmann (2009) study.

Some have utilized regulatory policies related to internalizing externalities such as including emission taxes in a competitive supply chain network model consisting of firms competing in an oligopolistic manner (Nagurney et al. (2013)). Taxing is one way of integrating external economic costs into the supply chain. Another approach is the market mechanism related to trading of emissions, carbon or other wastes emission. For example cap-and-trade market mechanisms have been an effective method of internalizing externalities and have been modeled by varying emission caps to determine supply chain economic performance and integrating environmental issues into supply chain decisions (Cruz and Liu (2011); Dhavale and Sarkis (2015); Diabat and Simchi-Levi (2009); Zakeri et al. (2015)).

Alternatively, some models have explicitly and uniquely focused on environmental objectives. One such model focused on transportation depots and operations emissions reduction under an explicit and singular environmental objective function is Harris et al. (2014). Yet, competitive modeling can extend beyond just alternative designs in the supply chain. For example, a competitive supply chain network model for fashion that incorporates marketing and reputational efforts can also be a way to design supply chains. One such model for eco-labelling in the fashion industry and their supply chains introduced by Nagurney et al. (2015), in which, profit-maximizing behavior of the fashion firms which incur eco-labelling costs with information associated with the carbon footprints of their supply chains was revealed to the consumers. These consumers show their preferences for the branded products of the fashion firms through their demand price functions, which include the carbon emissions information.

What we have presented on recent research directions is the development and application of decision and optimization modeling with respect to the carbon emissions integration within the supply chain. Environmental supply chain research, as mentioned previously, has seen extensive work on solid waste management and recycling. These supply chain models have focused on the capture of value remaining in products at the end of a product’s life through remanufacturing (Fleischmann et al. (1997); Guide and Wassenhove (2009); Guide Jr. et al. (2003); Gungor and Gupta
Although these papers lay a solid foundation for our work, the investigations were limited to the static case, which is only a preliminary step in understanding what happens in the real world. In addition, the inclusion of environmentally driven freight carriers as one of main tiers of any green supply chain network comprising manufacturers, retail stores, and demand markets for long-term planning is rarely modeled.

In reality, there is more than one opportunity for supply chain entities to acquire returns and to make sustainable operational and strategic decisions, so the study of dynamic green production and pricing policies in multiperiod planning horizon settings is of great importance in theory and practice. In addition, extending multiple systemic network models to incorporate multiple stages, environmental and business objectives in multiperiod fashion is still an area requiring attention. This conclusion has also been supported by reviews of the green and sustainable supply chain management literature (Benjaafar et al. (2013); Seuring (2007); Tang and Zhou (2012); Varsei et al. (2014)).

We note that, in this paper, we focus on environmental and economic sustainability of the supply chain network. However, one can argue that environmental and economic sustainability can lead to social sustainability. Carroll (1979) defined four categories of corporate social and sustainable responsibility including economic, legal, ethical, and discretionary/philanthropic responsibilities. The study described the economic responsibility as "to produce goods and services that society desires and to sell them at a profit," which is consistent with the financial objective of a corporation. We argue that environmentally sustainable products can reduce the negative social externality of production cost (Heal, 2005). Economic sustainability will lead a firm to engage in philanthropic and social activities which will increase customer-company identification (Homburg et al., 2013). For example, Bauman and Skitka (2012) argued that a company's social and responsible engagement would strengthen the trust and commitment of employees and increase organizational attractiveness, which would help to recruit and retain employees.

One important systemic tool that can provide useful insights, and has not seen much work in the environmental supply chain arena is network equilibrium models. For example, the integration of freight carriers network into supply chain network equilibrium provides a basis for effective supply chain management (Friesz et al. (2008); Liu and Nagurney (2012); Nagurney et al. (2015); Yamada et al. (2011)). Given that few studies have addressed the tradeoff between investment in the reduction of the carbon (ecological) footprint and the possible long term benefits and cost savings in a supply chain, a call for research in this area using these techniques provides valuable competitive and policy insights. This paper seeks to fill the gaps and build on this foundation.

In this paper, we present a multiperiod supply chain with freight carriers network model in which firms (manufacturers, retailers, and carriers) try to maximize the net present value of their investment in ecologically friendly technology and the future cash flows from savings from production, inventory, transaction, and transportation costs. It seeks a comprehensive evaluation across multiple tiers of a supply chain, over multiple periods, and with multiple objectives. In particular, the frame-
work developed in this paper can be used to determine the effects of environmental sustainability policies in the supply chain network by changing the supply chain energy rating requirements. It can also capture customer preferences at demand markets based on the perceived product environmental quality criterion. Moreover, the framework captures the effects of the time and the cost (discount rate) of the investment in green technology energy on supply chain environmental sustainability.

In particular, the framework developed in this paper can be used to determine the effects of environmental sustainability policies in the supply chain network by changing the supply chain energy rating requirements. It can also capture customer preferences at demand markets based on the perceived product environmental quality criterion. Moreover, the framework captures the effects of the time and the cost (discount rate) of the investment in green technology energy on supply chain environmental sustainability.

Although these complexities do exist, the model can be flexibly applied to provide numerous directions for further investigation. That is, the model can be applied in a focused manner to provide greater depth and insights on particular parameters that may include environmental concerns amongst the various partners or policy insights if particular parametric ranges are provided. These insights can prove valuable to researchers, practitioners and policy makers. Model details and foundations are now presented.

3. The Multiperiod Supply Chain Freight Carrier Network Model

In this section, a multiperiod supply chain network with freight carriers is modeled and presented (Figure 1). The time planning horizon is discretized into periods: \( t; t = 1, \ldots, T \). The supply chain network consists of \( M \) manufacturers, each one denoted by \( i_t; i = 1, \ldots, M \), \( O \) carriers, each one defined by \( o_t; o = 1, \ldots, O \), \( N \) retailers, with a typical one denoted by \( j_t; j = 1, \ldots, N \), and \( K \) demand markets, with a typical demand market denoted by \( k_t; k = 1, \ldots, K \). The manufacturers produce the substitutable products and send them to the retailers via freight carriers. Finally, customers at the demand markets buy these products from retailers. During any planning period, manufacturers and retailers need to define the amount of products held in their inventory or sold to their lower level. The carriers manage their shipment price and quantity from manufacturers to retailers as well as the accumulation size of the backlog service.

Considering the environmental impact of production, transportation, and consumption of products, each firm in the supply chain selects the appropriate technology initially and subsequently the carbon footprint rate which affects the functionality of the firm for the entire planning period. The carbon footprint represents the efficiency of each entity and impacts the final profits.

We assume that the higher the initial technology investment, the greener the technology and, hence a smaller carbon footprint for future planning periods. Also, we assume that cost functions are convex and continuously differentiable and that the network entities are competing in a noncooperative fashion during the planning horizon.

There is a tradeoff between the initial investment for the technology and its footprint effect throughout the planning period. A company can make a major investment to lower its variable
costs for the future or can limit the initial investment and expect higher variable costs regarding the carbon emission cost throughout the planning horizon. Hence, the model measures the economic and environmental tradeoff to determine the optimal profit considering the net present value of future variable costs (with respect to emission cost) including production, inventory, transaction, and transportation costs and the initial cost of investment. Table 1 provides the definitions of the model’s variables, parameters, and functions. The subsequent sections detail the behavior and the optimality condition of each network entity.

### 3.1 The Behavior of Manufacturers and their Optimality Conditions

In this supply chain network, manufacturers compete with each other in the production of substitutable products with a production cost of $PC_{it}(S_t, \delta_{mi})$ for each manufacturer $i$ in period $t$. The production cost of manufacturer $i$ may not only depend on the production of $i$ but also on the production of all other manufacturers during that period. For every product that is manufactured, there would be an environmental cost which is related to the energy rating level. By investing more in technology with a higher energy rating and decreasing its carbon emissions, the environmental cost of production also would be lower. We have the same argument for the inventory and the transaction cost of products for manufacturer $i$.

The utility of each manufacturer is the net present value of the difference between its total income from selling the products to the retailers and its total cost including production, transaction, and inventory costs, shipping expenses as well as the initial investment cost. The price that manufacturer $i; i = 1, \ldots, M$ charges retailer $j; j = 1, \ldots, N$ at time period $t; t = 1, \ldots, T, p_{ijt}^*$, is an endogenous variable and will be determined once the entire multiperiod supply chain-freight carrier equilibrium model is solved. Each manufacturer $i$ is faced with the following NPV optimization problem:
Table 1: Notation for the Supply Chain Network with Freight Carriers Model

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_{ijt} )</td>
<td>Price manufacturer ( i ) charges retailer ( j ) for a unit of his product in time period ( t ).</td>
</tr>
<tr>
<td>( S_{it} )</td>
<td>Supply of manufacturer ( i ) at time period ( t ), with ( S_{it} ) grouping the production of all manufacturers in period ( t ).</td>
</tr>
<tr>
<td>( q_{ijt}^1 )</td>
<td>Quantity amount of product that manufacturer ( i ) sends to retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( \delta_{mi} )</td>
<td>Energy rating of manufacturer ( i ), with ( \delta_{mi} ) grouping the energy rating of all manufacturers.</td>
</tr>
<tr>
<td>( \delta_{co} )</td>
<td>Energy rating of carrier ( o ), with ( \delta_{co} ) grouping the energy rating of all carriers.</td>
</tr>
<tr>
<td>( \delta_{rj} )</td>
<td>Energy rating of retailer ( j ), with ( \delta_{rj} ) grouping the energy rating of all retailers.</td>
</tr>
<tr>
<td>( \delta_{max} )</td>
<td>Maximum possible level of energy rating.</td>
</tr>
<tr>
<td>( PC_{it}(S_{it}, \delta_{mi}) )</td>
<td>Production cost function for manufacturer ( i ) for its production in period ( t ).</td>
</tr>
<tr>
<td>( TC_{ijt}(q_{ijt}^1, \delta_{mi}) )</td>
<td>Transaction cost between manufacturer ( i ) and retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( I_{it} )</td>
<td>Inventory level of manufacturer ( i ) in period ( t ).</td>
</tr>
<tr>
<td>( WC_{it}(I_{it}, \delta_{mi}) )</td>
<td>Warehouse cost of inventory in period ( t ) for manufacturer ( i ) in period ( t ).</td>
</tr>
<tr>
<td>( R_{ijat}(p_{ijat}^2, \delta_{co}) )</td>
<td>Transportation service demand function for carrier ( o ) to ship the products from manufacturer ( i ) to retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( p_{ijat}^2 )</td>
<td>Price that carrier ( o ) charges manufacturer ( i ) for carrying products to retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( q_{ijt}^2 )</td>
<td>Quantity of manufacturer ( i )'s products that carrier ( o ) ships to retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( CC_{ijat}(q_{ijat}^2, \delta_{co}) )</td>
<td>Unit transportation cost for carrier ( o ) for carrying the product from manufacturer ( i ) to retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( B_{ijt} )</td>
<td>Carrier ( o )'s backlog of service for manufacturer ( i ) in period ( t ).</td>
</tr>
<tr>
<td>( AC_{ijat}(B_{ijat}, \delta_{co}) )</td>
<td>Accumulation cost of carrier ( o )'s service backlog for manufacturer ( i ) in period ( t ).</td>
</tr>
<tr>
<td>( Y_{jt} )</td>
<td>Retailer ( j )'s supplies of the product in time period ( t ).</td>
</tr>
<tr>
<td>( p_{ijt}^1 )</td>
<td>Price of selling product at retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( q_{ikt} )</td>
<td>Amount of products sold to demand market ( k ) via retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( Z_{jt} )</td>
<td>Inventory level at retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( IC_{ijt}(Z_{jt}, \delta_{rj}) )</td>
<td>Retailer ( j )'s inventory cost in period ( t ).</td>
</tr>
<tr>
<td>( TC_{jkt}(q_{jkt}^3, \delta_{rj}) )</td>
<td>Transaction cost between retailer ( j ) and customers at demand market ( k ) in period ( t ).</td>
</tr>
<tr>
<td>( HC_{ijt}(Y_{jt}, \delta_{rj}) )</td>
<td>Holding cost of supplies at retailer ( j ) in period ( t ).</td>
</tr>
<tr>
<td>( p_{ikt}^4 )</td>
<td>Market price of product at demand market ( k ). The ( p_{ikt}^4 ) are grouped into the vector ( p_{it}^4 ), representing the price of products at demand markets during period ( t ).</td>
</tr>
<tr>
<td>( D_{jkt}(p_{ikt}^4, \delta_{rj}) )</td>
<td>Demand function of product sold at retailer ( j ) for demand market ( k ) in period ( t ).</td>
</tr>
<tr>
<td>( SC_{jkt}(q_{jkt}^4) )</td>
<td>Transaction cost associated with obtaining the product by consumers at demand market ( k ) from retailer ( j ) during time period ( t ).</td>
</tr>
<tr>
<td>( TSI_i(\delta_{mi}) )</td>
<td>Manufacturer ( i )'s total investment in sustainable technology with energy rating ( \delta_{mi} ).</td>
</tr>
<tr>
<td>( TSI_o(\delta_{co}) )</td>
<td>Carrier ( o )'s total investment in sustainable technology with energy rating ( \delta_{co} ).</td>
</tr>
<tr>
<td>( TSI_j(\delta_{rj}) )</td>
<td>Retailer ( j )'s total investment in sustainable technology with energy rating ( \delta_{rj} ).</td>
</tr>
<tr>
<td>( r )</td>
<td>Supply chain NPV discount rate.</td>
</tr>
</tbody>
</table>

