LOW CARBON LOGISTICS THROUGH SUPPLY CHAIN DESIGN AND COORDINATION

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16. Abstract

In this project, we propose to address carbon emissions in logistics through supply chain design, planning and coordination. We argue that (1) supply chain design, planning, and coordination can help reduce carbon emissions significantly, (2) supply chain-wide collaboration can lead to lower emissions at lower cost for the entire supply chain, and (3) imposing supply chain-wide emissions limits can make emissions reductions more economical for the entire supply chain by recognizing the differential capabilities of firms in meeting emission standards and by allowing internal carbon offsetting to take place between firms within the same supply chain.

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Low Carbon Logistics: An Executive Summary

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The results from this project are described in the following two reports:

- Benjaafar, S., Y. Li and M. Daskin, "Carbon Footprint and the Management of Supply Chains: Insights from Simple Models," CFIRE-CTS Technical Report, University of Minnesota, 2010.
- Qi, L., S. Benjaafar, and S. Kennedy, "The Carbon Footprint of UHT Milk," CFIRE-CTS Technical Report, University of Minnesota, 2010.

Below, we provide an executive summary of each.

In the first report, we show how carbon emission concerns could be integrated into operational decision-making with regard to procurement, transportation, production, and inventory management. We show how, by associating carbon emission parameters with various decision variables, traditional planning and logistics models can be modified to support decision-making that accounts for both cost and carbon footprint. We examine how the values of these parameters as well as the parameters of regulatory emission control policies affect cost and emissions. We use the models to study the extent to which carbon reduction requirements can be addressed by operational adjustments, as an alternative (or a supplement) to costly investments in carbon-reducing technologies. We also use the models to investigate the impact of collaboration among firms within the same supply chain on their costs and carbon emissions and study the incentives firms might have in seeking such cooperation. We provide a series of insights that highlight the impact of operational decisions and supply chain collaboration on carbon emissions.. In particular, we show that (1) it is possible, through operational adjustments alone, to significantly reduce emissions without significantly increasing cost; (2) different regulatory policies can achieve the same reduction in emission levels; however, the corresponding costs to the firms can be different; (3) the cost of reducing emissions can be substantially lower if firms within the same supply chain collaborate; and (4) although collaboration always leads to lower supply chain costs, it can increase, depending on the regulatory policy, supply chain emissions; it can also lead to a shift in operational responsibilities within the supply chain.

In the second report, we analyze the carbon footprint of UHT milk. UHT refers to the partial sterilization of milk using Ultra-High Temperature processing. UHT milk can be stored unrefrigerated because of the longer lasting sterilization effect of high temperature processing and has a typical shelf life of more than three months. Because UHT milk does not require refrigeration after processing and because it has a longer shelf life than milk that does not undergo UHT processing, it has been argued that it could significantly reduce the carbon footprint of fluid milk. Surprisingly, our analysis shows, that UHT milk has in fact a higher carbon footprint than milk that requires refrigeration in the US and only a marginally lower carbon footprint in the UK. In particular, our analysis shows that the emission reduction potential for UHT is significantly affected by packaging material. UHT is packaged in Aseptic cartons are that typically a mix of paper, polyethylene (LDPE), and aluminum, with a tight polyethylene inside layer. The mixture of materials makes the cartons costly to recycle, so most are land filled post-consumer usage, contributing to the relatively large footprint of UHT packaging.

However, our analysis does also highlight opportunities for improving the carbon footprint of UHT milk. Developing methods for cheap aseptic carton recycling is one way to make UHT milk more environmentally competitive. Introducing larger size packaging for UHT milk could further improve the carbon competitiveness of UHT milk. A shift to UHT milk could reduce the frequency of trips consumers make to buy milk, the refrigeration requirements at home, and the percentage of wasted milk due to spoilage in the home. Over the long term, a shift in the US to UHT milk could lead to a reorganization of the dairy supply chain with regard to how milk is collected, processed, and distributed. For example, regional fluctuations in milk supply due to seasonal effects could be mitigated by keeping milk in stock when supply is high, reducing or even eliminating the need for long distance shipment of fresh milk. In developing countries where refrigerated transport and storage is limited or expensive, UHT milk provides an opportunity to increase access to and affordability of fluid milk to larger segments of the population.

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The Carbon Footprint of UHT Milk

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Abstract

In this paper, we analyze the carbon footprint of UHT milk. UHT refers to the partial sterilization of milk using Ultra-High Temperature processing. UHT milk can be stored unrefrigerated because of the longer lasting sterilization effect of high temperature processing and has a typical shelf life of more than three months. Because, UHT milk does not require refrigeration after processing and because it has a longer shelf life than milk that does not undergo UHT processing, it has been argued that it could significantly reduce the carbon footprint of fluid milk. Perhaps surprisingly, our analysis shows, that UHT milk has in fact a higher carbon footprint than milk that requires refrigeration in the US and only a marginally lower carbon footprint in the UK. We identify causes for this higher carbon footprint and discuss opportunities for increasing the carbon efficiency of UHT milk.

Keywords: Carbon footprint, UHT milk, supply chain modeling, lifecycle analysis

1. Introduction

A major factor impacting global warming is the increase in the levels of green house gases (GHG) in the atmosphere. GHG refer to gases that absorb and reemit thermal radiation in the Earth's atmosphere. While there remains some debate about the extent to which the increased GHG levels are the result of man-made actions (e.g., the burning of fossil fuels) as opposed to natural causes, what is increasingly accepted is that human factors play a part in this increase. Since little can be done, if anything, about any increase in GHG due to natural causes, the focus must be on sources of GHG emissions that can be controlled.

With this in mind, many industries, on their own in some cases and with significant public and governmental prodding in other instances, have become increasingly sensitive to the impact that their operations are having on the environment in general and global warming and GHG emissions in particular. Many firms are voluntarily reducing their emissions while others are acting in response to increased governmental regulation or because of pressures from their own consumers. Both firms and consumers are also increasingly looking for alternative products and materials with lower GHG footprints. Green house gases include carbon dioxide, methane, and nitrous oxide, among others. However, because carbon dioxide is the most prevalent of these green house gases, GHG emissions are often referred to as carbon emissions and all emissions are usually measures in CO_2 equivalent units.

Positioning a product as having lower emissions requires documenting the entire supply chain of the product and in some cases its entire lifecycle, from raw material production to consumer usage and end of life disposal and reuse. This has given rise to the notion of a product's carbon footprint, an aggregate measure of all emissions associated with the production, packaging, distribution, and retail of the product. Manufacturers and large retailers have gone as far as labeling their products with the corresponding carbon footprint; see for example the recent initiatives by Tesco in the UK and Wal-Mart in the US (Leahy 2007; Schwartz 2009).

Dairy products represent a major part of agricultural products in the United States, generating a total revenue for the industry of over $46 billion in 2007 (IBIS 2007) with over 9 million cows producing over 180 billion pounds of milk per year (USDA 2007a, 2008). There are more than 1,000 milk processing plants, manufacturing 57 billion pounds of fluid milk annually with an estimated economic impact of approximately $20 billion (IDFA 2007).

Milk produced on the farm is typically pasteurized to kill microorganisms that accelerate spoilage. Pasteurization improves milk safety and extends its shelf life. Refrigerated milk sold in stores is normally pasteurized using *high-temperature short-time* (HTST) processing, also known as flash pasteurization). HTST processing maintains the original color and flavor of milk better than other pasteurization processes. However, HTST milk is perishable with a relatively short shelf life of approximately 2 weeks and must be kept refrigerated throughout its entire lifecycle (from raw production to final consumption). Most of the milk processed, sold, and consumed in the US is HTST-processed; see Table 1.

An alternative to HTST processing is ultra-high temperature (UHT) processing. UHT processing refers to the partial sterilization of food by heating it for a short time, around 1–2 seconds, at a temperature exceeding 135°C , which is the temperature required to kill spores in milk. UHT milk can be stored unrefrigerated because of the longer lasting sterilization effect, and has a typical shelf life of more than three months. As shown in Table 1, the market share of UHT milk varies dramatically worldwide. Although there is no difference in the nutritious qualities of UHT and HTST milk (USDA 2009), UHT milk has historically faced resistance from consumers in Northern Europe and the United States, where consumers have been uneasy about drinking non-refrigerated milk and to flavor differences between the two milks.

Because UHT milk does not require refrigeration after processing and because it has a longer shelf life, it has been argued that it has a lower environmental impact in terms of carbon emissions. Particularly, the carbon footprint of fluid milk (the carbon emissions associated with milk production, processing, distribution, retail, consumption, and end of life disposal) could be significantly reduced by increasing the percentage of UHT milk produced and sold in the US. This point of view has been advocated in other countries as well. For example, the United Kingdom (UK) has set an objective of increasing the percentage of UHT milk produced in the UK to 90% of all milk production by 2020 in an effort to mitigate carbon emissions associated with dairy products (Elliott 2007).

This point of view is however not without controversy since UHT is also associated with higher energy consumption at the processing stage (a study, as early as 1979, compared the energy consumption in the processing of UHT milk with HTST milk and estimated a net increase of 800-1000 kJ/kg milk for UHT processing, see (Anon 1979). UHT and HTST also have different packaging requirement which could affect their relative carbon footprints. The objective of this study is to provide more conclusive evidence regarding the carbon footprint of both UHT and HTST milk and to present insights into factors that could affect carbon-advantage of one type of milk relative to the other and identify opportunities for further carbon emission reductions. The importance of assessing the potential impact of increased production and consumption of UHT milk could be significant given that fluid milk is responsible for about 1% of total carbon emissions in the US, or about 28.8 million tons CO_2-equivalent of GHG; see (Thoma *et al.* 2009) and (McReynolds 2009). The results of our study may also serve as a template for similar studies involving UHT processes for fruit juices, cream, yogurt, wine, and soups, among others.

Table 1- UHT milk share of fluid milk market in selected countries (Elliott 2007; China Genetics 2006; Thoma *et al.* 2009)

Country	**Market Share**
Spain	95.70%
France	95.50%
Brazil	74%
Germany	66.10%
Italy	49.80%
China	38%
Austria	20.30%
UK	8.40%
US	<1%

2. The Carbon Footprint of HTST Milk

Both UHT and HTST milk have similar life cycles, as depicted in Figure 1, including phases of production, processing, packaging, distribution, retail, and consumption. The milk is first produced at farms by cows. The raw milk is collected and then transferred into temporary holding tanks at the farms. It is then transported to processing plants by tanker trucks. Almost all of the milk in the United States is pasteurized in the processing plants, with few exceptions involving milk destined for the production of raw milk cheeses or for sale raw in few states where it is allowed. The heat treatment used for pasteurization depends on the final products – normally lower temperatures are used for HTST milk and higher heat treatments are used for UHT milk. After homogenization and sometimes vitamin fortification, the processed milk is packaged in the processing plants. Thus, as shown in Figure 1, a subsystem of packaging material production is also associated with the processing plants. Most of the HTST milk is contained in plastic jugs. UHT milk and its packaging (mostly so called *aseptic* cartons) are sterilized separately and then combined and sealed in a sterilized environment. The packaged milk is shipped to retail stores where it becomes ready for sale. Finally, the fluid milk is purchased, stored in home, and consumed by customers. Because of the inevitable mismatch between supply and demand, a small fraction of milk shipped to the retailers is returned to the distributors where it is disposed.

To our knowledge, there are two studies that examined the full life cycle carbon footprint of HTST milk. The first is by a group of researchers from the University of Arkansas who reported recently their preliminary results regarding estimates of carbon emissions from different phases of the fluid milk life cycle in the US (Thoma *et al.* 2009). The second is by Tesco, a large retailer in the UK, who began recently placing labels indicating the carbon footprint of milk it sells under its own brand (Kanter 2009); see Figure 2.

