Carbon Footprint and the Management of Supply Chains

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Research team

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Funding

- NSF: Optimizing the supply chain for carbon footprint (with Mark Daskin)
- USDOT/MnDOT: Low carbon logistics
- Hong Kong RGC: Addressing Carbon Emissions through Operational Excellence and Supply Chain Coordination (with Yanzhi Li)
Related papers

- Chen et al., “Stochastic Inventory Management with Carbon Constraints”
- Hua, Z, Zhang, W. and S. Benjaafar, “Cost versus Carbon Footprint in Supplier Selection”
Background

- Growing consensus that carbon emissions is a leading cause of **global warming**
- Growing pressure to enact **legislation** to curb the amount of these emissions
- Increased consumer awareness and demand for **low carbon footprint products**
- Growing number of **voluntary industry initiatives** (carbon labeling, climate exchanges, voluntary emission reporting, energy efficiency certification, etc)
A focus on physical processes

Improve energy efficiency of **physical processes and facilities** and/or reduce carbon emissions through investment in **new technology**

- energy efficient facilities
- fuel efficient vehicles
- alternative fuels and renewable sources of energies – wind, solar, bio-fuels
- carbon offsetting projects
A focus on physical processes overlooks causes of carbon emissions rooted in business processes and operational practices
Transportation-related emissions are driven by **business decisions** as much as they are (if not more) by the **fuel efficiency of vehicles** used.
The lean bandwagon

- Reduce inventory, shipment sizes, production batches
- Implement **frequent deliveries** with little or no advance notice in a **just-in-time** mode
- Use **rapid-response logistics** (trucking, air freight, courier)
- **Outsource** everything you can
- Source from the **lowest-cost supplier**
- Increase **product variety** and **mass customize**
- Centralize warehousing
A focus on individual firms

- A focus on individual firms ignores important factors that emerge from the interaction among the multiple firms that constitute each supply chain.
- Emissions by one firm are often driven by business decisions made by other firms.
- Firm-level initiatives do not recognize the potential of supply chain-wide emission reductions from collaboration among firms within the same supply chain.
Carbon emissions and OR/MS

- Little or no existing literature
- The OR/MS community has been largely absent from the discussion on carbon emissions
- A growing literature on sustainable operations (Lifecycle analysis, closed-loop supply chains, ISO standards, environmental compliance and certification)
- Extensive (and growing) literature in industrial ecology, environmental economics, and public policy
A need for “Operations” models that incorporate carbon emission concerns

- To understand how accounting for carbon emissions (either as a constraint or as a decision criterion) might affect operational decisions
- To inform operations managers on how government policies (e.g., mandatory emission caps, taxes on carbon emissions, and emission cap-and-trade) might affect operational decision-making
- To study how the scope of emission carbon responsibilities and how these responsibilities are allocated among members of the same supply chain could affect the costs and emissions of various firms
Our research agenda

- Show how carbon emission concerns could be integrated into operational decision-making
- Investigate the extent to which concerns about carbon emissions can be addressed by adjusting operational decisions
- Study the impact of different government policies on operational decisions and on overall carbon emissions in the supply chain
- Investigate the impact of incorporating carbon emissions on the structure of optimal operational decisions
Examples of operational models

- Lot sizing and economic order quantity models
- Stochastic inventory models
- Facility location models
- Supplier selection models
- Congestion models with capacity selection
Policy instruments for limiting carbon emissions

- **Quantity-based**: strict emission caps (time-based versus output-based)
- **Price-based**: carbon tax, cap-and-trade
- **Hybrid instruments**: cap-and-offset; cap-and-price (systems with safety valve)
- **Other instruments**: subsidies

...also, **market incentives**: carbon-dependent market share or pricing
The lot sizing problem