Maximize

\[
\sum_{t=1}^{T} \frac{1}{(1+r)^t} \left\{ \sum_{j=1}^{N} p_{ijt} q_{ijt}^1 - PC_{it}(S_{it}, \delta_{mi}) - \sum_{j=1}^{N} TC_{ijt}(q_{ijt}^1, \delta_{mi}) - WC_{it}(I_{it}, \delta_{mi}) \right. \\
\left. - \sum_{j=1}^{N} \sum_{o=1}^{O} R_{ijat}(p_{ijat}^2, \delta_{co}) q_{ijat}^2 \right\} - TSI_i(\delta_{mi})
\]

subject to:

\[
S_{i1} - I_{i1} \geq \sum_{j=1}^{N} q_{ijt}^1
\]

\[
I_{it(t-1)} + S_{it} - I_{it} \geq \sum_{j=1}^{N} q_{ijt}^1, \quad \forall t = 2, \ldots, T
\]

\[
q_{ijt}^1 = \sum_{o=1}^{O} R_{ijat}(p_{ijat}^2, \delta_{co}), \quad \forall j, t
\]
and the nonnegativity constraints: 

\[ q_{ijt}^1 \geq 0, \quad S_{it} \geq 0, \quad I_{it} \geq 0, \quad 0 \leq \delta_{mi} \leq \delta_{max}, \quad \forall j, t. \]

Objective function (1) presents the net present value of the manufacturer’s profit for the planning period and the initial cost of investment for the technology. The first term in the brackets is the manufacturer’s revenue from product sales to retailers. The other terms show production, transaction, inventory, and shipment costs, respectively.

Constraints (2) and (3) denote the flow conservation equations for each manufacturer, which ensure that the inventory in the warehouse from the previous period plus the current production amount should be equal the current inventory and the sale to all retailers during the current period. We know that the shipment via all carriers between a manufacturer-retailer pair should be equal to the transaction between them during any planning period as in (4).

Constraint (5) ensures that manufacturers select those carriers for shipping the products that are as environmentally efficient as they are themselves. In addition, there is a maximum acceptable energy rating level which is technologically available. The nonnegativity constraints do not restrict the energy rating level to not exceed the maximum rate.

We assume that the manufacturers compete noncooperatively. For each manufacturer, we also assume that the production, inventory, and transaction cost functions are convex and continuously differentiable and the utility function is concave. The feasible set consisting of equations (2) through (5) with the constraints following consisting of bounds on the variables is assumed to be convex. Based on the Nash equilibrium concept Cournot (1897); Nash (1950, 1951), each manufacturer will optimize its production quantity, inventory flow, transactions with the retailers, and the energy rating level, given the optimal levels of the competitors. The optimality conditions for manufacturer \( i; i = 1, \ldots, M \) simultaneously can be expressed as the following variational inequality, determine \( (q^1, S^*, I^*, \delta^{max}, \mu^1, \theta^*, \eta^*) \in K^1 \) satisfying:

\[
\sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{TC}_{ijt}(q_{ijt}^1, \delta_{mi})}{\partial q_{ijt}} \right) + \mu_{it}^* + \theta_{ijt}^* \right] \times (q_{ijt}^1 - q_{ijt}^*) \\
+ \sum_{i=1}^{M} \left[ \frac{\partial \text{TI}_i(\delta_{mi})}{\partial \delta_{mi}} \right] + \sum_{t=1}^{T} \sum_{i=1}^{M} \frac{1}{(1+r)^t} \left( \frac{\partial \text{PC}_{it}(S_{it}^*, \delta_{mi})}{\partial S_{it}} \right) - \frac{\partial \text{WC}_{it}(I_{it}^*, \delta_{mi})}{\partial I_{it}} + \sum_{j=1}^{N} \frac{\partial \text{TC}_{ijt}(q_{ijt}^1, \delta_{mi})}{\partial \delta_{mi}} + \sum_{o=1}^{O} \left[ \eta_{io} + \eta_{io}^* \right] \right] \times (\delta_{mi} - \delta_{mi}^*) \\
+ \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{PC}_{it}(S_{it}^*, \delta_{mi})}{\partial S_{it}} \right) - \frac{\partial \text{WC}_{it}(I_{it}^*, \delta_{mi})}{\partial I_{it}} \right] + \sum_{t=1}^{T} \sum_{i=1}^{M} \frac{1}{(1+r)^t} \left( \frac{\partial \text{WC}_{it}(I_{it}^*, \delta_{mi})}{\partial I_{it}} \right) + \mu_{it}^* - \mu_{(i+1)}^* \times (I_{it} - I_{it}^*) \\
+ \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{WC}_{it}(I_{it}^*, \delta_{mi})}{\partial I_{it}} \right) + \mu_{it}^* \right] \times (I_{it} - I_{it}^*) \\
+ \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{TI}_i(\delta_{mi})}{\partial \delta_{mi}} \right) + \mu_{it}^* \right] \times (S_{it} - S_{it}^*) + \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{TI}_i(\delta_{mi})}{\partial \delta_{mi}} \right) + \mu_{it}^* - \mu_{(i+1)}^* \right] \times (I_{it} - I_{it}^*) \\
+ \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{TI}_i(\delta_{mi})}{\partial \delta_{mi}} \right) + \mu_{it}^* \right] \times (S_{it} - S_{it}^*) + \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial \text{TI}_i(\delta_{mi})}{\partial \delta_{mi}} \right) + \mu_{it}^* - \mu_{(i+1)}^* \right] \times (I_{it} - I_{it}^*) \\
\forall (q^1, S, I, \delta, \mu, \theta, \eta^1) \in K^1
\]
multipliers associated with constraints (2) and (3), and θ and η are the Lagrange multipliers associated with constraints (4) and (5), respectively. The nonnegativity of inventory ensures that we have no back-order in any planning period.

3.2 The Behavior of Freight Carriers and their Optimality Conditions

The carriers ship the products from manufacturers to the retailers and charge manufacturers for the shipments at each period \( t ; t = 1, \ldots, T \). The shipping quantity depends on the transportation service demand function, \( R_{ijot}(p^2_{t}, δ_{co}) \), and the price carriers charge the manufacturers, \( p^2_{ijot} \). Carrier \( o \) has a known transport demand function \( R_{ijot}(p^2_{t}, δ_{co}) \) for shipping the products from manufacturer \( i \) to retailer \( j \), which has a negative relationship with price \( p^2_{ijot} \), a positive relationship with its energy rating \( δ_{co} \), and a positive one with the other carriers’ prices. The initial higher investment cost which subsequently leads to a higher energy rating and future lower carbon emission impacts positively transportation service demand and the carrying cost of products to the retailers.

Carrier \( o \) competes with other carriers in a noncooperative manner to offer the best price of shipment for carrying the products between any manufacturer-retailer pair, determines the optimal amount of product delivered between the pairs, \( q^2_{ijot} \), defines the backlog size of service for manufacturer \( i, B_{iot} \), and its environmental efficiency rate, \( δ_{co} \). Carrier \( o \) seeks to maximize its profit, which can, hence, be described as follows:

\[
\text{Maximize} \quad \sum_{t=1}^{T} \frac{1}{(1 + r)^t} \left \{ \sum_{i=1}^{M} \sum_{j=1}^{N} R_{ijot}(p^2_{t}, δ_{co})q^2_{ijot} - \sum_{i=1}^{M} \sum_{j=1}^{N} CC_{ijot}(q^2_{ijot}, δ_{co})q^2_{ijot} - \sum_{i=1}^{M} AC_{iot}(B_{iot}, δ_{co}) \right \} - TSI_o(δ_{co})
\]

subject to:

\[
\sum_{j=1}^{N} R_{ijo}(p^2_{1}, δ_{co}) - B_{io1} \geq \sum_{j=1}^{N} q^2_{ijo1}, \quad \text{for all } i
\]

\[
B_{io(t-1)} + \sum_{j=1}^{N} R_{ijot}(p^2_{t}, δ_{co}) - B_{iot} \geq \sum_{j=1}^{N} q^2_{ijot}, \quad \forall t = 2, \ldots, T
\]

\[
\sum_{t=1}^{T} \sum_{j=1}^{O} q^2_{ijot} = \sum_{t=1}^{T} q^1_{ijot}, \quad \forall i, j
\]

and

\[
p^2_{ijot} \geq 0, \quad B_{iot} \geq 0, \quad q^2_{ijot} \geq 0, \quad 0 \leq δ_{co} \leq δ_{max}, \quad \forall i, j, t.
\]

The first term of objective function (7) presents the net present value of carrier \( o \)’s revenue and the second and third terms define the NPV of the carrying cost of products between the manufacturers and the retailers and the accumulation cost of backlog services, respectively. Constraints (8) and (9) ensure that carrier \( o \)’s accumulation from the previous period and the new shipment order, both from manufacturer \( i \), is bigger than the current backlog and the carrier’s delivery to all retailers from manufacturer \( i \) at any period.