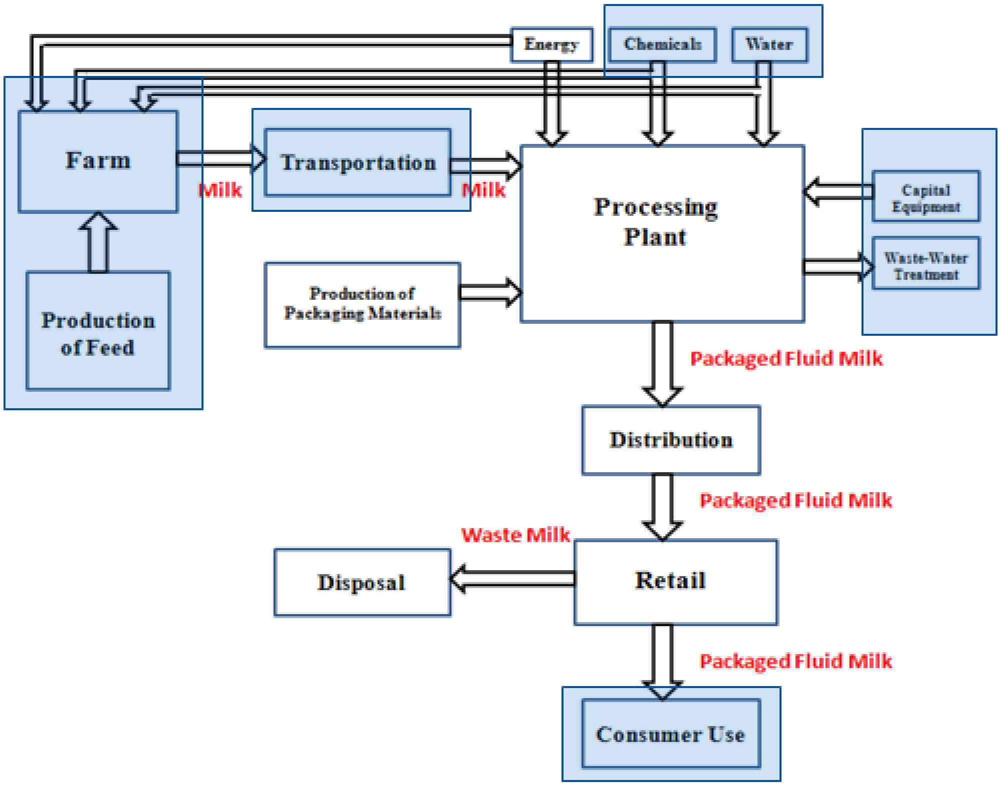

Figure 1 – A schematic of the full life cycle supply chain of fluid milk (shaded areas represent carbon emissions that are identical for both HTST and UHT milk)

Figure 2 – A pint of milk for sale at a Tesco supermarket in London displaying carbon footprint labels (Kanter 2009).

According to Thoma *et al.* (2009), 76.7% of total carbon emissions of fluid milk in the US is emitted at the farm. This is mainly due to the methane emitted when the cow ruminates and the feed is broken down in the cow's first stomach and intestines (Association 2006). Other phases in the fluid milk supply chains, such as processing, distribution, packaging, retail, and consumer use, generate 6.8%, 4.6%, 1.5%, 3.3%, and 7.2%, respectively; see Table 2. Similar to the results reported in Thoma *et al.*, Tesco's carbon labels reveal that the production of milk accounts for over 70% of total carbon emissions; see Table 3. As farm production is responsible for more than half of the carbon footprint of milk, efforts have been made to reduce the associated carbon emissions, such as increasing the length of the grazing season (so as to reduce the carbon footprint of the cow's feed) and also improving other aspects of the cow's diet to reduce the amount of methane produced from rumination (Casey and Holden 2005; Murphy and Moorepark 2008).

Several comments regarding Table 2 and Table 3 are worth making here. The total carbon footprint of the pasteurized milk in the US (1291.8 gCO_2e/liter milk) is less than that in the UK (1408.4 g CO_2e/liter milk). If we take a look at each individual phase, it is obvious that the major difference comes from distribution and retail. We find that the percentage from processing and packaging in the US (12.2%) is more than that the UK (9.4%), while the opposite is true for distribution and retail (5.2% and 13.1%). This appears due to differences in package sizes in the US and the UK, as more than 65% of fluid milk in the US is packaged into one-gallon jugs while the majority of the milk in the UK is packed into one pint bottles (USDA 2007b). Larger size packaging results in more efficient transportation and storage, which perhaps explains the lower carbon emissions from transportation and retail in the US. The higher carbon emissions in processing and packaging in the US appears to be due to less efficient processing in the plants, since otherwise larger packaging would imply lower emissions. The carbon emission from consumer use in the UK (62.0 gCO_2e/liter milk) is much lower than that in US (92.7 gCO_2e/liter milk)) can also be explained by the smaller packaging size. In the remainder of the paper, we rely on the data in tables 1 and 2 in making emission comparisons between UHT and HTST milk.

Table 2 - Carbon emissions from the various phases in the fluid milk life cycle in the US (Thoma *et al.* 2009)

Phases in the life cycle	**Carbon emissions**		**Percentage of the total**
Production	990.9	g CO_2e/liter milk	76.7%
Processing	87.5	g CO_2e/liter milk	6.8%
Packaging	59.1	g CO_2e/liter milk	4.6%
Distribution	18.9	g CO_2e/liter milk	1.5%
Retail	42.6	g CO_2e/liter milk	3.3%
Consumer use	92.7	g CO_2e/liter milk	7.2%
Total	1291.8	g CO_2e/liter milk	100.0%

Table 3 - Carbon emissions from the various phases in the fluid milk life cycle in the UK (Park 2009)

Phases in the life cycle	**Carbon emissions**		**Percentage of the total**
Production	1029.5	g CO_2e/liter milk	73.1%
Processing and Packaging	132.4	g CO_2e/liter milk	9.4%
Distribution and Retail	184.5	g CO_2e/liter milk	13.1%
Consumer use	62.0	g CO_2e/liter milk	4.4%
Total	1408.4	g CO_2e/liter milk	100%

3. The Carbon Footprint of UHT Milk

In this section, we describe our methodology for estimating the carbon footprint of UHT milk. We first state the following assumptions.

- Carbon emissions prior to milk processing are the same for both UHT and HTST.
- In estimating carbon emissions at the processing stage, we account for only emissions due to energy consumption (this is reasonable since processing is energy intensive and nearly all emissions can be attributed to energy usage).
- Since UHT milk must be refrigerated once its packaging is opened, we assume the carbon footprints of UHT and HTST are the same in the consumption stage.

In the following subsections, we provide the details regarding how we calculated the carbon emissions at each stage of the UHT milk life cycle.

3.1 Milk processing

There has been several studies of energy consumption of UHT processed milk dating to at least the 1980s; see for example (Biziak *et al.* 1981; Chandarana *et al.* 1984). A comprehensive comparison between the energy requirements of UHT and HTST processing was reported in Chandarana *et al.* (1984) and we use the results of that study in our calculations. In particular, Chandarana *et al.* (1984) concluded that UHT processing consumes 522-616 kJ/kg milk while HTST consumes 217-228 kJ/kg milk, which means that UHT processing requires an additional 294-399 kJ/kg milk (or 303-411 kJ/liter milk) (Jones 2002).

Electricity, natural gas and other fuels (e.g., bunker C, light fuel oil and propane) are three major energy sources for fluid milk plants. Although the proportion of each source consumed is dependent on the locally available natural resources, electricity represents by far the largest percentage (40%-100%) of total energy usage for all plants (NDC Canada 2001; Hospido *et al.* 2003). Therefore, it is reasonable for us to base our carbon emission calculations as if electricity were the only energy source. The influence of other energy options on carbon footprint will be discussed in the Section 4.

The carbon emission per kWh (3600kJ) electric power is on average about 0.6 kg CO_2-equivalent in the US, i.e. 0.1688 gCO_2e/kJ (USEPA 2000). Thus, an additional 303-411 kJ/liter milk in energy consumption due to UHT processing corresponds to an extra carbon emission of 51.16-69.38 gCO_2e/liter milk.

3.2 Packaging

Regular pasteurized milk is contained in plastic bottles, mostly one-gallon in size in the US and one-pint in size in the UK. Aseptic packaging (typically cartons made of layers of paper, plastic and aluminum) is required for UHT milk to form a tight seal against microbiological organisms, contaminants, and degradation, eliminating the need for refrigeration. Most commonly used aseptic cartons are one liter in size (current technology of aseptic packaging prevents much larger sizes and places a hard constraint on UHT milk container sizes). According to a report published by TetraPak® (a major aseptic carton producer), a one-liter Tetra Brik has 113.4 grams of CO_2-equivalent, a quarter of the carbon footprint of a one quart PET plastic bottles (TetraPak 2008). Thus, the carbon emission associated with the aseptic packaging for UHT milk is 113.4 gCO_2e/liter milk.

From Table 2, we can observe that the reported carbon footprint of HTST milk packaging in the US is lower than that of one-liter aseptic carton. However, in the report from TetraPak, one quart PET plastic bottle emits almost three times more carbon than an aseptic carton. Are the results from Thoma *et al.* (2009) contradictory to those from TetraPak Canada (2008)? We believe that the reason for the disagreement between these numbers lies in the packaging size. As we mentioned earlier, over 65% of fluid milk is packaged into one-gallon plastic jugs in the US, which consumes less raw material than the one-quart bottles. As much of the carbon emission of the packaging comes from raw material, it is then clear that one-gallon plastic jug has a lower footprint than the one-quart bottle (Thoma *et al.* 2009).

3.3 Distribution

In contrast to HTST milk, UHT milk does not require refrigerated transportation. This of course is one of the main carbon advantages of UHT milk. Other than the fact that UHT milk does not have to be shipped in refrigerated trucks, we assume that the geographic distribution patterns are the same as those for HTST milk (i.e., the location of the plants and stores and the truck routes are identical for the two types of milk), so that the transportation distances associated with both types of milk are the same.

The differences in energy consumption between refrigerated and ambient road transport have recently been investigated by Tassou *et al.* (2009) and we use their results. They showed that CO_2 emissions of refrigerated food product transportation is about 20% higher than ambient food transportation, 90% of which is due to the extra fuel burned in transportation and 10% from refrigerant leakage. We also use the results from (David 2009) who concluded that the capacity utilization of trailer trucks can be 40% higher transporting UHT milk than transporting HTST milk, because aseptic cartons can be more compactly loaded in the truck. Thus, the overall carbon emissions associated with UHT are about 60% of those associated with HTST milk.

3.4 Retail

As no refrigeration is required for UHT milk, there are no CO_2 emissions due to the refrigerants and the electricity consumption of the refrigerators, which causes most of the emissions in retail for HTST milk (Thoma *et al.* 2009). Hence, we assume that carbon emissions associated with the retail of UHT milk is negligible.

3.5 Consumer use

We assume that consumer usage and behavior is the same for both UHT and HTST milk (i.e. the retail locations, the purchasing frequency and the amount of milk purchased each time). Note that similar to HTST milk, UHT milk must be kept refrigerated once the packaging is opened. There might be additional carbon emission savings with UHT milk if it leads to fewer trips to the store because of the possibility of buying milk in larger quantities. However, such savings are likely to be relatively modest.

3.6 Waste reduction

A certain percentage of all fluid milk stock initially shipped to retailers is returned to the supplier because the milk did not sell before its due date (e.g., interviews with several retailers in the Minneapolis/St Paul area reveal that this percentage is approximately 5% for this particular market; this is viewed consistent with numbers in most other US markets). Expired milk cannot be salvaged nor put to other uses and must go into the waste stream. With a shift to UHT milk, with a shelf life of several months, we expect the percentage of milk returned to the supplier to be significantly reduced or even eliminated (this is consistent with other food products with longer shelf lives). Reducing the percentage amount of returned milk reduces the overall carbon footprint for fluid milk by reducing the amount of milk that must be produced, processed, transported, and stocked in stores. In this study, we use the figure of 3% as a potential reduction in the overall carbon footprint of fluid that could be attributed to the reduction in the amount of milk that is wasted. A sensitivity analysis can be easily carried out to evaluate the impact of varying this percentage. We should note that waste reduction has been generally overlooked as a potentially significant carbon advantage of UHT milk.