Minimize operational cost

- fixed and variable purchasing/production costs
- inventory holding costs
- shortage costs

subject to constraints on carbon emissions
Problem parameters

d_t : demand in period t,  \( t = 1, \ldots, T \)
h_t : unit inventory holding cost in period t
F_t : fixed ordering cost in period t
c_t : variable ordering cost in period t
b_t : unit backordering cost in period t
\hat{h}_t : carbon emission per unit of inventory held in period t
\hat{F}_t : carbon emissions per order placed/produced in period t
\hat{c}_t : carbon emissions per unit ordered/produced in period t
C : cap on emissions over the planning horizon
Decisions

$q_t$ : order quantity placed/produced in period $t$

$y_t = 1$ if an order is placed/produced in period $t$; 0 otherwise

$I_t$ : inventory carried from period $t$ to period $t+1$

$B_t$ : amount of backorder carried from period $t$ to $t+1$
A single firm with strict emission caps

Minimize \[ \sum_{t=1}^{T} (F_t y_t + c_t q_t + h_t I_t + b_t B_t) \]

subject to

\[ I_{t-1} - B_{t-1} + q_t - d_t = I_t - B_t, \quad \forall t \]

\[ \sum_{t=1}^{T} \hat{F}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t \leq C, \]

\[ q_t \leq \left( \sum_{t'=1}^{T} d_{t'} \right) y_t, \quad \forall t \]

\[ I_t, B_t, q_t \geq 0, \quad \forall t \]

\[ y_t \in \{0, 1\}, \quad \forall t \]
A single firm with strict emission caps

Minimize \[ \sum_{t=1}^{T} (F_t y_t + c_t q_t + h_t I_t + b_t B_t) \]

subject to

Operational cost
\[ I_{t-1} - B_{t-1} + q_t - d_t = I_t - B_t, \quad \forall t \]

Emission constraint
\[ \sum_{t=1}^{T} \hat{F}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t \leq C, \]
\[ q_t \leq \left( \sum_{t'=1}^{T} d_{t'} \right) y_t, \quad \forall t \]
\[ I_t, B_t, q_t \geq 0, \quad \forall t \]
\[ y_t \in \{0,1\}, \quad \forall t \]
Carbon capacity versus production capacity

- Carbon capacity (caps on emissions) may cover multiple periods or even the entire planning horizon.

- Carbon capacity consumed in one period affects the available carbon capacity in future periods.

- Carbon capacity is consumed not only by production, but also by order processing, transportation, and inventory holding.

- Carbon capacity is consumed even if no production or procurement activity is taking place.
Similar formulations for systems with …

- carbon tax, cap-and-offset, cap-and-trade, etc
- systems with choice of technology and subsidies
- systems with carbon-dependent demand/pricing
The case of multiple firms

- One firm faces **end-demand**; other firms fulfill orders from upstream firms.

- Orders generated by an upstream firm becomes **demand for one or more of the downstream firms**.

- Firms could generate orders **independently** of each other or could **collaborate**.

- Firms could assume responsibility for their **carbon emissions independently** or could share the responsibility.
The case of multiple firms

**Firm 1:**

Minimize \[ \sum_{t=1}^{T} (F_{1,t} y_{1,t} + c_{1,t} q_{1,t} + h_{1,t} I_{1,t} + b_{1,t} B_{1,t}) \]

subject to

\[ I_{1,t-1} - B_{1,t-1} + q_{1,t} - d_{1,t} = I_{1,t} - B_{1,t}, \forall t \]

\[ \sum_{t=1}^{T} \hat{F}_{1,t} y_{1,t} + \hat{h}_{1,t} I_{1,t} + \hat{c}_{1,t} q_{1,t} \leq C_{1}, \]

\[ q_{1,t} \leq \left( \sum_{t'=1}^{T} d_{1,t'} \right) y_{1,t}, \forall t \]

\[ I_{1,t}, B_{1,t}, q_{1,t} \geq 0, \forall t \]

\[ y_{1,t} \in \{0,1\}, \forall t \]
The case of multiple firms

Firm 2:

Minimize \[ \sum_{t=1}^{T} (F_{2,t} y_{2,t} + c_{2,t} q_{2,t} + h_{2,t} I_{2,t}) \]
subject to

\[ I_{2,t-1} + q_{2,t} - q^{*}_{1,t} = I_{2,t}, \quad \forall t \]

\[ \sum_{t=1}^{T} \hat{F}_{2,t} y_{2,t} + \hat{h}_{2,t} I_{2,t} + \hat{c}_{2,t} q_{2,t} \leq C_{2}, \]

\[ q_{2,t} \leq \left( \sum_{t'=t}^{T} q^{*}_{1,t'} \right) y_{2,t}, \quad \forall t \]

\[ I_{2,t}, q_{2,t} \geq 0, \quad \forall t \]

\[ y_{2,t} \in \{0,1\}, \quad \forall t \]
Multiple firms with cooperation

Minimize

\[
\sum_{i=1}^{2} \sum_{t=1}^{T} (F_{i,t} y_{i,t} + c_{i,t} q_{i,t} + h_{i,t} I_{i,t})
\]

subject to

\[
I_{1,t-1} - B_{1,t-1} + q_{1,t} - d_{1,t} = I_{1,t} - B_{1,t}, \quad \forall t
\]

\[
I_{2,t-1} + q_{2,t} - q_{1,t} = I_{2,t}, \quad \forall t
\]

\[
\sum_{t=1}^{T} \hat{F}_{i,t} y_{i,t} + \hat{h}_{i,t} I_{i,t} + \hat{c}_{i,t} q_{i,t} \leq C_{i}, \quad i = 1, 2
\]

\[
q_{1,t} \leq \left( \sum_{t'=t}^{T} d_{1,t'} \right) y_{1,t}, \quad q_{2,t} \leq \left( \sum_{t'=t}^{T} q_{1,t'} \right) y_{2,t}, \quad \forall t
\]

\[
I_{2,t}, B_{2,t}, q_{2,t} \geq 0, \quad y_{2,t} \in \{0, 1\}, \quad \forall t
\]
... with cooperation and a shared emission cap

Minimize \( \sum_{i=1}^{2} \sum_{t=1}^{T} (F_{i,t} y_{i,t} + c_{i,t} q_{i,t} + h_{i,t} I_{i,t}) \)

subject to

\[
I_{1,t-1} - B_{1,t-1} + q_{1,t} - d_{1,t} = I_{1,t} - B_{1,t}, \quad \forall t
\]

\[
I_{2,t-1} + q_{2,t} - q_{1,t} = I_{2,t}, \quad \forall t
\]

\[
\sum_{i=1}^{2} \sum_{t=1}^{T} \hat{F}_{i,t} y_{i,t} + \hat{h}_{i,t} I_{i,t} + \hat{c}_{i,t} q_{i,t} \leq C_{1} + C_{2},
\]

\[
q_{1,t} \leq \left( \sum_{t' = t}^{T} d_{1,t'} \right) y_{1,t}, \quad q_{2,t} \leq \left( \sum_{t' = t}^{T} q_{1,t'} \right) y_{2,t}, \quad \forall t
\]

\[
I_{2,t}, B_{2,t}, q_{2,t} \geq 0, \quad y_{2,t} \in \{0,1\}, \quad \forall t
\]
Data requirements

- **Scope 1** and **scope 2** emissions
- Emissions directly affected by operational decisions
- Data from **life-cycle assessment** (LCA) studies
- Data from **economic Input-output** (EIO) analysis
- **Industry reported** data (e.g., CDP data)
- Data for **standard processes** (e.g., EPA data)
Insights from the models
Observation 1: *It is possible to significantly reduce emissions without significantly increasing cost.*
This is possible when...

- decisions that minimize cost are different from those that minimize emission

- drivers of cost are different from drivers of emissions:

\[
\frac{F_t}{h_t} \neq \frac{\hat{F}_t}{\hat{h}_t}
\]

- the region around the cost-optimal solution is relatively flat
The graph illustrates the relationship between order quantity and cost/emission. The x-axis represents the order quantity, while the y-axis shows cost and emission. The graph shows a downward trend for cost as order quantity increases, and an upward trend for emission. There are vertical dashed lines indicating specific order quantities where the cost and emission curves intersect.
What happens otherwise?