Equality (10) is a joint constraint for all carriers and requires that the summation of deliveries made by all carriers between a particular manufacturer-retailer pair during the entire planning period.
horizon, $\sum_{t=1}^{T} \sum_{o=1}^{O} q_{ijot}^2$, is equal to the total sale between that manufacturer and the accompanying retailer in all periods. In other words, we make sure that retailers will receive their orders completely from each manufacturer which are paid for and shipped via carriers in spite of receiving them in different time periods. Joint constraints cause the game to take the form of a generalized Nash equilibrium problem (GNEP) (Facchinei and Kanzow (2007)). Generally, (7)-(10) represent a special class of GNEP that has jointly convex constraints, eq. (10), which depend on other carriers' variables and are convex with respect to all variables (Von Heusinger and Kanzow (2009)). In order to deal with the joint constraint (10) for all carriers, we modify it to two inequality constraints as:

$$\sum_{t=1}^{T} \sum_{o=1}^{O} q_{ijot}^2 \geq \sum_{t=1}^{T} q_{ijt}^1, \quad \forall i, j$$

and

$$\sum_{t=1}^{T} \sum_{o=1}^{O} q_{ijot}^2 \leq \sum_{t=1}^{T} q_{ijt}^1, \quad \forall i, j$$

and dual Lagrange multipliers $\nu^+$ and $\nu^-$ (c.f. Hobbs and Pang (2004)) are applied for (11) and (12), respectively. The set consisting of constraints (8), (9), (11), and (12), with the constraints of bounds following (10), is assumed to be convex.

We assume that the freight carriers compete in a noncooperative manner in the sense of Nash and the shipment and accumulation costs are continuously differentiable and convex. Then, the optimality conditions for all carriers $o; o = 1, \ldots, O$, simultaneously, can be expressed as the following variational inequality: determine $(p^2, q^2, B^*, \delta^*, \mu^2, \nu^1) \in K^2$ satisfying

\[
\begin{align*}
\sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{1+r} \left( -R_{ijot}(p^2, \delta^*) - \frac{\partial R_{ijot}(p^2, \delta^*)}{\partial p_{ijot}} p_{ijot} - \mu_{iot} \right) - \frac{\partial R_{ijot}(p^2, \delta^*)}{\partial p_{ijot}} p_{ijot} - \mu_{iot} \right] \\
\times [p_{ijot}^2 - p_{ijot}^2] + \sum_{o=1}^{O} \left[ \frac{1}{1+r} \left( \frac{\partial TS_{jo}(\delta^*)}{\partial \delta^*} + \frac{\partial CC_{jot}(q_{ijot}^2, \delta^*)}{\partial \delta^*} q_{ijot}^2 + \frac{\partial AC_{jot}(B_{ijot}, \delta^*)}{\partial \delta^*} \right) - \frac{\partial R_{ijot}(p^2, \delta^*)}{\partial p_{ijot}} p_{ijot} - \mu_{iot} \right] \\
\times [\delta^*] \times [\delta^*] \times [\delta^*] \\
+ \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{1+r} \left( \frac{\partial CC_{jot}(q_{ijot}^2, \delta^*)}{\partial q_{ijot}^2} q_{ijot}^2 + CC_{jot}(q_{ijot}^2, \delta^*) - \nu_{ij}^+ + \nu_{ij}^- + \mu_{iot} \right) \right] \\
\times [q_{ijot}^2 - q_{ijot}^2] \\
\end{align*}
\]

\[
\begin{align*}
+ \sum_{t=1}^{T-1} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{1+r} \left( \frac{\partial AC_{jot}(B_{ijot}, \delta^*)}{\partial B_{ijot}} - \mu_{iot(t+1)} + \mu_{iot} \right) \right] \times [B_{ijot}^* - B_{ijot}^*] \\
+ \sum_{i=1}^{M} \sum_{o=1}^{O} \left[ \frac{1}{1+r} \left( \frac{\partial AC_{jot}(B_{ijot}, \delta^*)}{\partial B_{ijot}} + \mu_{iot} \right) \right] \times [B_{ijot}^* + B_{ijot}^*] \\
+ \sum_{i=1}^{M} \sum_{o=1}^{O} \left[ \sum_{j=1}^{N} R_{ijot}(p_{ij}^2, \delta^*) - B_{ijot}^* - \sum_{j=1}^{N} q_{ijot}^2 \right] \times [\mu_{iot} - \mu_{iot}] \\
+ \sum_{t=2}^{T} \sum_{i=1}^{M} \sum_{o=1}^{O} \left[ B_{ijot}^*(t-1) + \sum_{j=1}^{N} R_{ijot}(p_{ij}^2, \delta^*) - B_{ijot}^* - \sum_{j=1}^{N} q_{ijot}^2 \right] \times [\mu_{iot} - \mu_{iot}] \\
+ \sum_{i=1}^{M} \sum_{o=1}^{O} \left[ \sum_{j=1}^{N} q_{ijot}^2 - \sum_{t=1}^{T} q_{ijt}^1 \right] \times [\nu_{ij}^- - \nu_{ij}^+] + \sum_{i=1}^{M} \sum_{o=1}^{O} \left[ - \sum_{j=1}^{N} q_{ijot}^2 + \sum_{t=1}^{T} q_{ijt}^1 \right] \times [\nu_{ij}^- - \nu_{ij}^+] \geq 0, \\
\forall (p^2, q^2, B, \delta^*, \mu^2, \nu^1) \in K^2
\end{align*}
\]
where $\mathcal{K}^2$ is a convex set and is defined as $\mathcal{K}^2 \equiv \{(p^2, q^2, B, \delta_c, \mu^2, \nu^1)| \forall j t o t \geq 0, q^2 j t o t \geq 0, B j t o t \geq 0, 0 \leq \delta_{co} \leq \delta_{max}, \mu_{iot} \geq 0, \nu^2_{ij} \geq 0, \nu^3_{ij} \geq 0 \forall i, j, o, t and (8), (9), and (10) hold\}$ and $\mu^2$ is the Lagrange multipliers associated with (8) and (9).

### 3.3 The Behavior of Retailers and their Optimality Conditions

Retailers in this model are in Cournot-Nash competition and have transactions with manufacturers and demand markets and also interact with the carriers in all planning periods $t; t = 1, \ldots, T$. Retailer $j$ competes to find the optimal order quantity from each manufacturer, $q^3 j t$, its supply, $Y j t$, the sales volume to demand market $k$, $q^3 j k t$, the level of inventory, $Z j t$, for any planning period, and the best energy rating, $\delta_{rj}$ for its technologies. The prices of products at the retailers, $(p^3 j t; j = 1, \ldots, N)$, are endogenous variables and will be determined after we solve the model. We group the retailer $j$’s sales volumes during period $t$ into the vector $q^3 j t$ and its order from all manufacturers into the vector $q^3 j t$.

Retailer $j$ incurs an inventory cost of $IC j t(Z j t, \delta_{rj})$ to take care of the inventory, a transaction cost to have business with the demand markets, $TC j k t(q^3 j k t, \delta_{rj})$, as well as a holding cost of $HC j t(Y t, \delta_{rj})$ for its supplies. The holding cost of retailer $j$ can be affected by the supplies of other retailers. The energy rating of retailer’s technologies impacts all retailer’s costs positively and needs to be maximized while the initial investment cost, $TSI j (\delta_{rj})$, is considered. The behavior of retailer $j$ who seeks the maximum net present profit can be formulated as follows:

Maximize 
$$
\sum_{t=1}^{T} \frac{1}{(1+r)^t} \left\{ p^3 j t \sum_{k=1}^{K} q^3 j k t - IC j t(Z j t, \delta_{rj}) - HC j t(Y t, \delta_{rj}) - \sum_{k=1}^{K} TC j k t(q^3 j k t, \delta_{rj}) - \sum_{i=1}^{M} \lambda_{iot} q^3 j t \right\} - TSI j (\delta_{rj})
$$

subject to:

$$
\sum_{t=1}^{T} Y j t = \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{o=1}^{O} q^3 j i o t
$$

$$
\sum_{t=1}^{T} Y j t = \sum_{t=1}^{T} \sum_{i=1}^{M} q^3 j i t
$$

$$
Y j t - Z j t \geq 0 \forall i
$$

$$
Z j(t+1) + Y j t - Z j t \geq \sum_{k=1}^{K} q^3 j k t, \forall t = 2, \ldots, T
$$

$$
\delta_{rj} \leq \delta_{mi}, \forall i
$$

and nonnegativity of variables as $q^3 j k t \geq 0, Y j t \geq 0, Z j t \geq 0, 0 \leq \delta_{rj} \leq \delta_{max} \forall k, t$.

Objective function (14) represents the net present value of total payout to retailers, inventory, holding, and transaction costs of retailers, the product fee that the manufacturers charge the retailers, and technology investment cost, respectively. The equality (15) is to ensure that retailers receive whatever they have paid for from carriers. This constraint checks that the flow of shipping from carriers throughout the whole planning period is the same as the retailers’ supply. Equality
(16) states that the supply of a retailer should be equal to its order quantity from all manufacturers throughout the planning period. Therefore, the carriers backlog the shipment if it is beneficial for them.

Constraints (17) and (18) ensure the flow of product between retailers and demand markets and model the balance between inventory and supply at the retailer level and the transactions between demand markets and retailers at each period. Constraint (19) has a similar implication as constraint (5) and guarantees that retailers have business transactions with manufacturers with environmental efficiency as high as theirs.

We assume that the inventory, transaction, and holding costs are convex and continuously differentiable and that the retailers compete noncooperatively. The constraints for the above optimization problem for each retailer are clearly convex. Then, the optimality conditions for all retailers \( j; j = 1, \ldots, N \) can simultaneously be formulated as the following variational inequality problem: determine \((q^{1*}, Y^{*}, \bar{q}^{3*}, Z^{*}, \delta_j^{*}, \mu^{3*}, \nu^{2*}, \eta^{2*}, \gamma^{*}) \in K^{3} \) such that

\[
\begin{align*}
\sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{1 + r} \partial_{I_{ij}}(Y^{*}_{ij}) \right] \times [q^{1}_{ij} - q_{ij}] + \sum_{j=1}^{N} \left[ \frac{\partial Y^{*}_{ij} - \partial Y^{*}_{ij}}{\partial \gamma^{*}_{ij}} \right] + \sum_{j=1}^{N} \left[ \frac{\partial Z^{*}_{ij} - \partial Z^{*}_{ij}}{\partial \gamma^{*}_{ij}} \right] + \sum_{j=1}^{N} \left[ \frac{\partial \eta^{*}_{ij} - \partial \eta^{*}_{ij}}{\partial \gamma^{*}_{ij}} \right] \\
\sum_{j=1}^{N} \left[ \frac{\partial Y^{*}_{ij} - \partial Y^{*}_{ij}}{\partial \gamma^{*}_{ij}} \right] + \sum_{j=1}^{N} \left[ \frac{\partial Z^{*}_{ij} - \partial Z^{*}_{ij}}{\partial \gamma^{*}_{ij}} \right] + \sum_{j=1}^{N} \left[ \frac{\partial \eta^{*}_{ij} - \partial \eta^{*}_{ij}}{\partial \gamma^{*}_{ij}} \right] \\
\end{align*}
\]

The behavior of the consumers at the demand markets for each period \( t; t = 1, \ldots, T \), is described in this section. We assume that consumers are environmentally conscious and retailer energy ratings

\[
\begin{align*}
3.4 & \quad \text{The Behavior of Consumers within the Demand Markets and their Optimality Conditions} \\
\text{The behavior of the consumers at the demand markets for each period } t; t = 1, \ldots, T, & \text{ is described in this section. We assume that consumers are environmentally conscious and retailer energy ratings}
\end{align*}
\]

\[
\begin{align*}
\end{align*}
\]
will influence their purchase behavior. They will be more likely to support and be attracted to environmentally sound, energy efficient retailers. Also, they take into account in making their consumption decisions not only the price charged for the product by the retailers, \( p_{jt}^4 \), but also the transaction cost to obtain these products, \( SC_{jkt}(q_{jkt}^3) \). In this case, retailers will be motivated to invest in higher energy rating technologies.