3.7 Total Carbon Footprint

The results of the analysis in Sections 3.1-3.6 are summarized in Tables 4 and 5 and provide the total carbon footprint estimates for convenience UHT milk in both the US and the UK. As we can see, and perhaps surprisingly, the estimated total carbon footprint for UHT milk is higher than that of HTST milk in the US case. In particular, the overall carbon footprint of UHT milk is approximately 2% higher in the US and less than 1% lower in the UK. The higher carbon footprint for UHT milk is due to higher carbon emissions from processing and packaging, despite the lower emissions from distribution and retail.

Given that our conclusion runs counter to some common views regarding the carbon advantage of UHT milk, it is worthwhile to consider the carbon footprint of UHT milk under the most favorable set of assumptions. We refer to this as *the best case scenario UHT milk carbon footprint*. Note that no changes can be made to the carbon emissions of UHT milk prior to processing at the plant to favor it over HTST milk since both types of milk are undifferentiated up to that point. First, let us consider emissions associated with UHT milk processing at the plant. Emissions at this stage are due to primarily energy consumption, namely consumption of electricity, natural gas, and other fuels. Carbon emissions would be lowest for UHT milk if all energy consumed in processing is in the form of natural gas (NDC Canada 2001). In the US, natural gas emits about one-third of the CO_2 emitted by electricity (USEPA 2009). To further favor UHT milk, we assume that the lower value of the range of emissions during processing is applicable. Making both assumptions leads to a modified carbon emission in the processing stage in the amount of 104.6 g CO_2e/liter (= 87.5+51.16/3). Third, we make the extreme assumption that carbon emissions associated with distribution and retail are negligible and can be treated as zero. We do leave the emission figure for packaging unchanged since the estimates are provided by the packaging manufacturer.

Table 6 and 7 summarize the resulting modified carbon footprints in the US and UK, respectively. As we can see, even with the somewhat generous treatment of UHT milk, its estimate of carbon footprint in the US is still higher than that of HTST. However, the carbon footprint of UHT milk in the UK becomes 7% lower than of HTST milk. As mentioned earlier, the differences between the US and UK numbers are due to differences in the carbon emissions in distribution phase of HTST milk. This result indicates that the UHT milk may significantly reduce the carbon footprint when the packaging size is relatively small. UHT milk cannot benefit much from the carbon reduction from non-refrigerated distribution, resulting in either a higher total carbon emission or only a marginal benefit.

Table 4 – Estimated carbon footprint of UHT milk in the US

Phases in the life cycle	HTST Milk		UHT Milk	
Production	990.9	g CO_2e/liter milk	990.9	g CO_2e/liter milk
Processing	87.5	g CO_2e/liter milk	138.7-156.9*	g CO_2e/liter milk
Packaging	59.1	g CO_2e/liter milk	113.4	g CO_2e/liter milk
Distribution	18.9	g CO_2e/liter milk	11.3**	g CO_2e/liter milk
Retail	42.6	g CO_2e/liter milk	0	g CO_2e/liter milk
Consumer use[10]	92.7	g CO_2e/liter milk	92.7	g CO_2e/liter milk
Total	1291.8	g CO_2e/liter milk	1306.6-1324.2***	g CO_2e/liter milk

* 87.5+ 51.2-69.4=138.7-156.9 (see section 3.1)
** 18.9*60% = 11.3 (see section 3.3)
*** 1306.6=1347.0×0.97, 1324.2 = 1365.2×0.97 (see section 3.6)

Table 5 – Estimated carbon footprint of UHT milk in the UK

Phases in the life cycle	HTST Milk		UHT Milk	
Production	1029.5	g CO_2e/liter milk	1029.5	g CO_2e/liter milk
Processing	132.4	g CO_2e/liter milk	138.7-156.9*	g CO_2e/liter milk
Packaging			113.4	g CO_2e/liter milk
Distribution	141.9	g CO_2e/liter milk	85.1**	g CO_2e/liter milk
Retail	42.6	g CO_2e/liter milk	0.0	g CO_2e/liter milk
Consumer use	62.0	g CO_2e/liter milk	62.0	g CO_2e/liter milk
Total	1408.4	g CO_2e/liter milk	1385.8-1403.5***	g CO_2e/liter milk

* The US data were used.
** 141.9*60%≈85.1 (see section3.3)
*** 1385.8=1428.7×0.97, 1403.5=1446.9×0.97 (see section 3.6)

Table 6 – Best case carbon footprint scenario for UHT milk in the US

Phases in the life cycle	**HTST Milk**		**UHT Milk**	
Production	990.9	g CO_2e/liter milk	990.9	g CO_2e/liter milk
Processing	87.5	g CO_2e/liter milk	**104.6***	g CO_2e/liter milk
Packaging	59.1	g CO_2e/liter milk	113.4	g CO_2e/liter milk
Distribution	18.9	g CO_2e/liter milk	**0.0**	g CO_2e/liter milk
Retail	42.6	g CO_2e/liter milk	0.0	g CO_2e/liter milk
Consumer use[10]	92.7	g CO_2e/liter milk	92.7	g CO_2e/liter milk
Total	1291.8	g CO_2e/liter milk	1301.6	g CO_2e/liter milk

*87.5+51.16/3 = 104.6 (see section 3.1 and 3.7)

Table 7 – Best case carbon footprint scenario for UHT milk in the UK

Phases in the life cycle	**HTST Milk**		**UHT Milk**	
Production	1029.5	g CO_2e/liter milk	1029.5	g CO_2e/liter milk
Processing	132.4	g CO_2e/liter milk	**104.6**	g CO_2e/liter milk
Packaging			113.4	g CO_2e/liter milk
Distribution	141.9	g CO_2e/liter milk	**0.0**	g CO_2e/liter milk
Retail	42.6	g CO_2e/liter milk	0.0	g CO_2e/liter milk
Consumer use	62.0	g CO_2e/liter milk	62.0	g CO_2e/liter milk
Total	1408.4	g CO_2e/liter milk	1309.5	g CO_2e/liter milk

4. Discussion and Conclusion

To our knowledge, our paper provides the first comprehensive comparison of the carbon footprint of UHT and HTST milk and to provide evidence as to whether UHT milk presents an opportunity for reducing the carbon footprint of fluid milk. Our analysis shows that the emission reduction potential for UHT is significantly by packaging material and size. For big packaging size (e.g. one-gallon jug in the US), the carbon reduction in distribution and retail are not sufficient to overcome the increase in emissions due to processing and packaging. If the packaging size is one pint like the UK case, up to 7% reduction of carbon footprint may be achieved for UHT milk. This is compounded by the fact that most emissions associated with fluid milk occur at the farm and due to the methane produced by the cows. Reducing these emissions is likely to yield the greatest environmental benefit.

However, our analysis does highlight opportunities for improving the carbon footprint of UHT milk. Clearly reducing carbon emissions from packaging could have an impact on the relative advantage of UHT milk. Aseptic cartons are typically a mix of paper, polyethylene (LDPE), and aluminum, with a tight polyethylene inside layer. The mixture of materials makes the cartons costly to recycle, so most are land filled post consumer-usage, contributing to the relatively large footprint of UHT packaging. Thus, developing methods for cheap aseptic carton recycling would be one way to eventually make UHT milk more environmentally competitive. Mourad *et al.* investigated the influence of the recycling rate of aseptic cartons on the carbon footprint of UHT milk in 2008 (Mourad *et al.* 2008). They found that a 14% emission reduction could be accomplished by increasing the recycling rate from 2% to 22% (only cardboard recycling). Alternatively, carbon footprint could be reduced by developing packages made of recyclable materials instead of mixture-made cartons. For example, SABIC recently announced the development of a new high density polyethylene (HDPE) grade designed to meet the specific needs of milk products., including pasteurized, extended shelf life, and UHT milk (SABIC 2008). Introducing larger size packaging for UHT milk, particularly in the US where the typical packaging of HTST milk is the one gallon jug, could further improve the carbon competitiveness of UHT milk. As mentioned earlier, an additional carbon advantage for UHT milk is its impact on consumer usage. A shift to UHT milk could indeed reduce the frequency of trips consumers make to buy milk, the refrigeration requirements at home, and the percentage of wasted milk due to spoilage in the home. Over the long term, a shift in the US to UHT milk could lead to a reorganization of the dairy supply chain with regard to how milk is collected, processed, and distributed. For example, regional fluctuations in milk supply due to seasonal effects could be mitigated by keeping milk in stock when supply is high, reducing or even eliminating the need for long distance shipment of fresh milk. There are of course other, non-carbon related, potential benefits to UHT milk. In developing countries where refrigerated transport and storage is limited or expensive, UHT milk provides an opportunity to increase access to and affordability of fluid milk to larger segments of the population.

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Carbon Footprint and the Management of Supply Chains: Insights from Simple Models

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Abstract

Using relatively simple and widely used models, we illustrate how carbon emission concerns could be integrated into operational decision-making with regard to procurement, production, and inventory management. We show how, by associating carbon footprint parameters with various decision variables, traditional models can be modified to support decision-making that accounts for both cost and carbon footprint. We examine how the values of these parameters as well as the parameters of regulatory emission control policies affect cost and emissions. We use the models to study the extent to which carbon reduction requirements can be addressed by operational adjustments alone, as an alternative to costly investments in carbon-reducing technologies. We also use the models to investigate the impact of collaboration among firms within the same supply chain on their costs and carbon emissions and study the incentives firms might have in seeking such cooperation. We provide a series of insights that highlight the impact of operational decisions on carbon emissions and the importance of operational models in evaluating the impact of different regulatory policies and in assessing the benefits of investments in more carbon efficient technologies. In doing so, our objective is not to provide a comprehensive treatment of any single issue, but to highlight the types of issues that arise when carbon footprint considerations are incorporated in supply chain management. Our objective is also to highlight an emerging research area in operations that is potentially rich with new problems and with societal impact.

Keywords: supply chains, carbon emissions, carbon footprint, climate control, environmental policy, supply collaboration and coordination

1. Introduction

There is growing consensus that carbon emissions (emissions from carbon dioxide and other greenhouse gases) are a leading cause of global warming. Governments are under growing pressure to enact legislation to curb the amount of these emissions. Firms worldwide, responding to the threat of such legislation or to concerns raised by their own consumers, are undertaking initiatives to reduce their carbon footprint. However, these initiatives have focused for the most part on reducing direct emissions. For example, firms are replacing energy inefficient equipment and facilities, finding less polluting sources of energy, or instituting energy savings programs[1]. While there can be value in such efforts, they tend to ignore a potentially more significant source of emissions, one that is driven by business practices and operational policies.

For example, determining how frequently supply deliveries are made is likely to have a greater impact on carbon emissions than the energy efficiency of the vehicles used to make these deliveries. In fact, one could argue that many of the popular business practices, such as *just-in-time* manufacturing and *lean* production, which favor frequent deliveries with less than truck-load shipments, small production runs, and multiple regional warehouses, have more of an impact on the carbon footprint of a firm than the energy efficiency of individual units deployed in production or distribution. Similarly, decisions that firms make regarding where to locate facilities, from which suppliers to source, and what mode of transportation to use can significantly affect its carbon footprint.

Moreover, a focus on direct emissions ignores important factors that emerge from the interaction among the multiple firms that constitute each supply chain. Multiple actors taking actions based on their own self-interests, and without coordination with others, are not likely to make decisions that always minimize emissions for the entire supply chains. For example, if one firm requires shipments from its suppliers under short notice, then suppliers have little choice but to keep large inventories. For certain products, such as those requiring refrigeration, the associated carbon footprint can be significant. The need to respond quickly to suppliers may also require staging inventories in multiple locations that are close to the customers, further increasing the carbon footprint. The lack of coordination among multiple firms within the supply chain can also increase the overall carbon footprint. For example, coordinating production schedules among suppliers to the same customers could allow joint shipments, resulting in fewer emissions per delivery. However, acting on their own, the suppliers may have little incentive to pursue such coordination. Clearly, efforts to reduce the carbon in a supply chain cannot afford to ignore the need to coordinate these efforts across the entire supply chain.