- Affecting the emission parameters (e.g., investing in new technology)
- Investing in carbon-offsets, engaging in carbon trading
- Curtailing demand and/or moving production to less regulated countries (carbon leakage)
Similar insights apply to ...

- stochastic inventory models
- facility location models
- congestion models with capacity selection
What happens under alternative policies?

- **Carbon tax:**
  
  Minimize \( \sum_{t=1}^{T} (F_t + \alpha \hat{F}_t)y_t + (c_t + \alpha \hat{c}_t)q_t + (h_t + \alpha \hat{h}_t)I_t + b_tB_t \)

- **Cap-and-trade (price):**
  
  Minimize \( \sum_{t=1}^{T} (F_t + p\hat{F}_t)y_t + (c_t + p\hat{c}_t)q_t + (h_t + p\hat{h}_t)I_t + b_tB_t - pC \)

- **Cap-and-offset:**
  
  Minimize \( \sum_{t=1}^{T} F_t y_t + c_t q_t + h_t I_t + p \left( \sum_{t=1}^{T} (f_t y_t + \hat{h}_t I_t + \hat{c}_t q_t) - C \right)^+ \)
Observation 2: *Without an operational model, it is difficult to assess whether or not investing in more carbon-efficient technologies is justified*
Observation 3: *The benefit from more energy-efficient technology is affected by the type of emission control policy.*
Observation 4: *The presence of carbon constraints increases the value of supply chain collaboration*
Observation 5: Collaboration can lead to increases in the cost and carbon emissions of some of the firms.
Collaboration affects operational responsibility across the supply chain

\[ \hat{h}_1 = 1 - \gamma, \ h_2 = 1 + \gamma \]
Observation 6: A supply chain-wide emission cap leads to lower emissions at lower costs; it also increases the value of collaboration.
Observation 7: The benefit derived from collaboration can be significantly affected by the type of regulatory policy that is in effect.
Observation 8: **Collaboration, if it does not involve all members of the supply chain, can increase the cost and emissions of those firms left out**

A three-firm supply chain: firm3 → firm 2 → firm1
More in the papers...

- There are more insights and theory
- More models with carbon footprint considerations
  - problems with more complex structures (multiple stages, multiple products, multiple suppliers)
  - Other types of models (multi-period stochastic inventory models, facility location models, and congestion models)
  - Other features (supplier selection, coalition formation, carbon-dependent demand, carbon market dynamics)
- Empirical work on carbon footprint measurement and carbon footprint parameter estimation
Conclusion

- Strong connection between carbon footprint and operational decisions
- Carbon footprint concerns can be incorporated in most existing operational models
- The OM (and more broadly OR/MS) community can offer decision support tools and insights to both managers and policy makers that no one else can
- Exciting new research opportunities and opportunities to make a difference
Lessons learned from the EU experience

- Reductions in carbon emissions in the covered sectors of approximately 5%
- Limited economic impact, with the imposed caps estimated to cost less than 1% of total GDP by 2020
- Firms in nearly all sectors covered by emission caps have been able to profit from the introduction of a cap-and-trade system
  - Sale of emission allowances, undertaking cost-efficient emission reduction measures, passing the cost of carbon to consumers
- Despite generous emission caps, firms in many sectors have found simple and cheap ways to significantly reduce their energy consumption
Questions, comments, ideas?
Some future research directions

- Extensions to other operational decisions and other models of operations
- Supply chain carbon footprint measurement (scope, boundaries, allocation), reporting, and auditing
- Modeling cooperation when carbon footprint responsibility is shared
- Modeling competition among firms, when market share is affected by carbon footprint
- Integrated operations and carbon management (carbon trading, managing investments in offsets, hedging against carbon price volatility)
- Empirical research (e.g., impact of environmental regulation on firm behavior; impact of standards; impact of allocation schemes)