Let \( p_{kjt}^4 \) denote the price that consumers at demand market \( k \) are willing to pay for the product supplied at retailer market \( j \) during period \( t \). Also, for each demand market \( k \) we assume a demand function \( D_{kj}(p^4, \delta_{rj}) \), which depends not only on the price of the product at that demand market but also on the prices of the product at the other demand markets and retailer’s carbon footprint. It is assumed that the demand functions and the transaction cost are continuous. In a sustainable supply chain network in which all entities are taking into account the planning horizon, consumers at the demand markets are not an exception. This behavior is consistent with welfare maximization in which consumers consider the net present value of their transactions. In equilibrium, the following conditions hold for consumers at demand market \( k; k = 1, \ldots, K \), in period \( t; t = 1, \ldots, T \): For all retailer \( j; j = 1, \ldots, N \),

\[
\frac{1}{(1 + r)^t} [p_{jt}^3 + SC_{jkt}(q_{jkt}^3)] = \frac{1}{(1 + r)^t} p_{kjt}^4, \quad \text{if} \quad q_{jkt}^3 > 0,
\]

\[
\geq \frac{1}{(1 + r)^t} p_{kjt}^4, \quad \text{if} \quad q_{jkt}^3 = 0
\]

and

\[
D_{kj}(p^4, \delta_{rj}) \begin{cases} 
q_{jkt}^3, & \text{if} \quad p_{kjt}^4 > 0, \\
\leq q_{jkt}^3, & \text{if} \quad p_{kjt}^4 = 0.
\end{cases}
\]

Condition (21) states that, in equilibrium, if the consumers at demand market \( k \) purchase the product from retailer \( j \), then the price that consumers are willing to pay is equal to the price charged by the retailer for the product plus the transaction cost of purchase. Otherwise, there will be no transaction between the retailer and demand market pair. Conditions (22) also state that if equilibrium price the consumers at the demand market are willing to pay for the product purchased from retailers \( j \) is positive, then the quantities purchased from the retailers will be precisely equal to the demand for that product at the demand market. The amount of purchase from retailers exceed from the demand at demand markets if the price is zero.

In equilibrium, conditions (21) and (22) must hold simultaneously for all demand markets \( k; k = 1, \ldots, K \) at all time periods. These conditions correspond to the well-known spatial price equilibrium conditions (cf. Nagurney (1999); Takayama and Judge (1964)). We can now express these equilibrium conditions as the following variational inequality: determine \((q^3, p^4) \in K^4\)

\[
\sum_{t=1}^{T} \sum_{j=1}^{N} \sum_{k=1}^{K} \frac{1}{(1 + r)^t} [p_{jt}^3 + SC_{jkt}(q_{jkt}^3) - p_{kjt}^4] \times [q_{jkt}^3 - q_{jkt}^3] + \sum_{t=1}^{T} \sum_{k=1}^{K} \sum_{j=1}^{N} [q_{jkt}^3 - D_{kj}(p_{kjt}^4, \delta_{rj})] \times [p_{kjt}^4 - p_{kjt}^4] \geq 0,
\]

\[
\forall (q^3, p^4) \in K^4 \quad (23)
\]

where \( K^4 \equiv \{(q^3, p^4)|q_{jkt}^3 \geq 0, p_{kjt}^4 \geq 0, \forall j, t\} \) is a convex set.
3.5 The Equilibrium Conditions of the Multiperiod Supply Chain Network with Freight Carriers

In equilibrium, the optimality conditions of all the manufacturers, all the carriers, all the retailers, and the equilibrium conditions for all the demand markets must be simultaneously satisfied and the product flows between the distinct tiers of the decision makers must coincide so that no decision maker has any incentive to alter his transactions/shipments.

Definition 1: The Equilibrium State of the Multiperiod Supply Chain Network with Freight Carriers

The equilibrium state of the multiperiod supply chain network with freight carriers is one where: all manufacturers have achieved optimality for their production levels, the retailers’ order levels, inventory levels, and the energy rating level (cf. (6)); all carriers have achieved optimality for the prices of shipment, the amount of deliveries, and the backlog sizes as well as their energy rating level (cf. (13)); all retailers have achieved optimality for the order quantities from manufacturers, the inventory levels, and the sales volume to demand markets besides the level of energy rating (cf. (20)), and, finally, the equilibrium conditions for all demand markets hold (cf. (23)).

Under the above definition, the product flows between the distinct tiers of the decision makers coincide and the product flows and prices satisfy the sum of the optimality conditions (6), (13), (20), and (23). We now state the theorem:

Theorem 1: Variational Inequality Formulation

The equilibrium conditions governing the multiperiod supply chain - freight carrier model are equivalent to the solution of the variational inequality problem given by: determine

\[(q^1, q^2, q^3, S^*, I^*, \delta_m^*, B^*, \delta_c^*, Y^*, Z^*, \delta_r^*, p^1, \mu^1, \mu^2, \mu^3, \theta^*, \eta^1, \eta^2, \nu^1, \nu^2, \gamma^*) \in K,\]

satisfying

\[
\langle F(X^*), X - X^* \rangle \geq 0, \quad \forall X \in K
\]  

(24)

where \(X \equiv (q^1, q^2, q^3, S, I, \delta_m, B, \delta_c, Y, Z, \delta_r, p^1, \mu^1, \mu^2, \mu^3, \theta, \eta^1, \eta^2, \nu^1, \nu^2, \gamma)\) and

\[
F(X) \equiv (F_{q^1}, F_{q^2}, F_{q^3}, F_{S}, F_{I}, F_{\delta_m}, F_{B}, F_{\delta_c}, F_{Y}, F_{Z}, F_{\delta_r}, F_{p^1}, F_{\mu^1}, F_{\mu^2}, F_{\mu^3}, F_{\theta}, F_{\eta^1}, F_{\eta^2}, F_{\nu^1}, F_{\nu^2}, \gamma)
\]

and

\[
F_{q^i,j,t}, F_{q^i,j,t}, F_{p^i,j,t}, F_{S,j,t}, F_{I,j,t}, F_{\delta^i_m,j,t}, F_{B_o,j,t}, F_{\delta^c,j,t}, F_{Y,j,t}, F_{Z,j,t}, F_{\delta^r,j,t}, F_{\mu^i,j,t}, F_{\eta^1,j,t}, F_{\eta^2,j,t}, F_{\nu^1,j,t}, F_{\nu^2,j,t}, \gamma_{i=1,...,M,j=1,...,N,o=1,...,O,k=1,...,K,t=1,...,T}
given in the Appendix. The term \(\langle \cdot, \cdot \rangle\) denotes the inner product in \(N\)-dimensional Euclidean space.

The complete formulation of the variational inequality (24) and the proof of existence of its solution, the closed form solutions of the supply chain prices, the qualitative studies, and the algorithm used are provided in the Appendix.

4. Numerical Examples and Discussion

In this section, we provide some numerical examples in order to illustrate the model, investigate the impact of investment parameters, and also discuss the results. The modified projection method was implemented in MATLAB and the computer system used was a DELL XPS 13 laptop. In comparison with the Euler method (cf. Dupuis and Nagurney (1993)), each iteration of the modified projection method is more complex (provided in the Appendix). In fact, the modified projection
method requires two steps with each step of the same order of complexity as the computation step in the Euler method as a discrete-time algorithm. The convergence criterion that we use is that the absolute value of the flows and prices between two successive iterations differed by no more than $10^{-5}$. All the functional forms and parameter values are determined so that the existence of solutions and the conditions for convergence are ensured. We set the parameter $\omega = 0.02$ and the tolerance $\varepsilon = 0.00001$ for all computations of the numerical examples in this section.

Example 1

The supply chain network in Example 1 includes two manufacturers, $M = 2$; two retailers, $N = 2$; two carriers, $O = 2$; and two demand markets, $K = 2$; competing over five planning periods, $T = 5$. These two manufacturers serve both retailers and ship their products via two carriers. Also, consumers within the two demand markets are equally as likely to purchase from either of the two retail outlets. This leads to the network representation in Figure 2. The cost functions at each level are similar for the entities in that level (i.e., the same functional forms are used for both manufacturers, for both retailers, and for both carriers). The recommended discount rate according to the Federal Office of Management and Budget$^1$ is three percent ($r = 3\%$) and all cost functions are separable. The parameters and cost functions are defined below. The energy rating, $\delta$, is treated as a cost reduction factor in the multiperiod planning model and should be maximized. All $\delta$s are normalized to be between 0 and 1. Hence, they can decrease production, inventory, transaction, and shipment costs and are shown with negative coefficients in these cost functions. In any cost function related to production, inventory, transaction, and transportation, the linear terms reflect the unit costs and the quadratic terms reflect the fact that the marginal cost increases as the quantity approaches the maximum capacity.

\footnote{\url{http://cbkb.org/toolkit/discounting/}}
The manufacturers’ production costs function are:

\[ PC_{it}(S_{it}, \delta_{mi}) = \alpha^t S_{it} + 0.05(S_{it})^2 - \delta_{mi} S_{it}, \quad i = 1, 2, t = 1, \ldots, 5. \quad (25) \]

\[ \alpha^t = [2, 2.5, 3, 3.5, 4], \quad \alpha^{2t} = [3, 4, 4.5, 5, 5.5]. \]

The manufacturers’ inventory costs are:

\[ WC_{it}(I_{it}, \delta_{mi}) = 1.05 I_{it} + 0.002(I_{it})^2 - \delta_{mi} I_{it} + 10, \quad i = 1, 2; t = 1, \ldots, 5. \quad (26) \]

The transaction costs between manufacturers and retailers are:

\[ TC_{ijt}(q_{ijt}, \delta_{mi}) = 1.5 q_{ijt} + 0.8(q_{ijt})^2 - \delta_{mi} q_{ijt}, \quad i = 1, 2; j = 1, 2; t = 1, \ldots, 5. \quad (27) \]

The holding costs of supplies at the retailers are:

\[ HC_{jt}(Y_{jt}, \delta_{rj}) = 3 Y_{jt} + 0.05 (Y_{jt})^2 - \delta_{rj} Y_{jt}, \quad j = 1, 2; t = 1, \ldots, 5. \quad (28) \]

The inventory costs at the retailers are:

\[ IC_{jt}(Z_{jt}, \delta_{rj}) = 1.01 Z_{jt} + 0.002(Z_{jt})^2 - \delta_{rj} Z_{jt}, \quad t = 1, \ldots, 5. \quad (29) \]

The transportation demand functions for the carriers are:

\[ R_{ijot}(p_{ijot}^2, \delta_{co}) = 20 - 1.5 p_{ijot}^2 + 0.5 \sum_{c \neq o} p_{ijct}^2 + 3\delta_{co}, \quad i = 1, 2; j = 1, 2; o = 1, 2; t = 1, \ldots, 5. \quad (30) \]

The transportation costs for the carriers are:

\[ CC_{ijot}(q_{ijot}^2, \delta_{co}) = 1.1 q_{ijot}^2 + 0.003 q_{ijot}^2 - \delta_{co} q_{ijot}^2, \quad i = 1, 2; j = 1, 2; o = 1, 2; t = 1, \ldots, 5. \quad (31) \]

The accumulation costs of carriers are:

\[ AC_{iot}(B_{iot}, \delta_{co}) = B_{iot} + 0.001(B_{iot})^2 - \delta_{co} B_{iot}, \quad i = 1, 2; o = 1, 2; t = 1, \ldots, 5. \quad (32) \]

The investment cost functions for manufacturers, carriers, and retailers are defined, respectively, as:

\[ TSI_1^i = 500 + 300(\delta_{mi})^2, \quad i = 1, 2. \quad (33) \]

\[ TSI_2^o = 500 + 200(\delta_{co})^2, \quad o = 1, 2. \quad (34) \]

\[ TSI_2^j = 500 + 200(\delta_{rj})^2, \quad j = 1, 2. \quad (35) \]

To have a sustainable supply chain network, the assumption is to have higher energy ratings which will lower carbon emissions during the planning horizon. To meet these emissions reduction goals, investment in relatively high priced technology may be required (Fehrenbacher (2015)). It is assumed that the initial technology costs are higher for the manufacturers by comparison with the retailers and the carriers.