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[1] See recent comprehensive reports on this subject from McKinsey (2009a, 2009b).

Although a lot has been written about the carbon footprint of supply chains in the popular press and in trade magazines (see for example Economist 2009, Butner et al. 2009, Brody and Ben-Hamida 2008, Parry et al. 2007, Plambeck 2007, Lash and Wellington 2007, Carbon Trust 2006, among many others), and although numerous websites, non-profit organizations, trade groups, and government bodies have been dedicated to the issue (see Benjaafar and Li 2009 and the references therein), the research community in Operations Management (OM) and Operations Research (OR) has been mostly absent from these efforts. For example, an extensive search in the journals published by INFORMS did not yield any papers dealing directly with the issue of carbon emissions and operations. There is of course significant literature on sustainability and operations in general; see Kleindorfer et al. (2005), Linton et al. (2007), Srivastava (2007) and Corbett and Klassen (2006) for reviews. However, the concern in that literature tends to be more focused on product recycling or reuse (e.g., Flapper 2005, Guide and Van Wassenhove 2006a, 2006b) or life cycle analysis (Matos and Hall, Guide Van Wassenhove 2009). There is extensive literature in economics on the design of markets for emissions and the trading of emission permits; e.g., Montgomery (1972), Laffont and Tirole (1996a, 1996b), Tietenberg (2006), Fankhauser and Hepburn (2009), Grubb and Neuhoff (2006), Subramanian and Talbot (2007), and the references therein. There is also extensive literature on environmental economics that examines the economic impact of different environmental policies; see Helm and Hepburn (2010), Neuhoff (2008), Nordhaus (2008), and Oppenheim and Beinhocker (2009). This literature does not deal with operational issues.

Given the potential impact of operational decisions on carbon emissions, there is clearly a need for Operations Management research that incorporates carbon emission concerns. In particular, there is a need for *model-based* research that extends quantitative models, which typically focus on either minimizing cost or maximizing profit, to include carbon footprint. These models could then be used to understand how accounting for carbon emissions (either as a constraint or as a decision criterion) might affect operational decisions. They could also be used to inform operations managers on how policies, such as mandatory emission caps, taxes on carbon emissions, and emission cap and trade, among others, ought to affect operational decision-making. Moreover, the models could be used to study how the specifics of these policies (e.g., the scope of carbon emission responsibilities and how these responsibilities are allocated among members of the same supply chain) would affect the costs and emissions of various firms.

This paper is a first step in this direction. Our objective in this paper is to draw attention to the strong connection between operational decisions across the supply chain and the carbon footprint of these supply chains and the extent to which concerns about carbon emissions can be addressed by adjusting operational decisions and improving collaboration among supply chain partners. Using relatively simple and widely used models, we illustrate how carbon emission concerns could be integrated into operational decision-making with regard to procurement, production, and inventory management. We show how, by associating carbon footprint parameters with various decision variables, traditional models can be modified to support decision-making that accounts for both cost and carbon footprint. We examine how the values of these parameters as well as the parameters of regulatory emission control policies affect cost and emissions. We use the models to study the extent to which carbon reduction requirements can be addressed by operational adjustments alone, as an alternative to costly investments in carbon-reducing technologies. We also use the models to investigate the impact of collaboration among firms within the same supply chain on their costs and carbon emissions and study the incentives firms might have in seeking such cooperation. A contribution of this paper is a set of insights, some of which would be difficult to obtain without the support of *operations* models such as the ones we consider here. A few of these insights are also surprising and point to important factors of which both managers and policy makers should be aware.

Although our model formulations and our analysis build on specific models for supply chain planning, namely single and multi-stage *lot-sizing* models, we believe that similar treatment could be extended to other common operations management models, including multi-location news-vendor models, economic order quantity models, multi-period stochastic inventory models, and supply chain coordination and contracting models, among many others (see Section 4 for further discussion). Moreover, throughout the paper, we make various assumptions when formulating the models and when carrying out numerical experiments. We do so mostly for the sake of illustrating how such models could be constructed and how useful insights could be derived. We believe that similar analysis and results could be obtained under alternative assumptions. Finally, we should note that our objective in this paper is neither to derive new theory nor to develop new methodology. Instead our goal is to highlight a potentially important new application area and a new set of managerial concerns. In this sense, we view the paper as a discussion starter and not a thorough and comprehensive treatment of the topic. Our hope is that the paper will inspire others to undertake the work necessary to fully explore many of the issues that are only highlighted here.

The rest of the paper is organized as follows. In Section 2, we introduce various formulations of production planning and procurement models for single and multiple firms that incorporate carbon emissions under varying regulatory policy assumptions. In Section 3, we use these models to obtain insights from numerical experiments and discuss the implications of these insights to management practice and to public policy making. In Section 4, we summarize key findings and offer ideas for future research.

2. Model Formulations

In this section, we present a series of model formulations that illustrate how carbon emissions considerations can be incorporated into operations management models. The models we formulate build on classic lot-sizing models for single and multiple firms. Our choice of models is motivated by (1) the widespread use of such models in practice, as they form the building block for many commercial supply chain planning applications, (2) the availability of standard tools for solving such models, and (3) the ability of these models to accommodate many of the relevant concerns associated with carbon emissions, including different regulatory policies. However, as mentioned earlier, we believe it is possible to develop models that are rooted in other operations management models and we view our treatment in this paper as providing a potential template for doing so.

To incorporate carbon emission concerns, we consider several regulatory policy settings, including settings where (a) firms are subject to mandatory caps on the amount of carbon they emit, (b) firms are taxed on the amount of emissions they emit, (c) firms can participate in a cap-and-trade system, and (d) firms can invest in carbon offsets to mitigate carbon caps. We consider systems involving a single firm as well as systems with multiple firms that operate either independently or coordinate their operations and carbon emissions. We consider variants of these systems with different assumptions regarding how carbon emissions are accounted for over time and how emissions are allocated among members of the same supply chain.

Model I: A Single Firm with Strict Carbon Caps

Consider the problem faced by a firm that must determine, over a specified planning horizon consisting of multiple periods with known demand, when and how much to order or when and how much to produce. In the absence of carbon emission considerations, the firm makes ordering decisions to minimize the sum of its fixed and variable ordering or production costs, inventory holding costs, and inventory shortage costs. Fixed ordering costs may correspond to transactions costs associated with placing an order with an outside supplier, such as transportation cost, or with initiating production internally, such as process setup cost. Variable costs may correspond to either unit purchasing or unit production costs. Inventory shortage costs are costs incurred if demand in one period cannot be fulfilled from inventory in that period, and can be in the form of either backorder costs or lost sales costs. In the presence of carbon emission considerations, the firm must account for the emissions associated with various decisions regarding ordering, production, and inventory holding. In particular, there may be emissions associated with placing an order with an outside supplier (e.g., emissions due to transportation) or with initiating production (e.g., emissions due to process setup). There may also be variable emissions associated with each unit ordered or produced (e.g., emissions due to the handling or the production of each unit) and emissions associated with the storage of each unit held in inventory in each period.

We use cost parameters f_t, c_t, h_t, and b_t, where for each period t, $t = 1, \ldots, T$, f_t denotes the fixed cost per order, c_t the variable cost per unit, h_t the cost per unit for inventory carried over from one period to the next, and b_t the cost per unit backordered in each period and T is the number of periods in the planning horizon. To account for carbon emissions, we introduce carbon footprint parameters $\hat{f}_t$, $\hat{c}_t$, and $\hat{h}_t$, where, for each period t, $\hat{f}_t$ denotes the amount of fixed carbon emissions associated with each order (e.g., transportation emissions or emissions associated with production), $\hat{c}_t$ the variable amount of carbon emissions per unit in each order (e.g., emissions due to the handling or the production of each unit), and $\hat{h}_t$ the amount of carbon emissions per unit of inventory held per period (emissions involved in the storage of each unit). The decision variables associated with the problem are denoted by y_t, q_t, I_t and B_t, where $y_t = 1$ if an order is placed in period t and $y_t = 0$ otherwise, q_t corresponds to the order quantity in period t, I_t is the amount of inventory carried from period t to period $t + 1$ and B_t is the amount of backorders also carried from period t to period $t + 1$. Finally, we let d_t refer to the demand in period t.

We consider a setting where the firm must adhere to a fixed cap C on emissions over the entire planning horizon. This cap could be mandated by a regulatory body external to the firm or could correspond to a decision made internally by management to adhere to specific limits on emissions (we later consider alternative regulatory policies under which emissions caps can be relaxed).

The problem faced by the firm can now be formulated as the following mixed integer linear program (MILP):

$$\text{Problem P1: Minimize } \sum_{t=1}^{T}(f_t y_t + c_t q_t + h_t I_t + b_t B_t) \tag{1}$$

subject to

$$I_t - B_t = I_{t-1} - B_{t-1} + q_t - d_t, \quad \text{for } t = 1, \ldots, T, \tag{2}$$

$$\sum_{t=1}^{T}(\hat{f}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t) \le C, \tag{3}$$

$$q_t \le \left(\sum_{t'=1}^{T} d_{t'}\right) y_t, \quad \text{for } t = 1, \ldots, T, \tag{4}$$

$$I_t, B_t, q_t \ge 0, \quad \text{for } t = 1, \ldots, T, \tag{5}$$

$$y_t \in \{0,1\}, \qquad \text{for } t = 1,\ldots,T. \tag{6}$$

The objective function in (1) minimizes the sum of fixed and variable ordering costs, holding costs, and backordering costs over the entire planning horizon. Constraints (2) are net inventory balance equations. Constraint (3) ensures that the cap on carbon emissions over the planning horizon is not exceeded. Constraints (4) ensure that $y_t = 1$ whenever $q_t > 0$. The remaining constraints are standard integrality and non-negativity constraints. The model in (1)-(6) and its many variants can be solved using standard MILP solution approaches; see for example Pochet and Wolsey (2006) for an extensive treatment and discussion of recent advances. In the numerical results we describe in Section 3, we use the commercial solver ILOG CPLEX to generate solutions for the example problems we consider (see the Appendix for details).

In the above formulation, we assume that there are no constraints on order sizes and that there are no supply leadtimes. We also assume that unfulfilled demand is backordered. It is of course possible to model systems with order size constraints or positive leadtimes. It is also possible to model systems where demand in each period must be fulfilled; otherwise, it is considered lost and incurs a lost sales cost. The model could also be extended to systems with multiple stages and to multiple products. The above formulation assumes that the carbon emission cap is over the entire planning horizon, but it is possible to model settings where the cap is over smaller subsets of periods or is associated with each period (see additional discussion in Section 3). The emission cap could also be associated with each unit produced or ordered. For example, firms may want to market products whose carbon footprint per unit does not exceed a certain threshold[2]. This can be accommodated by modifying constraints (3) as follows:

$$\sum_{t=1}^{T} (\hat{f}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t) \leq C \sum_{t=1}^{T} d_t, \tag{7}$$

where C now denotes the cap on carbon emissions per unit.

In defining the carbon emission parameters, we assume that they are linearly increasing in the associated decision variables. We make this assumption for the sake of demonstrating how such models can be constructed and to obtain in Section 3 insights for this important special case. There are of course settings where this may not hold and where emissions may increase in a non-linear fashion (e.g., convex or concave).

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[2] Various firms are starting to attach carbon footprint labels to many of their products and to position these products as greener alternatives; see for example Edwards-Jones et al. (2009), Ball (2009) and Brenton et al. (2008) for discussion and examples; see also various case studies reported by the Carbon Trust at www.carbontrust.org.

In the above formulation, we also assumed that the carbon emission parameters are readily available. However, a prerequisite for using the models described in this paper is estimating these parameters. Fortunately, significant effort is being made by various firms in documenting the carbon footprint of their various activities, as this would be required in documenting their compliance with regulatory policies or in communicating the carbon footprint of their products to consumers (see for example, the new EPA reporting requirement from large CO_2 emitters: http://epa.gov/climatechange/emissions/ghgrulemaking.html)[3].

Finally, it might be tempting to view *carbon capacity* limits (caps on carbon emissions) as being similar to capacity limits on production (or ordering), which are common in many models in operations managements. The differences are however significant. First, carbon capacity may cover multiple periods or even the entire planning horizon. In contrast, production capacity typically applies to each period. Second, carbon capacity consumed in one period affects the available carbon capacity in future periods, while production usually regenerates in each period. Third, carbon capacity is consumed not only by production, but also by order processing, transportation, and inventory holding. This means that carbon capacity can be consumed even if no production or procurement activity is taking place and by simply holding inventory. It also means that operating changes in one area (e.g., inventory) may induce or demand changes in other areas (e.g., production or transportation) due to the joint carbon capacity limit.

Model II: A Single Firm with Carbon Tax, Carbon Cap and Trade, or Carbon Offsets

An alternative to strict caps on emissions is not to restrict emissions but instead to penalize emissions using a *carbon tax*. A carbon tax can take on a variety of forms. In its simplest, the tax is a financial penalty linear in the number of carbon units emitted. To illustrate how a carbon tax would modify the problem formulation in (1)-(6), let α denote the amount of tax paid on each unit emitted (the carbon unit price), then the problem facing the firm can be restated as

$$\text{Problem P2: Minimize } \sum_{t=1}^{T}(f_t y_t + c_t q_t + h_t I_t + b_t B_t) + \alpha \sum_{t=1}^{T}(\hat{f}_t y_t + \hat{c}_t q_t + \hat{h}_t I_t) \qquad (8)$$

subject to (2), (4), (5) and (6). The objective function in (8) can be rewritten as

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[3] Various efforts are underway to establish *standards* for how carbon footprint for products and supply chains should be documented, measured, and reported; examples include the GHG Protocol by the World Resource Institute and the World Business Council for Sustainable Development, ISO 14064 by the International Organization for Standardization, and PAS 2050 by BSI British Standards, the Carbon Trust, and the Department for Environment, Food and Rural Affairs in the United Kingdom.; for references see BSI (2008a, 2008b), Carbon Trust (2007), WRI (2009), ISO (2006).

$$\text{Minimize } \sum_{t=1}^{T}\left(\tilde{f}_t y_t + \tilde{c}_t q_t + \tilde{h}_t I_t + b_t B_t\right), \tag{9}$$

where $\tilde{f}_t = f_t + \alpha \hat{f}_t$, $\tilde{c}_t = c_t + \alpha\hat{c}_t$, and $\tilde{h}_t = h_t + \alpha\hat{h}_t$. Hence, the problem reduces to one of pure cost minimization, albeit with cost parameters that reflect the cost of emissions.

Numerous variations on this formulation are possible. It is possible to incorporate alternative tax schemes, such as those in which tax penalties are non-linear in the emission quantities, making the tax either progressive (e.g., increasing convex) or regressive (e.g., increasing concave). It is also possible to incorporate tax schedules in which the unit penalty changes in discrete steps as a function of the emission quantity, including the case where taxes are not levied if emissions fall below a certain threshold (some of these variations could lead to non-linear optimization problems which, depending on the assumption, may be possible to linearize by approximating the tax penalties with a piece-wise linear function).

An alternative policy to either imposing strict caps or applying a carbon tax is a cap-and-trade system whereby firms are allowed to emit more than their prescribed caps but are penalized for doing so, with penalties increasing in the extent to which emissions exceed the cap. Firms are also rewarded for emitting less than their caps by receiving payments increasing in the difference between their caps and their actual emissions. This system of penalties and rewards is typically implemented via a trading market for carbon emissions, where firms can buy and sell the right to emit[4]. If we assume that prices set by the market are exogenous to decisions made by individual firms (i.e., the carbon market is significantly larger than the amounts of carbon sold and bought by any one individual firm) and if we assume that carbon prices are relatively stable over the firm's planning horizon, then we can reformulate the problem in (1)-(6) as follows:

$$\text{Problem P3: Minimize } \sum_{t=1}^{T}\left(f_t y_t + c_t q_t + h_t I_t + b_t B_t + p\left(e_t^+ - e_t^-\right)\right) \tag{10}$$

subject to

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

$$e_t^+, e_t^- \ge 0, \quad \text{for } t = 1,\ldots,T, \tag{12}$$

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[4] There are several active trading markets. The annual global market for carbon was recently valued at over $130 billion and expected to rapidly grow (Point Carbon 2009). The most important market is the European Trading System (ETS), which covers over 50% of all emissions in the European Union (EU). In the US, a cap-and-trade system is part of the US climate bill that was recently passed by the House of Representatives (it is also part of the California Assembly Bill 32 that regulates greenhouse gas emissions in the state of California). There are several regional trading markets already in place in the US, including the Regional Green House Gas Initiative (www.rggi.org) involving utility companies in the Northeast and Mid-Atlantic States. The Chicago Climate Exchange is a voluntary trading market with participation by companies from North America, US municipalities, states, and universities. For recent references on emission trading markets see Fankhauser and Hepburn (2009), Grubb and Brewer (2009), and Grubb and Neuhoff (2006), Capoor and Ambrosi (2009).

along with (2), (4), (5), and (6), where p is the prevailing market price per unit of carbon emission and e_t^+ and e_t^- denote respectively the amount of carbon credit the firm buys and sells in period t[5]. Note that the carbon credits bought serve to relax the effective cap on emissions, although it is costly to do so, while the carbon credits sold represent a new source of revenue

In the above formulation, we have assumed that the market price for carbon is fixed. However, in practice, price could be subject to volatility. This volatility could be assumed away if it is primarily of a short-term nature and if the long-term trend can be reliably forecast (a predictable increase or decrease in price can be easily incorporated into the model). It can also be assumed away if the firm employs financial options, such as those commonly used in the procurement of commodities, which guarantee the firm the option to buy or sell at a specified price. In some settings, it might of course be necessary to construct a model that explicitly accounts for price volatility and/or for the dynamics of the carbon exchange market. In particular, price, unless artificially fixed through government intervention, would be highly sensitive to the supply and demand for carbon, which is itself dependent on the imposed carbon cap. Hence, a more complete model would capture the dependency of price on the carbon cap C (see Section 4 for further discussion).

A third policy alternative to strict caps is to impose caps but to allow firms to invest in so-called *carbon offsets*. Offsets are investments a firm would make in carbon-reducing projects, typically offered by a third party, to offset emissions in excess of its specified cap[6]. Hence, it is essentially the same as the purchasing of emission credits in a cap-and-trade system, except that the underlying market mechanism is different (in a cap-and-trade system, the availability and pricing of emission credits are determined by a carbon exchange market, while the availability and pricing of offsets is determined by independent suppliers of such offsets). If we let p now denote the price per unit of carbon offset and e_t^+ denote the

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[5] Because the cap is imposed on the entire planning horizon, the formulation of P3 can be simplified by defining variables E^+ and E^- corresponding respectively to the total amount of carbon purchased and sold over the entire planning horizon such that $E^+ = \sum_{t=1}^{T} e_t^+$ and $E^- = \sum_{t=1}^{T} e_t^-$. We intentionally introduce period-specific emission trading variables to show how readily the formulation can be extended to settings where the emission price is period-dependent and to settings where the cap is imposed over intervals shorter than the entire planning horizon.

[6] The use of offsets is one of the main mechanisms available to countries under the Kyoto Protocol (and also under the pending US Climate Bill) for fulfilling their emission reduction commitments. In particular, industrialized countries can earn emission reduction credits from emission-reduction projects in developing countries (under the *Clean Development Mechanism*) or in other industrialized countries (under the *Joint Investment* system). For details, see NCEP (2009), Stern (2009), Carbon Trust (2009), Schapiro (2010); see also the recent report in the Economist (2009).

amount of carbon offset (in units of carbon emissions) the firm purchases, then the problem in (1)-(6) can be reformulated as

$$\text{Problem P4: Minimize } \sum_{t=1}^{T}\left(f_t y_t + c_t q_t + h_t I_t + b_t B_t + p e_t^+ \right) \tag{13}$$

subject to

$$\sum_{t=1}^{T}(\hat{f}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t) \leq C + \sum_{t=1}^{T} e_t^+, \tag{14}$$

$$e_t^+ \geq 0, \quad \text{for } t = 1,...,T, \tag{15}$$

along with (2), (4), (5), and (6). This formulation is similar to the one for cap and trade, except that a firm does not benefit from emitting less than its specified cap.

Model III: Multiple Firms with and without Collaboration

Let us consider now the problem faced by firms that operate within a supply chain consisting of other firms that serve as either suppliers or customers. In particular, consider a serial supply chain consisting of *N* firms, where firm *i* orders from firm *i* + 1, with *i* = 1, ..., *N* – 1. Each firm must determine when and how much to order from its "supplier firm" so that it minimizes its total costs over the entire planning horizon. Note that for firms, other than firm 1, demand corresponds to orders generated by its "customer firm" (in other words, the demand of firm *i* corresponds to the orders generated by firm *i* – 1). If each firm is subject to a strict emission cap, C_i for firm *i* =1, …, *N*, and if the firms operate independently, then the problem faced by firm *i*, for *i* = 2, …, *N*, can be formulated as

$$\text{Problem P5: Minimize } \sum_{t=1}^{T}(f_{i,t} y_{i,t} + c_{i,t} q_{i,t} + h_{i,t} I_{i,t}) \tag{16}$$

subject to

$$I_{i,t} = I_{i,t-1} + q_{i,t} - q_{i-1,t}^*, \quad \text{for } t = 1,...,T, \tag{17}$$

$$\sum_{t=1}^{T}(\hat{f}_{i,t} y_{i,t} + \hat{h}_{i,t} I_{i,t} + \hat{c}_{i,t} q_{i,t}) \leq C_i, \tag{18}$$

$$q_{i,t} \leq \left(\sum_{t'=t}^{T} q_{i-1,t'}^* \right) y_{i,t}, \quad \text{for } t = 1,...,T, \tag{19}$$

$$I_{i,t}, B_{i,t}, q_{i,t} \geq 0, \quad \text{for } t = 1,...,T, \tag{20}$$

$$y_{i,t} \in \{0,1\}, \quad \text{for } t = 1,...,T. \tag{21}$$

where the decision variables and cost and carbon emission parameters are indexed by *i* and *t* to indicate the fact that they are now firm-specific. We use the notation $q_{i,t}^*$ to indicate the optimal order quantity for firm *i* in period *t* obtained by firm *i* by solving the above optimization problem. Note that the vector of orders $(q_{i,1}^*,...,q_{i,T}^*)$ constitutes the vector of demands that firm *i* + 1 must satisfy.

For firm 1, the problem can be formulated similarly as

$$\text{Problem P6: Minimize } \sum_{t=1}^{T}(f_{1,t}y_{1,t}+c_{1,t}q_{1,t}+h_{1,t}I_{1,t}+b_{1,t}B_{1,t}) \tag{22}$$

subject to

$$I_{1,t-1}-B_{1,t-1}+q_{1,t}-d_{1,t}=I_{1,t}-B_{1,t}, \quad \text{for } t=1,...,T, \tag{23}$$

$$q_{1,t}\le\left(\sum_{t'=1}^{T}d_{t'}\right)y_{i,t}, \quad \text{for } t=1,...,T, \tag{24}$$

along with (18), (20) and (21).