The energy rating, \( \delta \), can be zero and should not be more than 1, (\( \delta_{max} = 1 \)). At a zero level, companies incur a minimum investment but will have the highest future production, inventory,
transaction, and shipment costs. Alternatively, a higher $\delta$ means higher initial investments, lower future costs, and a greener supply chain network. Hence, there is a tradeoff between present expenditures and future costs in a sustainable supply chain network with freight carriers. The unit transaction costs associated with transacting between the retailers and the demand markets are fixed and are independent of product flow:

$$SC_{1kt}(q_{1kt}^3) = 2, \quad SC_{2kt}(q_{2kt}^3) = 1 \quad k = 1, 2; t = 1, 2, 3, 4, 5.$$ (36)

The demand functions for customers within demand market 1 are defined to be less sensitive to future product prices, while customers within demand market 2 are defined to be more sensitive to future product prices.

$$D_{1j1}(p^4, \delta_{rj}) = 130 - 1.3p_{1j1}^4 + 2\delta_{rj}, \quad D_{1j2}(p^4, \delta_{rj}) = 110 - 1.1p_{1j2}^4 + 2\delta_{rj},$$

$$D_{1j3}(p^4, \delta_{rj}) = 80 - 0.9p_{1j3}^4 + 2\delta_{rj}, \quad D_{1j4}(p^4, \delta_{rj}) = 50 - 0.7p_{1j4}^4 + 2\delta_{rj},$$

$$D_{1j5}(p^4, \delta_{rj}) = 40 - 0.4p_{1j5}^4 + 2\delta_{rj}, \quad j = 1, 2.$$ (37)

$$D_{2j1}(p^4, \delta_{rj}) = 80 - 0.7p_{2j1}^4 + 2\delta_{rj}, \quad D_{2j2}(p^4, \delta_{rj}) = 120 - 1p_{2j2}^4 + 2\delta_{rj},$$

$$D_{2j3}(p^4, \delta_{rj}) = 150 - 1.2p_{2j3}^4 + 2\delta_{rj}, \quad D_{2j4}(p^4, \delta_{rj}) = 180 - 1.7p_{2j4}^4 + 2\delta_{rj},$$

$$D_{2j5}(p^4, \delta_{rj}) = 200 - 2p_{2j5}^4 + 2\delta_{rj}, \quad j = 1, 2.$$ (38)

The equilibrium solution, including the flows of products between different levels in this supply chain network, the prices charged for purchasing the products, $p^1, p^2$, and the shipment fees, $p^4$, are provided in Table 2.

### Table 2: Equilibrium Solution for Example 1

<table>
<thead>
<tr>
<th>Entity</th>
<th>Variables</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$t = 1$</td>
</tr>
<tr>
<td>S</td>
<td>$S_{1t*}$</td>
<td>75.28</td>
</tr>
<tr>
<td></td>
<td>$S_{2t*}$</td>
<td>74.33</td>
</tr>
<tr>
<td>$q^{1*}$</td>
<td>$q_{1jt*}$</td>
<td>35.53</td>
</tr>
<tr>
<td></td>
<td>$q_{2jt*}$</td>
<td>35.45</td>
</tr>
<tr>
<td>Manufacturers</td>
<td>$I^r$</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td>$I_{3t}$</td>
<td>4.22</td>
</tr>
<tr>
<td></td>
<td>$I_{2t}$</td>
<td>3.42</td>
</tr>
<tr>
<td>$p^{1*}$</td>
<td>$p_{1jt}$</td>
<td>i = 1, 2, j = 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i = 1, 2, j = 2</td>
</tr>
<tr>
<td></td>
<td>$\delta_{m}$</td>
<td>$\delta_{m1} = 1, \delta_{m2} = 1$</td>
</tr>
<tr>
<td>$q^{2*}$</td>
<td>$q_{jot}$</td>
<td>i = 1, j = 1, 2, o = 1, 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i = 2, j = 1, 2, o = 1, 2</td>
</tr>
<tr>
<td>Carriers</td>
<td>$R_{jot}$</td>
<td>i = 1, j = 1, 2, o = 1, 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i = 2, j = 1, 2, o = 1, 2</td>
</tr>
<tr>
<td>$p^{2*}$</td>
<td>$p_{jot}$</td>
<td>i = 1, j = 1, 2, o = 1, 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>i = 2, j = 1, 2, o = 1, 2</td>
</tr>
</tbody>
</table>

Continued
At equilibrium, manufacturers and carriers select the best available technology and invest at the highest level, so that, $\delta_m = 1, \delta_c = 1$, while retailers cannot afford expensive technology and invest with the minimum cost $\delta_r = 0$. Figure 3a shows that both manufacturers produce more in early periods due to lower cost of production and an increasing cost for subsequent periods. The results (Figure 3b) show that manufacturers’ inventory levels initially increase. Inventory then stabilizes, before decreasing to zero in the fifth period. This pattern takes advantage of the lower initial production costs to build inventory before higher production costs occur.

The carriers are better off by delivering the product to the retailers as soon as they get the orders from the manufacturers and not piling up the shipping services as the backlog (Figure 4a).
Therefore, the flow of shipment is similar to the flow of orders from manufacturers (Figure 4b). Also, they follow the same strategy for accumulating backlog as manufacturers for their inventory and have the highest backlog level in periods two and three and then deliver all the products and empty the service backlog at the end of planning period (period five). In addition, all network entities, manufacturers, retailers, and carriers end with no inventory or backlog as the model dictates.

Customers’ demand from each retailer outlet are presented in Figure 5a. In spite of a decrease in customers’ sensitivity for the prices in demand market 1, their purchases are reduced since the fix demand declined (from 130 to 40). On the other hand, customers’ purchases at demand market 2 increase and then decline due to high price sensitivity in the last two periods (Figure 5b).

Example 2

Example 1 data are used as the baseline in Example 2, but the time periods have been extended \(T = 10\). In addition, the production cost functions of the manufacturers have slightly changed. The new manufacturer production cost functions are shown in (39-40). These functions show that
production becomes more costly in future time periods as the $\alpha$ value is increasing from period 1 to period 10. The discount rate is kept at 3%.

\begin{align}
PC_{1t}(S_{1t}, \delta_{m1}) &= \alpha^{1t}S_{1t} + 0.05(S_{1t})^2 - \delta_{m1}S_{1t}, \quad t = 1, \ldots, 10, \\
PC_{2t}(S_{2t}, \delta_{m2}) &= \alpha^{2t}S_{2t} + 0.05(S_{2t})^2 - \delta_{m2}S_{2t}, \quad t = 1, \ldots, 10,
\end{align}

$\alpha^{1t} = [2, 2.5, 3, 3.5, 4, 4, 4.5, 4.5, 4.5, 4.5]$, $\alpha^{2t} = [3.5, 4, 4.5, 5, 5.5, 5.5, 5.5, 5.5, 5.5, 6, 6]$.

The first five demand functions are similar to Example 1. In addition, the demand functions for five additional periods are:

\begin{align}
D_{1j6}(p^4, \delta_{rj}) &= 40 - 0.4p_{1j6} + 2\delta_{rj}, \quad D_{1j7}(p^4, \delta_{rj}) = 40 - 0.4p_{1j7} + 2\delta_{rj}, \\
D_{1j8}(p^4, \delta_{rj}) &= 40 - 0.4p_{1j8} + 2\delta_{rj}, \quad D_{1j9}(p^4, \delta_{rj}) = 40 - 0.4p_{1j9} + 2\delta_{rj}, \\
D_{1j10}(p^4, \delta_{rj}) &= 40 - 0.4p_{1j10} + 2\delta_{rj}, \quad j = 1, 2.
\end{align}

\begin{align}
D_{2j6}(p^4, \delta_{rj}) &= 200 - 2p_{2j6} + 2\delta_{rj}, \quad D_{2j7}(p^4, \delta_{rj}) = 160 - 1.7p_{2j7} + 2\delta_{rj}, \\
D_{2j8}(p^4, \delta_{rj}) &= 130 - 1.5p_{2j8} + 2\delta_{rj}, \quad D_{2j9}(p^4, \delta_{rj}) = 130 - p_{2j9} + 2\delta_{rj}, \\
D_{2j10}(p^4, \delta_{rj}) &= 100 - p_{2j10} + 2\delta_{rj}, \quad j = 1, 2.
\end{align}

Table A1 (in the Appendix) provides the equilibrium results for Example 2 during 10 planning periods. Extending the planning period duration affects the production strategy for manufacturers. Figure 6a represents the level of production for both manufacturers. For the first five periods, manufacturers plan to produce more than the demand and increase the inventory levels (Figure 6b). However, after period five, the production plan follows a make-to-order strategy and production is at the level so as not to have extra supply pile up as inventory.

Retailers decrease their supply throughout the planning horizon and have no interest in accumulating inventory at their warehouses (Figure 7a). This interesting result is related to the retailers’ energy rating level for longer planning periods ($T = 10$). The equilibrium outcome ($\delta_{r1} = 1, \delta_{r2} = 1$) demonstrates that, for a longer planning horizon, both retailers are willing to invest in green technologies (corresponding to the highest level of energy rating) and make an effort into moving to
environmental friendly technologies. In fact, the longer scheduling horizon equips them sufficiently to meet the requirements for sustainable environmental processes and development and therefore, select the best technology.

Sustainable development is a process of reconciliation of the ecological, social, and economical obligations and it might be possible for the whole supply chain entities to enhance their business in a long-term orientation. In Figure 7b, we can see the customers’ demand from both retail outlets. The demand of customers within market 2 has a flash in period 9 which is related to their lower sensitivity with respect to price in compare with previous period (demand function $D_{2j9}$ vs $D_{2j8}$). In fact, we can see the customers’ responsiveness to price via the equilibrium solution.

![Figure 7: Manufacturers’ supply, inventory, and customers’ demand in Example 2](image)

These results clearly illustrate the importance of generating strategic flows in longer-term planning for supply chain equilibrium networks.

**Example 3**

This example follows the same network structure as Example 1 but with varying cost functions for all network parties in order to focus on constraints (5) and (19). Constraint (5) would require any of the manufacturers to consider the carriers that have the same or higher level of energy rating in comparison with their own energy rating level. Also, constraint (19) brings the same situation for retailers in choosing their manufacturing partners. In fact, these two constraints enforce supply chain entities to have a green network with other entities and limit their business within this network. In this example, the manufacturers’ production costs function are:

$$PC_{it}(S_{it}, \delta_{mi}) = \alpha^{it}S_{it} + 2.5(S_{it})^2 - \delta_{mi}S_{it}, \quad i = 1, 2, t = 1, \ldots, 5. \quad (43)$$

$$\alpha^{1t} = [10, 12.5, 15, 17.5, 20], \quad \alpha^{2t} = [17.5, 20, 22.5, 25, 27.5].$$

The manufacturers’ inventory costs are:

$$WC_{it}(I_{it}, \delta_{mi}) = 2.05I_{it} + 0.2(I_{it})^2 - \delta_{mi}I_{it} + 10, \quad i = 1, 2; \ t = 1, \ldots, 5. \quad (44)$$
The transportation demand functions for the carriers are:

\[ T_{ijt}(q_{ijt}, \delta_{mi}) = 2.5q_{ijt}^2 + 0.8q_{ijt}^2 - \delta_{mi}q_{ijt}, \quad i = 1, 2; j = 1, 2; t = 1, \ldots, 5. \]  

The holding costs of supplies at the retailers are:

\[ HC_j(Y_{jt}, \delta_{rj}) = 3Y_{jt} + 0.5(Y_{jt})^2 - \delta_{rj}Y_{jt}, \quad j = 1, 2; t = 1, \ldots, 5. \]  

The inventory costs at the retailers are:

\[ IC_j(Z_{jt}, \delta_{rj}) = 2.01Z_{jt} + 0.2(Z_{jt})^2 - \delta_{rj}Z_{jt}, \quad t = 1, \ldots, 5. \]  

The transportation demand functions for the carriers are:

\[ R_{ijot}(p_{it}^2, \delta_{co}) = 100 - 3.5p_{ijot}^2 + 0.5 \sum_{c \neq o} p_{ijct}^2 + 3\delta_{co}, \quad i = 1, 2; j = 1, 2; o = 1, 2; t = 1, \ldots, 5. \]  

The transportation costs for the carriers are:

\[ CC_{ijot}(q_{ijot}^2, \delta_{co}) = 2.1q_{ijot}^2 + 0.3q_{ijot}^2 - \delta_{co}q_{ijot}^2, \quad i = 1, 2; j = 1, 2; o = 1, 2; t = 1, \ldots, 5. \]  

The accumulation costs of carriers are:

\[ AC_{iot}(B_{iot}, \delta_{co}) = B_{iot} + 0.001(B_{iot})^2 - \delta_{co}B_{iot}, \quad i = 1, 2; o = 1, 2; t = 1, \ldots, 5. \]  

The investment cost functions for manufacturers, carriers, and retailers are defined, respectively, as:

\[ TSI_{1i}^1 = 500 + 360(\delta_{mi})^2, \quad i = 1, 2. \]  

\[ TSI_{2i}^2 = 500 + 360(\delta_{co})^2, \quad o = 1, 2. \]  

\[ TSI_{3j}^3 = 500 + 360(\delta_{rj})^2, \quad j = 1, 2. \]  

The unit transaction costs associated with transacting between the retailers and the demand markets have not changed. The demand functions for customers at demand market 1 and demand market 2 are as follows:

\[ D_{1j1}(p^4, \delta_{rj}) = 650 - 1.3p_{1j1}^4 + 2\delta_{rj}, \quad D_{1j2}(p^4, \delta_{rj}) = 550 - 1.1p_{1j2}^4 + 2\delta_{rj}, \]
\[ D_{1j3}(p^4, \delta_{rj}) = 400 - 0.9p_{1j3}^4 + 2\delta_{rj}, \quad D_{1j4}(p^4, \delta_{rj}) = 250 - 0.7p_{1j4}^4 + 2\delta_{rj}, \]
\[ D_{1j5}(p^4, \delta_{rj}) = 200 - 0.4p_{1j5}^4 + 2\delta_{rj}, \quad j = 1, 2. \]  

\[ D_{2j1}(p^4, \delta_{rj}) = 400 - 0.7p_{2j1}^4 + 2\delta_{rj}, \quad D_{2j2}(p^4, \delta_{rj}) = 600 - 1p_{2j2}^4 + 2\delta_{rj}, \]
\[ D_{2j3}(p^4, \delta_{rj}) = 750 - 1.2p_{2j3}^4 + 2\delta_{rj}, \quad D_{2j4}(p^4, \delta_{rj}) = 900 - 1.7p_{2j4}^4 + 2\delta_{rj}, \]
\[ D_{2j5}(p^4, \delta_{rj}) = 1000 - 2p_{2j5}^4 + 2\delta_{rj}, \quad j = 1, 2. \]  

The focus in this example is on energy rating constraints. Here, we vary the coefficient of \( \delta \) in cost functions (51)-(53) from 360 to 560 by increment of 20 and analyze the companies' capability in acquiring green technology. Then, we relax constraints (5) and (19) and repeat the same procedure.
to determine the companies' willingness in adopting green technology. In this situation (model without (5) and (19)), the manufacturers and the retailers decide upon technology investment without any enforcement for considering energy rating of their carriers or their manufacturers, respectively.

The outcome (Figure 8) shows that by enforcing the whole supply chain to adopt the best technology (before relaxation), all network entities can afford green technology up to a specific investment cost level (e.g. here in this example 440). Carriers can not afford higher investment and according to constraints (5) and (19), manufacturers’ and retailers’ energy rating level is limited to the level of carriers’ energy rating. Hence, in spite of possible capability to pay for more expensive technologies, manufacturers and retailers have to follow the carriers' policy for technology investment to maintain a green supply chain.

![Figure 8: Energy rating of all entities for different investment levels in an obliged network](image)

On the other hand, when constraints (5) and (19) are removed from the model and there is no obligation for the companies to keep a green supply chain, we observe a different result. These contradictory situations bring about interesting comparisons between the optimum strategies of network entities and their behavior. Figure 9 presents the behavior of the network entities under a relaxed circumstance. It shows that carriers follow the same attitude in technology investment in both circumstances (with and without constraints (5) and (19)) and do not invest if the fixed cost of technology is high (in this example higher than 440). However, both manufacturers and retailers behave differently.

In a relaxed circumstance, there is no constraint for retailers to purchase the products only from manufacturers that have the same or a higher level of energy rating than the retailer’s energy rating level. Also, manufacturers are not limited to have business only with carriers which have at least the energy rating level equal to the manufacturers’ energy rating level. In this network, manufacturers can afford more expensive technologies in comparison with retailers and then carriers. For this example, retailers can pay up to 480 (from 360 till 560) for green technologies, while manufacturers are able to invest in best technologies which are more expensive.

The shift as to whether an organization should invest in technology as prices vary is not surprising.
But, the results can help organizations, supply chain members, and policy makers determine whether subsidies or support for technology can make a difference. That is, if the cost of technology is close to a changeover point, policy makers may provide incentives to help support the greening effort. Also, in a closely collaborating supply chain, supplier development may include ways to help supply chain members to reduce costs or to subsidize partner technologies.

5. Conclusions and Managerial Insights

Global warming is a major international concern. Some of the hottest years on record have recently occurred and a vast majority of scientists believe that these global warming concerns are man-made, and thus need to be addressed. Investment in green technology (energy) is risky, where current costs of green energy are not competitive. On the other hand, the increasing level of pollution and fast consumption of natural resources have made many supply chain models that ignore such issues unsustainable. Consumers’ awareness of social and environmental responsibility and the reality of pollution and depletion of natural resources force companies to look for more sustainable ways of conducting business. One of the important aspects of sustainable operations is the application of green technologies to reduce pollution.

In this paper, we use a multiobjective model to investigate the development of multilayer green supply chain problems with different structures. For all forms of supply chain structures including restricted and relaxed form ones in short and long-term planning periods, we obtain the solutions to the optimal pricing, product flows, and energy rating levels.

The key insight derived from this study is that sustainability and greenness in supply chain should be viewed holistically, that is, in a macro way. Although each micro part of the supply chain gives rise to its own effects, impacts, and opportunities for improvement, effective greenness strategies require an analysis that encompasses the entire supply chain. It is also important for any firm in the supply chain to take a network approach to investment options. The network approach can lead to programs of collaboration, the rapid development of innovation in environmental technologies,
and allows firms to better understand the environmental impact of their supply chains.

Furthermore, by considering the full macro complexity in the observed systems, our results highlight that decisions to manage the production, inventory, shipment, and technology investment must be conditioned by the structure of any game that underlies the determination of decisions by supply chain partners. We note that the time and the cost of investment affect firms’ decisions, profitability, competitive advantage, and environmental impact. In the short run, the cost of green technologies investment may seem high; however, this cost would be less in the longer term planning in comparison with the indirect and hidden costs of liability for pollution and noncompliance with regulation as well as health and safety issues.

Our results also provide insights for government regulators and green NGOs that aim to promote green technology acquisition for sustainable growth. According to our modeling results, the benefits of sustainable supply chains include improving the image and legitimacy of products that have smaller ecological footprints. These benefits cannot be easily captured in a modeling framework and should be considered when encouraging and supporting supply chain member environmental initiative investments. For instance, Figures 8 and 9 for Example 3 demonstrate that in order to have a green supply chain, governments can decrease barriers of entry for green energy by taking steps to subsidize green technology adoption.

Without a doubt, prompt decisions on green investment not only reduce the future costs and lead to economic benefits for companies, but also improve a company’s image in building up business sustainability. The surge in consumer awareness and demand for greater sustainability intensifies the environmental prudence throughout the supply chain.

The results in this paper help policy-makers to understand why some policies are successful and others are not, and, therefore, are valuable for both the present and the future. Hence, to reduce a firm’s negative environmental impact, policy-makers should design policies that encourage firms to invest in energy efficient technology or penalize organizations that do not invest. Relevant policies may include tax incentives and friendly depreciation of the investment in the asset. In addition, governments have a range of tools available, including regulations, information and knowledge sharing programs, innovation policies, environmental subsidies, tax deductions, and tax exemptions.

6. Summary

Energy prices and environmental problems are major issues in today’s global economy, which is dealing with major challenges associated with climate change and environmental sustainability. Investment in energy efficient technology can reduce production costs, transportation costs, as well as reduce the environmental impact of production, sales, and the delivery of products. Firms in supply chains face competitive challenges due to increasing energy costs as well as pressure from consumers to produce environmentally friendly products.

In this paper, we address these concerns by developing a supply chain network model. Here, firms compete in a multiperiod fashion trying to maximize the net present value of their investment in ecologically friendly technology and future cash flows from savings from production, inventory,
transaction, and transportation costs. Net present value is applied to compute the benefit of a project over time which represents the most favorite method of dynamic investment appraisal. We also embed customers’ sensitivity toward carbon emissions and green technologies in their demand functions.

More specifically, we formulated and analyzed a multiperiod competitive supply chain network equilibrium model with freight carriers network. The manufacturers and retailers are engaged in a Cournot-Nash competition game while carriers compete via Bertrand and Cournot. In addition, customers within the demand markets with environmentally fulfillment mandates are spatially separated and have economic transactions with the retailers. The carriers charge manufacturers for shipping the product and retailers pay manufacturers for the products. To the best of our knowledge, this is the first multiperiod supply chain network with freight carriers in the existing supply chain literature, which includes environmental issues, multi-tier inventory optimization and net present value of network entities.

The modified projection method given in the Appendix was applied to compute the equilibrium flows, prices, and Lagrange multipliers, as well as the energy rating levels for the numerical examples. For these examples, nonlinear cost functions associated with the manufacturers, the carriers, and the retailers were examined. We also provide conditions for convergence of the algorithm.