In the above formulation, we assume that backordering is allowed only for firm 1. Other firms must satisfy orders in the same period the orders are received. It is of course possible to allow for backorders by firms other than firm 1. It is also possible to model settings in which firms can resort to an outside supplier to fulfill orders that they cannot (or prefer not to) fulfill themselves. This becomes important when the carbon constraint can lead to infeasibilities.

In the above formulation, we assume that firms make decisions about ordering and production independently of each other and ignore each other's capabilities and carbon emission constraints. The firms could obviously reduce the total supply chain cost by making these decisions jointly. Such collaboration is not uncommon in industry and there are industry initiatives, such as the Collaborative Forecasting, Planning, and Replenishment (CFPR) initiative, whose goal is to support such collaboration. As we explore in Section 3, the presence of carbon footprint constraints can provide additional impetus for such collaboration. In its simplest form, if firms were to collaborate, they would jointly solve the following problem:

$$\text{Problem P7: Minimize } \sum_{i=1}^{N}\sum_{t=1}^{T}(f_{i,t}y_{i,t}+c_{i,t}q_{i,t}+h_{i,t}I_{i,t})+\sum_{t=1}^{T}b_{1,t}B_{1,t} \tag{25}$$

subject to

$$I_{1,t}-B_{1,t}=I_{1,t-1}-B_{1,t-1}+q_{1,t}-d_{1,t}, \quad \text{for } t=1,...,T, \tag{26}$$

$$I_{i,t}=I_{i,t-1}+q_{i,t}-q_{i-1,t}, \quad \text{for } t=1,...,T,\ i=2,...,N, \tag{27}$$

$$\sum_{t=1}^{T}(\hat{f}_{i,t}y_{i,t}+\hat{h}_{i,t}I_{i,t}+\hat{c}_{i,t}q_{i,t})\le C_i, \quad \text{for } i=1,...,N, \tag{28}$$

$$q_{i,t}\le\left(\sum_{t'=1}^{T}d_{t'}\right)y_{i,t}, \quad \text{for } t=1,...,T,\ \ i=1,...,N, \tag{29}$$

$$I_{i,t},B_{i,t},q_{i,t}\ge 0, \quad \text{for } t=1,...,T,\ i=1,...,N \tag{30}$$

$$y_{i,t}\in\{0,1\}, \quad \text{for } t=1,...,T, \quad i=1,...,N. \tag{31}$$

The above formulation assumes that, although the firms collaborate, emission caps continue to be imposed individually on each firm. If it were possible for firms to share their emission caps, constraints (28) would be replaced by the following constraint:

$$\sum_{i=1}^{N}\sum_{t=1}^{T}(\hat{f}_{i,t}y_{i,t}+\hat{h}_{i,t}I_{i,t}+\hat{c}_{i,t}q_{i,t})\le\sum_{i=1}^{N}C_i. \tag{32}$$

Such sharing of the emission caps might be possible if the firms are not independent entities but are divisions owned by a single large firm. It might also be possible if the environmental regulation allows for carbon trading between members of the same supply chain (e.g., in the absence of an open market for carbon trading). Sharing of the emission cap is also possible when the cap is voluntary and the objective for the supply chain is to eventually certify that the end-product has a carbon footprint that does not exceed a certain threshold. For example, several large retailers (e.g., Wal-Mart in the US (Wal-Mart 2009) and Tesco in the UK (Tesco 2009)) are working with their suppliers to reduce the overall carbon footprint of the products they sell and to market these products as greener alternatives to those sold by competitors.

Finally, we note that the models incorporating a carbon tax, carbon cap-and-trade, and carbon offsets, discussed earlier for the case of a single firm can be readily extended to the case of multiple firms, with or without the sharing of the emission caps.

3. Insights from the Models

In this section, we illustrate how the models presented in the previous section can be used to obtain useful insights. The insights, presented in the form of a series of observations, are based on numerical results generated from solving the models for examples of problems with varying parameter values. The details of the experimental setup and the examples can be found in the Appendix. Representative subsets of these numerical results are summarized in Figures 1-15. Each of these figures is used to illustrate one or more qualitative effects that can arise when carbon emission considerations are incorporated into operational models. However, these figures (and the associated insights) are not meant to suggest that other effects are not possible or to suggest that the effects documented here are more important than others. Rather, they are meant to provide a template for how the models can be used to answer important questions and how these answers can be used to inform the decision making of various parties, including operating firms, policy makers, and government regulators, among others. Also, as mentioned earlier, our objective is not to provide a comprehensive treatment for each of the effects observed.

The rest of this section is organized into three subsections: §3.1 presents a series of observations based on model P1 and deals with setting in which there is a strict cap on emissions; §3.2 presents observations based on models P2, P3, and P4 and compares the impact of different regulatory policies; and finally §3.3 presents observations based on models P5, P6 and P7 and examines issues that arise from the interaction of multiple firms within a supply chain.

3.1 Systems with Strict Emission Carbon Caps

Observation 1: *Meaningful caps can be imposed on emissions with relatively limited impact on total cost.*

This observation is illustrated in Figure 1 which shows the impact of varying the emission cap on total cost and total emissions. As expected, reducing the emission cap increases total cost and reduces total emissions. However, what is perhaps surprising is the fact that the emission cap can be significantly reduced without significantly affecting the total cost. This also means that total emissions can be significantly cut without significantly increasing cost. In the example shown, reducing the emission cap from 2100 to 1785 reduces the average total amount of emissions by 15% but increases the average total cost by only 3%. These results suggest that adjustments in operational decisions (modifying order quantities in each period) can alone lead to significant reductions in carbon emissions while not significantly compromising overall cost[7].

Observations 2: *Emission caps can be met more cost-effectively by adjusting operational decisions than by investing in costly more energy-efficient technology*.

An alternative to adjusting operational decisions is for a firm to lower its carbon footprint parameters, $\hat{f}_t$, $\hat{c}_t$, and $\hat{h}_t$, by investing in more energy-efficient technology in the production, transportation and warehousing of its products. Figure 2 illustrates the impact of varying emission caps on total cost for technologies with varying levels of energy efficiency. As we can see, there is very little difference in total operational costs as emission caps are initially lowered for the different technologies, and only when the emission cap is significantly lower than the unconstrained emission values (more than 15% in the example shown) does investing in more energy-efficient technology begin to yield significant cost savings.

Observation 3: *Without "carbon-enhanced" operational models, it is impossible to assess the true cost of more energy-efficient technology or the true cost of a lower emission cap.*

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[7] This result is consistent with the well known robustness observed in lot sizing models, such as the EOQ model, where the cost function tends to be relatively *flat* in the region around the optimal solution.

Figure 2 illustrates rather dramatically that in the absence of operational models, such as the ones we describe in this paper, that incorporate carbon emission concerns, it is difficult, for both firms and policy makers, to assess the impact of lower emission caps on the economic welfare of firms and their consumers. Without such models, it is also impossible for a firm to decide whether or not investing in more energy-efficient facilities and processes is economically advantageous. Hence, "carbon-enhanced" operational model can serve the dual purpose of informing policy makers and of guiding industry adoption of more energy-efficient technologies.

Observation 4: *Tighter caps on emissions can paradoxically lead to higher total emissions*.

Figure 3 shows the impact of varying the emission cap when a cap is imposed on each period instead of the entire planning horizon. Perhaps surprisingly, lower emission caps in this case can lead to higher total emissions in some cases. This is due to the fact, that imposing emission caps on a period by period basis prevents firms from the possibility of emitting more in one period if this allows significantly less emissions in future periods. For example, consider a setting where the fixed emissions (emissions associated with initiating an order such as transportation) are relatively high. A firm could reduce its overall emissions by reducing the frequency of orders, but carrying more inventory in the periods immediately following the placement of an order. Because of the carbon emissions associated with carrying inventory, this could mean higher carbon emissions in those periods, potentially violating emission caps if they are imposed on a period by period basis.

This observation has two important implications. First, policy makers (and also firms) need to be aware that the specifics of how emission caps are implemented can have very different impacts on operational costs. Second, devising policies that provide firms with more flexibility in how and when they fulfill the required cap could allow the fulfillment of these caps at significantly lower costs. Examples of such policies are those that allow firms to borrow, to a certain extent, against their future emission quotas or to bank unused quotas for future use.

3.2 Systems with Carbon Offsets, Carbon Tax, and Cap-and-Trade

Observation 5: *Carbon offsets enable tighter emission caps by mitigating the impact of lowering emission caps on cost.*

Figure 4 illustrates the impact of varying the emission cap when a firm has the option of purchasing carbon offsets. The option to offset is valuable even when the unit carbon price is relatively high; firms resort to offsetting selectively and only to mitigate an even higher operational cost. This observation points to the importance for policy makers of supporting the emergence of a competitive market for offsets, which could drive the price of these offsets down achieving the dual benefit of maintaining low cost for the consumer and low carbon for the atmosphere.

Observation 6: *Under cap and trade, emission levels are not affected by emission caps and are affected only by the market price for carbon.*

Figure 5 shows the impact of varying carbon caps and carbon price on total emissions. The somewhat surprising result that emission levels are unaffected by emission caps can be explained as follows. Under cap and trade, the emission constraint in (11) is binding because

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

Consequently, Problem P3 can be reformulated as

$$\text{Minimize } \sum_{t=1}^{T}\left(f_t y_t + c_t q_t + h_t I_t + b_t B_t + p\left(\hat{f}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t \right)\right) - pC \qquad (33)$$

subject to (2), (4), (5), and (6), from which we can see that the optimal solution is always independent of the carbon cap *C*. This result perhaps points to a limitation of a cap-and-trade policy. The emission cap cannot be used as a direct lever to control emissions in the way other policies, such as a strict cap on emissions or a carbon tax, can. From (33), we can also see that the amount of carbon emissions would be the same under cap and trade as it would be under a carbon tax if the tax rate $\alpha = p$[8].

Although it is difficult to control carbon emissions directly under cap-trade by varying the carbon cap, a policy maker may indirectly affect the price of carbon, by affecting the demand and supply for carbon, and therefore also affect carbon emissions. In Figure 6, we illustrate the interaction between the carbon cap and carbon price by considering a simple linear carbon pricing model where $p = a - bC$, leading to the following modified objective function:

$$\text{Minimize } \sum_{t=1}^{T}(f_t y_t + c_t q_t + h_t I_t + b_t B_t) + (a - bC)\left(\sum_{t=1}^{T}\left(\hat{f}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t \right) - C\right) \qquad (34)$$

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[8] Letting $\alpha = p$, problems P2 and P3 have the same solution. That is firms would make the same operational decisions. However, the net cost to firms is lower under cap-and-trade because of the revenue they generate from selling carbon. This perhaps explains some of the resistance among the business community to legislation involving a carbon tax.

As we can see from Figure 6, a tighter cap now leads to lower carbon emissions. Moreover, the effect of the carbon cap on cost is no longer monotonic, with initial decreases in the carbon cap actually benefiting the firm due to the revenue associated with carbon selling.

In practice, predicting the market dynamics for carbon can be difficult, a difficulty compounded by the inherent uncertainty and volatility in how demand and supply affect price. In turn, this makes it difficult for both firms and policy makers to easily assess the impact of carbon emission considerations. This perhaps supports the argument that between cap-and-trade and a carbon tax, a carbon tax provides a simpler mechanism for reducing carbon emissions quickly and reliably (see Figure 7).

Observation 7: *Under cap-and-trade, a higher carbon price can lead to lower total cost.*

As we can see from Figure 8[9], the effect of carbon price, given a fixed carbon cap, on the total cost is not monotonic, with cost initially increasing and then decreasing. When carbon price is relatively low, the firm is mostly engaged in the buying of carbon. Therefore, higher carbon prices increase its carbon purchasing cost. When the carbon price is sufficiently high, the firm becomes engaged in the selling of carbon, as the firm finds it advantageous to adjust its operations and emit less carbon (this of course means that the operational cost increases but this increase is more than offset from the higher revenue generated by carbon selling).