Various aspects of the proposed framework are worthy of further discussion and investigation. For example, policy implications exist and carrier network analysis with multiple modes of shipment including full and partial load capacity are also concerns. In this paper, environmentally efficient processes and their outcomes are modeled in terms of cost reduction. However, this environment may be assessed via a social welfare perspective. That is, social dimensions can be integrated into the model. In addition, various policies such as government penalties for non-green entities and/or government subsidies to encourage environmental technology investments can be investigated. Another research area could focus on collaboration between various partners within a supply chain system instead of just assuming a noncooperative competition stance. This model can be extended to consider uncertainty in customer demand functions as well as in the freight carrier demand functions as possible stochastic extensions.

Last but not least, we can model supply chains that are planning to go green. For instance, the supermarket chain Kroger is making a big commitment to going green and becoming more sustainable by 2020\(^2\). Also, the giant retailer, Wal-Mart, unveiled a plan to make its supply chain greener which is expected to eventually cut about 20 million metric tons of greenhouse gas emissions from its supply chain by the end of 2015\(^3\). These retailers need a holistic view in order to design a network for reducing their carbon-footprint. In these cases, our model can be applied and tailored according to the specific supply chain structure. To implement the proposed model in a real business environment, well-calibrated costs and demand functions are critical. Specific such functions and real-world case studies may be good directions for future research.

Our work addresses a gap in the existing literature by capturing both Bertrand and Cournot competition for production and inventory flows. Prices of shipments in a multi-tiered multiperiod

\(^2\)http://fortune.com/2016/07/07/kroger-sustainability-goals/

\(^3\)http://www.nytimes.com/2010/02/26/business/energy-environment/26walmart.html
competitive supply chain-freight carrier network, along with the energy rating levels for each entity are also integrated as strategic variables. The framework, hence, provides a strong foundation for future research in this area.

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References


A Competitive Multiperiod Supply Chain Network Model with Freight Carriers and Green Technology Investment Option

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Appendix

The Complete Formulation of Variational Inequality (24)

\[
\begin{align*}
\sum_{t=1}^{T} & \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \frac{\partial TC_{ijt}(q^{*}_{ijt}, \delta_{mi})}{\theta_{ijt}} + \mu^*_{it} + \theta^*_{ijt} - \nu^*_{ijt} \right] \times [q_{ijt} - q^{*}_{ijt}] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{(1+r)^t} \frac{\partial CC_{ijot}(q^{*}_{ijot}, \delta_{co})}{\theta_{ijot}} + CC_{ijot}(q^{*}_{ijot}, \delta_{co}) - \nu^*_{ijot} + \nu^*_{ijot} + \mu^*_{iot} \right] \times [q^{*}_{ijot} - q^{*}_{ijot}] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{k=1}^{K} \left[ \frac{1}{(1+r)^t} \frac{\partial TC_{jkt}(q^{*}_{jkt}, \delta_{mj})}{\delta_{jkt}} + SC_{jkt}(q^{*}_{jkt}) - \mu^*_{jkt} + \mu^*_{jkt} \right] \times [q^{*}_{jkt} - q^{*}_{jkt}] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \frac{\partial PC_{it}(S^*_t, \delta_{mi})}{\delta_{sit}} - \mu^*_{it} \right] \times [S^*_it - S^*_it] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \frac{\partial WC_{it}(I^*_t, \delta_{mi})}{\delta_{hit}} + \mu^*_{it} - \mu^*_{(t+1)} \right] \times [I^*_it - I^*_it] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \left[ \frac{1}{(1+r)^t} \frac{\partial WC_{it}(I^*_t, \delta_{mi})}{\delta_{hit}} + \mu^*_{it} \right] \times [I^*_it - I^*_it] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{(1+r)^t} \frac{\partial TC_{ijot}(q^{*}_{ijot}, \delta_{co})}{\theta_{ijot}} + \mu^*_{iot} - \mu^*_{iot(t+1)} \right] \times [B^*_iot - B^*_iot] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{(1+r)^t} \frac{\partial TC_{ijot}(q^{*}_{ijot}, \delta_{co})}{\theta_{ijot}} - \mu^*_{iot} \right] \times [B^*_iot - B^*_iot] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{(1+r)^t} \frac{\partial AC_{iot}(B^*_iot, \delta_{co})}{\delta_{Biot}} - \mu^*_{iot} \right] \times [B^*_iot - B^*_iot] \\
& + \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{o=1}^{O} \left[ \frac{1}{(1+r)^t} \frac{\partial AC_{iot}(B^*_iot, \delta_{co})}{\delta_{Biot}} + \mu^*_{iot} \right] \times [B^*_iot + B^*_iot]
\end{align*}
\]
\begin{align*}
+ \sum_{t=1}^{T} \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial C_{ijot}(q^{ijot}_t, \delta_{co})}{\partial \delta_{co}} \right) q^{ijot}_t + \frac{\partial A_{ijot}(B_{coT}, \delta_{co})}{\partial \delta_{co}} - \frac{\partial R^{i}_{jot}(p^{2^*}_{ijt}, \delta_{co})}{\partial \delta_{co}} p^{2^*}_{ijt} \right] \\
- \mu_{iot} \frac{\partial R^{i}_{jot}(p^{2^*}_{ijt}, \delta_{co})}{\partial \delta_{co}} \Big] \times [\delta_{co} - \delta_{co}] + \sum_{i=1}^{T} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial H_{ijt}(Y^*_t, \delta_{ijt})}{\partial Y_{ijt}} \right) + \nu^*_t - \gamma^*_t \right] \times [Y^*_t - Y^*_t] \\
+ \sum_{i=1}^{T} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial IC_{ijt}(Z^*_t, \delta_{ijt})}{\partial Z_{ijt}} \right) - \mu^*_j + \mu^*_j \right] \times [Z^*_t - Z^*_t] \\
+ \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial IC_{ijt}(Z^*_t, \delta_{ijt})}{\partial Z_{ijt}} \right) + \frac{\partial TC_{ijt}(q^{ijot}_{kt}, \delta_{ijt})}{\partial \delta_{ijt}} \right] - \omega = \sum_{i=1}^{M} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial H_{ijt}(Y^*_t, \delta_{ijt})}{\partial Y_{ijt}} \right) + \nu^*_t - \gamma^*_t \right] \times [Y^*_t - Y^*_t] \\
+ \sum_{i=1}^{T} \sum_{j=1}^{N} \left[ \frac{1}{(1+r)^t} \left( \frac{\partial IC_{ijt}(Z^*_t, \delta_{ijt})}{\partial Z_{ijt}} \right) - \mu^*_j + \mu^*_j \right] \times [Z^*_t - Z^*_t],
\end{align*}

where \( \mathcal{K} \equiv \prod_{i=1}^{T} \mathcal{K}^i \).

**Proof.** With some algebraic manipulation and adding (6), (13), (20), and (23), it follows that the result is inequality (59). Now we can show the converse, that is, the solution to (59) is, in fact, an equilibrium as per Definition 1. If we add \( \frac{1}{(1+r)^t}(-p^{1^*}_{ijt} + p^{1^*}_{jot}) \) to the first set of brackets and \( \frac{1}{(1+r)^t}(p^{3^*}_{ijt} - p^{3^*}_{jot}) \) to the third set of brackets to variational inequality (59), inequality (59) will not change since the value of these additions is simply zero. However, the variational inequality formulation (59) with additional terms can be rewritten as the summation of variational inequalities (6), (13), (20), and (23). The proof is complete. \( \square \)

Now we can retrieve the equilibrium prices for the manufacturers, \( p^{1^*}_{ijt} \), for all \( i, j \) and \( t \), and
for the retailers, $p_{jt}^{3*}$, for all $j$ in any time period. After solving variational inequality (59), we can find the optimal values of the Lagrange multipliers: $\mu_{it}^*$, $\mu_{j}^*$, and $\theta_{jt}^*$. Then, from equation (6) the manufacturers’ prices can be recovered for any particular numerical problem), either (cf. (20)) set

$$p_{jt}^{1*} = (1 + r)^t(\mu_{it}^* + \theta_{jt}^*) + \frac{\partial TC_{ijt}(q_{ijt}^*, \delta_{mi})}{\partial q_{ijt}}$$

or, equivalently to (cf. (20))

$$p_{jt}^{1*} = (1 + r)^t\nu_{jt}^*.$$  

Also, to recover the retailer price, $p_{jt}^{3*}$ one can (after solving variational inequality (59) for the particular numerical problem), either (cf. (20)) set

$$p_{jt}^{3*} = (1 + r)^t\mu_{jt}^* + \frac{\partial TC_{jkt}(q_{jkt}^*, \delta_{rk})}{\partial q_{jkt}},$$

for any $j$, $k$, and $t$, such that $q_{jkt}^* > 0$, or (cf. (23)) for any $q_{jkt}^* > 0$, set

$$p_{jt}^{3*} = p_{kjt}^{3*} - SC_{jkt}(q_{jkt}^*).$$

Under the above pricing mechanism, the optimality conditions (6), (13), and (20) as well as the equilibrium conditions (23) also hold separately.

**Qualitative Studies**

Here, we provide some qualitative properties of the solution to variational inequality (59), in particular, the existence results.

The feasible set underlying the variational inequality problem (59) is not compact. Therefore, we cannot derive existence of a solution simply from the assumption of continuity of the functions. However, by imposing a rather weak condition, we can guarantee the existence of a solution pattern. Let

$$\mathcal{K}_b = \{(q^1, q^2, q^3, S, I, \delta_m, p^2, B, \delta_c, Y, Z, \delta_r, p^4, \mu^1, \mu^2, \mu^3, \theta, \eta^1, \eta^2, \nu^1, \nu^2, \gamma) | 0 \leq q^1 \leq b_1; 0 \leq q^2 \leq b_2; 0 \leq q^3 \leq b_3; 0 \leq S \leq b_4; 0 \leq I \leq b_5; 0 \leq \delta_m \leq \delta_{max}; 0 \leq p^2 \leq b_6; 0 \leq B \leq b_7; 0 \leq \delta_c \leq \delta_{max}; 0 \leq Y \leq b_8; 0 \leq Z \leq b_9; 0 \leq \delta_r \leq \delta_{max}; 0 \leq p^4 \leq b_{10}; 0 \leq \mu^1 \leq b_{11}; 0 \leq \mu^2 \leq b_{12}; 0 \leq \mu^3 \leq b_{13}; -b_{14} \leq \theta \leq b_{15}; 0 \leq \eta^1 \leq b_{16}; 0 \leq \eta^2 \leq b_{17}; 0 \leq \nu^1 \leq b_{18}; -b_{19} \leq \nu^2 \leq b_{20}.$$ 

$$-b_{21} \leq \gamma \leq b_{22}\}$$

where $b = (b_1, \ldots, b_{22}, \delta_{max}) \geq 0$ and $\delta_{max} = \delta_{max}$. These conditions guarantee that $\mathcal{K}_b$ is a bounded and closed convex subset of $R^{A_1+A_2+A_3+A_4}$ where $A_1 = (I + 2MNT + 3MT + MO)$, $A_2 = (O + 2MNOT + 2MOT + MN)$, $A_3 = (2N + MNT + 3NT + MN)$, and $A_4 = (NKT + KT)$. Hence, the following variational inequality admits at least one solution $X^b \in \mathcal{K}_b$ since $\mathcal{K}_b$ is compact and $F$ is continuous.

$$\langle F(X^b), X - X^b \rangle \geq 0, \quad \forall X^b \in \mathcal{K}_b.$$
Following Kinderlehrer and Stampacchia (1980) (see also Theorem 1.5 in Nagurney (1999)), Lemma 1 can hold as:

Lemma 1. Variational inequality (24) admits a solution if and only if there exists a $b > 0$ such that variational inequality (65) admits a solution in $K_b$ with

\[
q^1 < b_1, \quad q^2 < b_2, \quad q^3 < b_3, \quad S < b_4, \quad I < b_5, \quad \delta_m < \delta^b_{\text{max}}, \quad p^2 < b_6, \quad B < b_7, \\
\delta_c < \delta^b_{\text{max}}, \quad Y < b_8, \quad Z < b_9, \quad \delta_v < \delta^b_{\text{max}}, \quad p^4 < b_{10}, \quad \mu^1 < b_{11}, \quad \mu^2 < b_{12}, \quad \mu^3 < b_{13}, \\
b_{14} < \theta < b_{15}, \quad \eta^1 < b_{16}, \quad \eta^2 < b_{17}, \quad \nu^1 < b_{18}, \quad b_20 < \nu^2 < b_{20}, \quad b_{21} < \gamma < b_{22}. \quad (66)
\]

Under the conditions in Theorem 2 given below, it is possible to construct a $b$ set large enough so that the restricted variational inequality (65) will satisfy the boundedness condition (66) and, therefore, the existence of a solution to the original variational inequality problem (59) is guaranteed under Lemma 1.

Theorem 2: Existence

Suppose that there exist positive constants $M, N, R$, such that:

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial TC_{ijt}(q^1_{ijt}, \delta_{mi})}{\partial q^1_{ijt}} \right) \geq R, \quad \forall q^1 \text{ with } q^1_{ijt} \geq M, \quad \forall i, j, t \quad (67)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial CC_{ijot}(q^2_{ijot}, \delta_{co})}{\partial q^2_{ijot}} \right) + CC_{ijot}(q^2_{ijot}, \delta_{co}) \geq R, \quad \forall q^2 \text{ with } q^2_{ijot} \geq M, \quad \forall i, j, o, t \quad (68)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial TC_{jkt}(q^3_{jkt}, \delta_{rj})}{\partial q^3_{jkt}} + SC_{jkt}(q^3_{jkt}) \right) \geq R, \quad \forall q^3 \text{ with } q^3_{jkt} \geq M, \quad \forall j, k, t \quad (69)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial PC_{it}(S^t_{it}, \delta_{mi})}{\partial S^t_{it}} \right) \geq R, \quad \forall S \text{ with } S^t_{it} \geq M, \quad \forall i, t \quad (70)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial WC_{it}(I^t_{it}, \delta_{mi})}{\partial I^t_{it}} \right) \geq R, \quad \forall I \text{ with } I^t_{it} \geq M, \quad \forall i, t \quad (71)
\]

\[
\frac{1}{(1 + r)^t} (-R^1_{ijot}(p^2_{ijot}, \delta_{co}) - \frac{\partial R^4_{ijot}(p^2_{ijot}, \delta_{co})}{\partial p^2_{ijot}} p^2_{ijot}) \geq R, \quad \forall p^2 \text{ with } p^2_{ijot} \geq M, \quad \forall i, j, o, t \quad (72)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial AC_{iot}(B_{tot}, \delta_{co})}{\partial B_{tot}} \right) \geq R, \quad \forall B \text{ with } B_{tot} \geq M, \quad \forall i, o, t \quad (73)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial HC_{jt}(Y^t_{jt}, \delta_{rj})}{\partial Y^t_{jt}} \right) \geq R, \quad \forall Y \text{ with } Y^t_{jt} \geq M, \quad \forall j, t \quad (74)
\]

\[
\frac{1}{(1 + r)^t} \left( \frac{\partial IC_{jt}(Z^t_{jt}, \delta_{rj})}{\partial Z^t_{jt}} \right) \geq R, \quad \forall Z \text{ with } Z^t_{jt} \geq M, \quad \forall j, t \quad (75)
\]

Then variational inequality (59) as well as (24) admit at least one solution.
Proof. Follows from Lemma 1. See also the proof of existence for Proposition 1 in Nagurney and Zhao (1993) and Nagurney et al. (2003).

The existence of a solution to this optimisation problem can be verified with Theorem 2 described above (Meng et al. (2007)). Besides that, Geiger and Kanzow (1996) demonstrated that any stationary point of the unconstrained minimisation problem is its global minimum under the conditions where $F(X)$ is monotone and continuously differentiable.

Computational Procedure

An algorithm is presented which can be applied to solve the variational inequality problem (59). The algorithm which is proposed is the modified projection method of Korpelevich (1976).

The Modified Projection Method

Step 0: Initialization

Start with $X^0 \in \mathcal{K}$, as a feasible initial point, and let $\tau = 1$. Set $\omega$ such that $0 < \omega < \frac{1}{L}$, where $L$ is the Lipschitz constant for function $F(X)$.

Step 1: Computation

Compute $\bar{X}^{\tau}$ by solving the variational inequality subproblem:

$$\langle \bar{X}^{\tau} + \omega F(X^{\tau-1}) - X^{\tau-1}, X - \bar{X}^{\tau} \rangle \geq 0, \quad \forall X \in \mathcal{K}. \quad (77)$$

Step 2: Adaptation

Compute $X^{\tau}$ by solving the variational inequality subproblem:

$$\langle X^{\tau} + \omega F(\bar{X}^{\tau}) - X^{\tau-1}, X - X^{\tau} \rangle \geq 0, \quad \forall X \in \mathcal{K}. \quad (78)$$

Step 3: Convergence Verification

If $\max |X^{\tau} - X^{\tau-1}| \leq \varepsilon$ with $\varepsilon > 0$, a pre-specified tolerance, then stop; else, set $\tau = \tau + 1$, and go to Step 1. (We set the parameter $\omega = 0.02$ and the tolerance $\varepsilon = 0.00001$ for all computations of the numerical examples in Section 4).

Theorem 3: Convergence

If $F(X)$ is monotone and Lipschitz continuous, and a solution to the VI exists, then the modified projection method is guaranteed to converge to a $X^*$ satisfying the VI.
# Table A1: Equilibrium Results for Example 2

<table>
<thead>
<tr>
<th>Entity</th>
<th>Variables</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$t = 1$</td>
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<tr>
<td>$S^*$</td>
<td>$S_{1t}^*$</td>
<td>76.81</td>
</tr>
<tr>
<td></td>
<td>$S_{2t}^*$</td>
<td>75.60</td>
</tr>
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</tr>
<tr>
<td></td>
<td>$I_{2t}^*$</td>
<td>3.44</td>
</tr>
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</table>

**Manufacturers**

| $p_{ijt}^1$ | $i = 1, j = 1$ | 9.38 | 9.66 | 9.95 | 10.25 | 10.56 | 10.87 | 11.20 | 11.54 | 11.88 | 12.24 |
| $i = 1, j = 2$ | 9.82 | 10.11 | 10.41 | 10.73 | 11.05 | 11.38 | 11.72 | 12.07 | 12.43 | 12.81 |
| $q_{ijt}^1$ | $i = 1, j = 1, 2$ | 36.22 | 36.48 | 36.75 | 37.04 | 37.34 | 37.64 | 37.96 | 38.28 | 38.61 | 38.94 |
| $i = 2, j = 1, 2$ | 36.08 | 36.34 | 36.61 | 36.89 | 37.18 | 37.48 | 37.79 | 38.11 | 38.43 | 38.76 |
| $\delta_m^*$ | $\delta_{m1}^* = 1, \delta_{m2}^* = 1$ | 93.31 | 96.94 | 96.96 | 79.10 | 82.23 | 79.98 | 60.93 | 56.49 | 59.48 | 43.52 |

**Carriers**

| $q_{i jot}^3$ | $i = 1, j = 1, 2, o = 1, 2$ | 17.16 | 17.50 | 17.85 | 18.20 | 18.56 | 18.92 | 19.28 | 19.66 | 20.05 | 20.44 |
| $i = 2, j = 1, 2, o = 1, 2$ | 17.08 | 17.43 | 17.78 | 18.13 | 18.48 | 18.84 | 19.20 | 19.58 | 19.96 | 20.36 |
| $R_{i jot}^2$ | $i = 1, j = 1, 2, o = 1, 2$ | 18.11 | 18.24 | 18.38 | 18.52 | 18.67 | 18.82 | 18.98 | 19.14 | 19.30 | 19.47 |
| $i = 2, j = 1, 2, o = 1, 2$ | 18.04 | 18.17 | 18.31 | 18.45 | 18.59 | 18.74 | 18.90 | 19.06 | 19.22 | 19.38 |
| $P_{i jot}^3$ | $i = 1, j = 1, 2, o = 1, 2$ | 4.89 | 4.76 | 4.62 | 4.48 | 4.33 | 4.18 | 4.02 | 3.86 | 3.70 | 3.53 |
| $i = 2, j = 1, 2, o = 1, 2$ | 4.96 | 4.83 | 4.69 | 4.55 | 4.41 | 4.26 | 4.10 | 3.94 | 3.78 | 3.62 |
| $B_{i ot}^*$ | $i = 1, o = 1, 2$ | 1.91 | 3.38 | 4.43 | 5.06 | 5.28 | 5.09 | 4.47 | 3.43 | 1.95 | 0.00 |
| $i = 2, o = 1, 2$ | 1.91 | 3.39 | 4.44 | 5.08 | 5.30 | 5.11 | 4.49 | 3.45 | 1.95 | 0.00 |
| $\delta_c^*$ | $\delta_{c1}^* = 1, \delta_{c2}^* = 1$ | 93.31 | 96.94 | 96.96 | 79.10 | 82.23 | 79.98 | 60.93 | 56.49 | 59.48 | 43.52 |

**Retailers**

| $Y^*$ | $Y_{1t}^*$ | 38.72 | 51.49 | 51.62 | 51.85 | 51.94 | 51.95 | 51.96 | 51.97 | 51.98 | 51.99 |
| $Y_{2t}^*$ | 38.73 | 51.50 | 51.73 | 51.86 | 51.95 | 51.96 | 51.97 | 51.98 | 51.99 | 51.99 | 51.99 |
| $q^{3*}$ | $q_{11t}^3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $q_{12t}^3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $q_{22t}^3$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Z^*$ | $Z_{1t}^*$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $Z_{2t}^*$ | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| $p^{3*}$ | $p_{1t}^3$ | 60.83 | 62.68 | 64.91 | 67.17 | 68.49 | 70.62 | 72.85 | 75.08 | 77.31 | 79.54 |
| $p_{2t}^3$ | 60.83 | 62.68 | 64.91 | 67.17 | 68.49 | 70.62 | 72.85 | 75.08 | 77.31 | 79.54 | 79.54 |

Continued
Table A1

<table>
<thead>
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<th>Variables</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Markets</td>
<td>$D^*_1j, j = 1, 2$</td>
<td>51.49 41.87 23.27 6.49 15.23 14.66 14.75 14.23 13.39 13.29</td>
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<tr>
<td></td>
<td>$D^*_2j, j = 1, 2$</td>
<td>38.65 58.24 73.69 71.47 68.15 65.32 46.18 27.86 60.48 30.23</td>
</tr>
<tr>
<td>$p^*_1$</td>
<td>$p^*_1k_1, k = 1, 2$</td>
<td>61.93 63.76 65.26 65.02 66.93 68.34 68.13 69.42 71.52 71.77</td>
</tr>
<tr>
<td>$p^*_2$</td>
<td>$p^*_2k_1, k = 1, 2$</td>
<td>61.83 63.68 65.20 64.99 66.92 68.36 68.17 69.49 71.62 71.90</td>
</tr>
</tbody>
</table>