Observation 8: *The benefit from more energy-efficient technology is affected by the type of emission control policy.*

This observation is illustrated in Figure 9 which shows how technologies with varying energy efficiency affect operational cost. As we can see, as energy efficiency initially increases, the benefit is higher under a strict emission cap policy. Under such a policy, firms have no alternatives to mitigating the impact of the cap, the way they have under cap and trade or cap and offset. The benefit eventually levels off once the energy efficiency is sufficient to essentially make the carbon constraint irrelevant. This diminishing effect is absent under cap-and-trade (and similarly under a carbon tax) since there is always an incentive to reduce emissions and generate corresponding income. The benefit of more energy-efficient technologies is lower under a cap-and-offset policy than under a cap-and-trade policy since more energy-efficient technology can only be used to avoid the cost of exceeding the cap.

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[9] The figure is based on the original model P3 where the carbon price is independent of the cap.

These results suggest that if part of the objective of policy makers is to promote the adoption of greener technology, then certain policies can be significantly more effective than others. In particular, in the early stages of technology development where the energy gains from alternative technologies are relatively modest, then a policy of imposing strict emission caps may be the most effective. On the other hand, if the gains from alternative technologies can be substantial, then a cap-and-trade policy or a carbon tax may be more effective in motivating the firms to adopt the more energy-efficient technologies.

3.3 Systems with Multiple Firms with and without Collaboration

Observation 9: *The presence of carbon constraints increases the value of supply chain collaboration.*
Figures 10 and 11 show the effect of varying the carbon cap on the percentage reduction in cost achieved from collaboration in a supply chain consisting of two firms under a policy of strict caps[10] The curves show the cost reductions associated with each firm and with the entire supply chain. As we can see, total supply chain cost can be significantly reduced by having the firms collaborate. This benefit derives of course from having firms adjust their decisions to take into account the implications of these decisions on the cost of other firms. The benefits of these adjustments are more important in the presence of carbon caps than without them, as they allow firms to achieve these caps more cost effectively (the right-most segments of the curves correspond to settings where the emission cap is very high and where the benefit from collaboration is not due to the presence of the emission cap). The benefit from collaboration is not monotonic in the carbon cap level, with the benefit highest when the carbon cap is in the mid-range and less significant when the cap is very low or very high. When the cap is very low, firms have less room to make adjustments in their operations. On the other hand, when the cap is very high, the supply chain has less need for firms to make adjustments, although there continues to be some value to collaboration.

Observation 10: *Collaboration can lead to increases in the cost and carbon emissions of some of the firms.*
As we can see from Figure 10, although total supply chain cost is lower with collaboration, the cost of firm 1 can be higher. This is because firm 1, which faces end demand in this two-firm example, adjusts its order sizes to reduce the cost of firm 2. The resulting reduction in the cost of firm 2 more than offsets the

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[10] Percentage cost reduction due to collaboration = 100%×(cost without collaboration – cost with collaboration)/cost without collaboration.

increase in the cost of firm 1. As shown in Figure 12, these adjustments in order sizes mean that the emissions could also increase with collaboration, although always remaining within the cap. The fact that cost for some of the firms can increase with collaboration would require that contractual arrangements are in place that would suitably compensate these firms. In principle, such compensation is always possible since there is a net surplus for the supply chain. However, the specifics of how the surplus is divided among the firms can affect the long term success of the collaboration (see Section 4 for further discussion). With collaboration, the operational responsibilities within the supply chain of the different firms could also be significantly affected. Figure 13 shows how, when firms collaborate, the amount of inventory held by each firm is affected by the difference in the inventory holding carbon footprint. Collaboration allows the responsibility for holding inventory to be shifted to the firm that is more carbon efficient. In practice, this may require further adjustments to the physical infrastructure of the supply chain to accommodate this shift (e.g., investment in more warehousing facilities by one of the firms).

Observation 11: *Imposing supply chain-wide emission caps leads to lower emissions at lower costs; it also increases the value of collaboration.*

Figure 11 illustrates the impact of imposing a shared emission cap on the entire supply chain instead of individual caps on each firm. As we can see, the reduction in cost to the supply chain can be substantial, particularly when the emission caps are tight. A shared cap provides firms within the same supply chain with the flexibility of having some firms emit more than their individual cap if it can be offset with less emissions from other firms. This allows firms that are more cost effective at reducing their carbon footprint to take on a greater responsibility in meeting the overall carbon cap. As with individual caps, cooperation among the firms could mean that some firms would see their individual costs increase. Here too, a compensation scheme would need to be put in place first for firms to agree to cooperate.

Observation 12: *The benefit derived from collaboration can be significantly affected by the type of regulatory policy that is in effect.*

As we can see from Figure 14, the benefit derived from supply chain collaboration is sensitive to the type of regulatory policy that is in place. Some policies provide greater incentives than others for collaboration. In particular, collaboration is most beneficial when there is a strict cap and this cap is in the middle range. The benefit under cap and offset is less significant since firms have the option of meeting their carbon caps via the purchase of offsets. Therefore, having a supply chain partner that can help them meet their cap requirements becomes less important. Under cap and trade, collaboration can be greatly beneficial when the cap is high. In this case, the benefit from collaboration derives primarily from the ability of the supply chain to sell higher amounts of carbon to the market.

Observation 13: *Collaboration, if it does not involve all members of the supply chain, can increase the cost and emissions of those firms left out.*

This could occur under a variety of scenarios. One such example is illustrated in Figure 15 for a supply chain consisting of three firms, where firm 2 is the supplier of firm 1 and firm 3 is the supplier of firm 2. Firms 1 and 2 collaborate but firm 3 makes decisions on its own. The cost to firm 3 can be significantly higher than when firms 1 and 2 do not collaborate. In this example, when firms 1 and 2 collaborate, changes in the order sizes from firm 2 to firm 3 lead firm 3 to incur higher shortage costs. Similar effects can be observed with respect to carbon emissions. Hence, partial collaboration can be harmful to the firms that do not participate, in terms of cost, and to the environment in terms of carbon emissions.

4. Concluding Comments and Directions for Future Research

In this paper, we presented a series of models that illustrate how carbon footprint considerations could be incorporated into operational models. We showed how, using relatively simple models, important insights can be obtained to inform decision making by both operating firms and policy makers. These insights highlight the impact of operational decisions on carbon emissions and the extent to which adjustments to operations can mitigate emissions. They also point to the importance of operational models in evaluating the impact of different regulatory policies and in assessing the benefits of investments in more carbon efficient technologies. The results emphasize the important role operational models can play in predicting how different policies could affect the “bottom line” for firms and the benefit to the environment. The models and the insights show that the introduction of carbon emission regulation could provide an additional impetus for firms to collaborate and coordinate their operations. They also point to the need for regulatory policies that take a more holistic view of carbon emissions. In particular, shifting away from a firm-based focus to a supply chain-wide focus in controlling emissions might achieve the dual objective of lower emissions at lower cost. As we mentioned in the introduction, our objective in this paper is not to provide a comprehensive treatment of any particular issue, but to highlight the breadth of issues that might arise when carbon emission considerations are incorporated into operational decision making.

Some of the insights we have obtained appear to be consistent with effects observed in countries where emissions have been subject to regulation. For example, Grubb and Brewer (2009), in a recent report on lessons learned from the EU experience, make the following observations: (1) introducing a cap-and-trade system has had a significant impact on carbon emissions, with reductions of up to 5% since 2005 in the covered sectors (see also Ellerman and Buchner 2008); (2) this reduction in emissions has had a limited economic impact (according to the, with the imposed caps estimated to cost less than 1% of total GDP by 2020); (3) firms in nearly all sectors covered by emission caps have been able to profit from the introduction of a cap-and trade system, either from the selling of some of their emission allowances, undertaking cost-efficient emission reduction measures, or by passing the cost of carbon to consumers; and (4) despite generous emission caps, firms in many sectors, most notably the cement industry, have found simple and cheap ways to significantly reduce their energy consumption. There are undoubtedly factors other than those captured in our models that contribute to these observations. However, the observations seem to support for the robustness of some of the insights we obtained from the models.

Avenues for future research are numerous. We highlight a few of these below. In doing so, our goal is not to provide a comprehensive list but simply to emphasize the richness of operational problems that could be revisited with carbon footprint in mind. As highlighted in this paper, there are numerous facets to how environmental concerns and government policies might affect operations. The analysis we carried out in this paper highlights some of these interactions. However, each of the issues raised in the paper, as well as others, is worthy of more comprehensive and more rigorous treatment. Our hope is that we provide inspiration for this follow-up work.

The analysis we carried out in this paper was based on specific models of operations management, namely variants of traditional lot sizing models. Similar analysis could be carried out using other common models of operations such as newsvendor models, economic order quantity models, or models for stochastic dynamic inventory control. Using these models, it might be possible to characterize analytically the impact of carbon emission limits and carbon prices on the structure of optimal policies.

In this paper, we have focused on decisions regarding production and procurement. There are of course other operational decisions that are affected by concerns for carbon emissions, including facility location, supplier selection, capacity planning, choice of transportation mode, and raw material and component selection, among many others. Constructing “carbon-enhanced” models for these decisions could uncover new ways in how operational adjustments can be used to mitigate carbon emissions.

Moreover, it would be useful to extend the modeling to more complex supply chain structures, such as those involving assembly or distribution, and to supply chains with multiple products with shared components and resources. With these more complex supply chains, there are additional opportunities for supply chain collaboration that arise from the possibility of joint replenishment and transportation and/or production coordination. This increased collaboration could however make it more difficult to accurately assign the carbon footprint to the various parties or the various products involved. For example, if the products were to be assigned a carbon footprint label, schemes must be devised to correctly and fairly attribute carbon emissions to products that share the same production facilities, warehouses or transportation vehicles.

Insights described in this paper revealed the importance of interactions between firms in determining overall emission levels and corresponding costs. There is an opportunity to build models to analyze both cooperative and competitive interactions that may result from carbon emissions. For example, it would be useful to study how collaborative coalitions might form, how costs and revenues might be shared among members of these coalitions, and the characteristics of cost and revenue sharing schemes that lead to coalition stability. It would also be useful to study how competing firms or supply chains modify their decisions to take into account emission levels of other firms, when these levels affect market share (because of environmental concerns by customers) or when they affect profitability (because emission levels affect the availability and price of carbon).

A few countries are discussing the possibility of charging carbon tariffs for imported goods that would take into account the carbon footprint of these goods. Once implemented, such tariffs would obviously have a significant impact on global supply chains and international trade. In particular, this could impact decisions firms make about where to locate facilities, from which suppliers to procure, and in which markets to sell. For policy makers, it is important that if tariffs are imposed, they do generate the desired positive impact on the environment while minimizing the cost to firms and consumers. Therefore, it would be important to develop models that could guide policy makers in devising the right set of tariffs and to assist operating firms in optimizing their operations in the presence of such tariffs.

In our analysis, we have assumed that the carbon price (in settings involving carbon trading or the purchasing of carbon offsets) is fixed. In practice, carbon prices are likely to fluctuate and this fluctuation may be significant (for example, the unit price of carbon in Europe, where a carbon trading market already exists, has seen fluctuations over the past 5 years ranging from a high of €30.00 to a low of less than €1.00). As firms make operational decisions regarding how much to emit, it becomes important to take into account the variability in carbon prices. Therefore, it would be important to develop stochastic models that integrate operational decisions with decisions regarding carbon trading and carbon hedging.

In this paper, we have focused on the role of quantitative models in informing the decisions of both firms and policy makers. It would be useful to carry out empirical work that can be used to validate or enrich the results from the analytical models. For example, there is already carbon emission control legislation that has been in place in various countries, such as those in the EU, for several years now. It might be possible to further document the impact this legislation has had on the operations of various firms in those countries and on emission levels and carbon prices. In particular, it would be useful to identify the types of operational adjustments that firms have made in response to climate control legislation and the impact these adjustments have had on emissions and cost. It would also be of interest to compare how differences in legislation from country to country (e.g., those that have adopted a carbon tax versus those with a cap-and-trade system) have affected differently operational decisions made in those countries.

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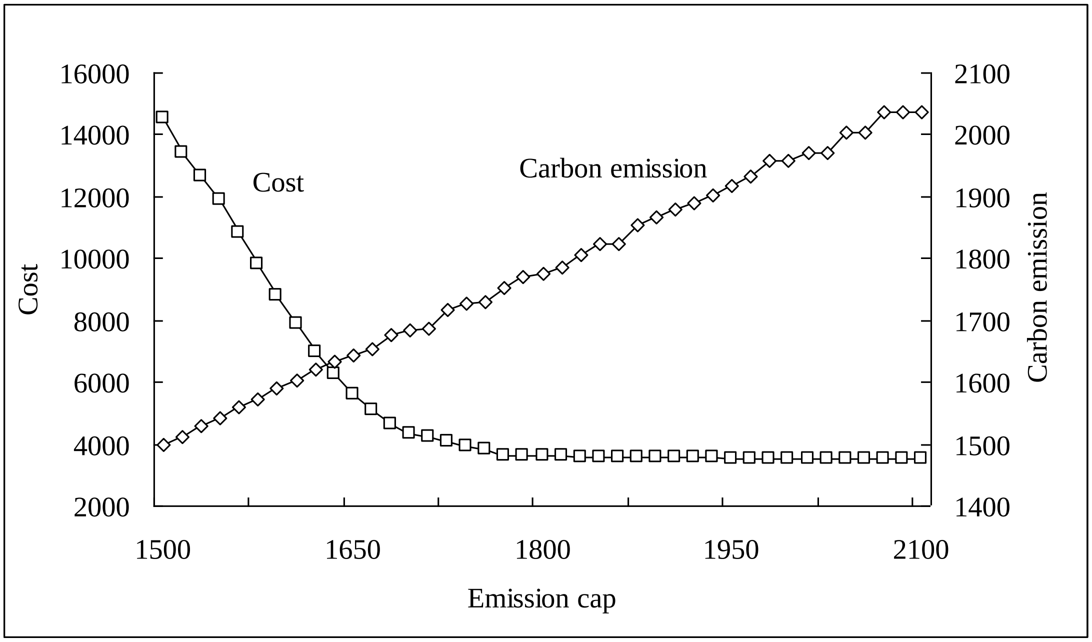

Figure 1: The effect of emission cap on cost and carbon emission

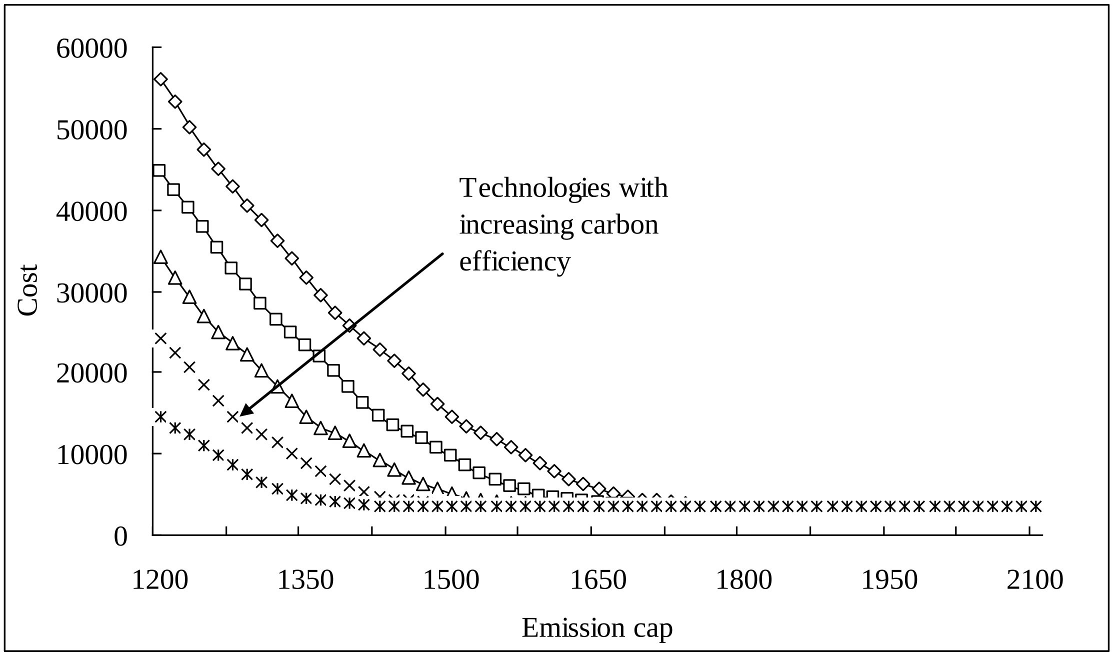

Figure 2: The effect of carbon efficiency and emission cap on cost (the cost shown does not include the investment cost needed to reduce the carbon footprint parameters)

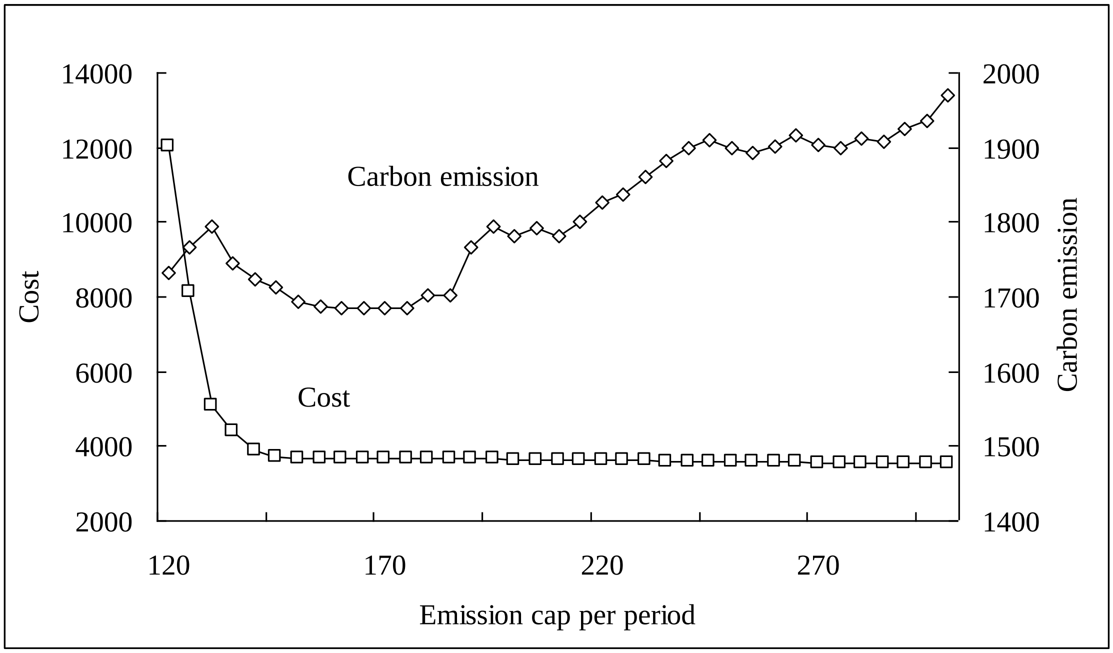

Figure 3: The effect of emission cap on cost and carbon emission when the emission cap is imposed on each period

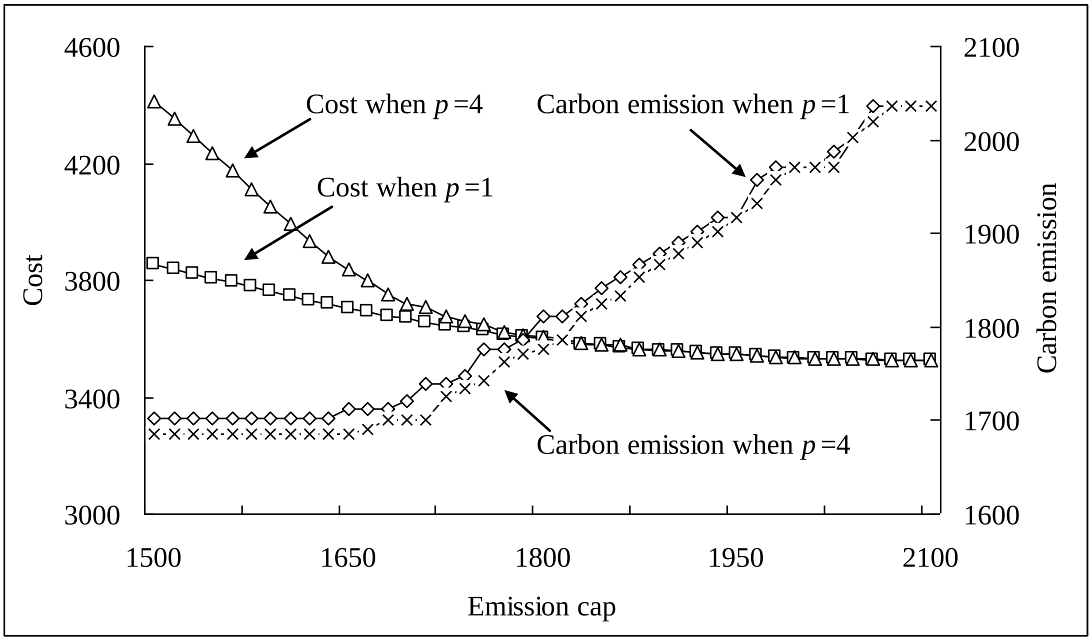

Figure 4: The effect of emission cap and carbon offset price on cost and carbon emission

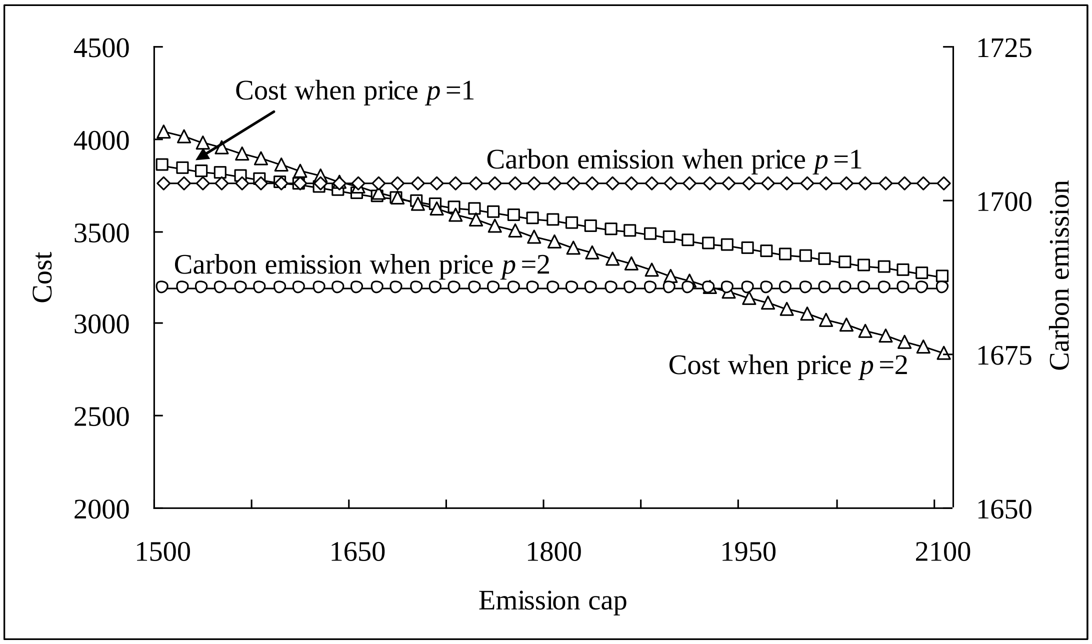

Figure 5: The effect of emission cap and carbon price on cost and carbon emission under cap and trade

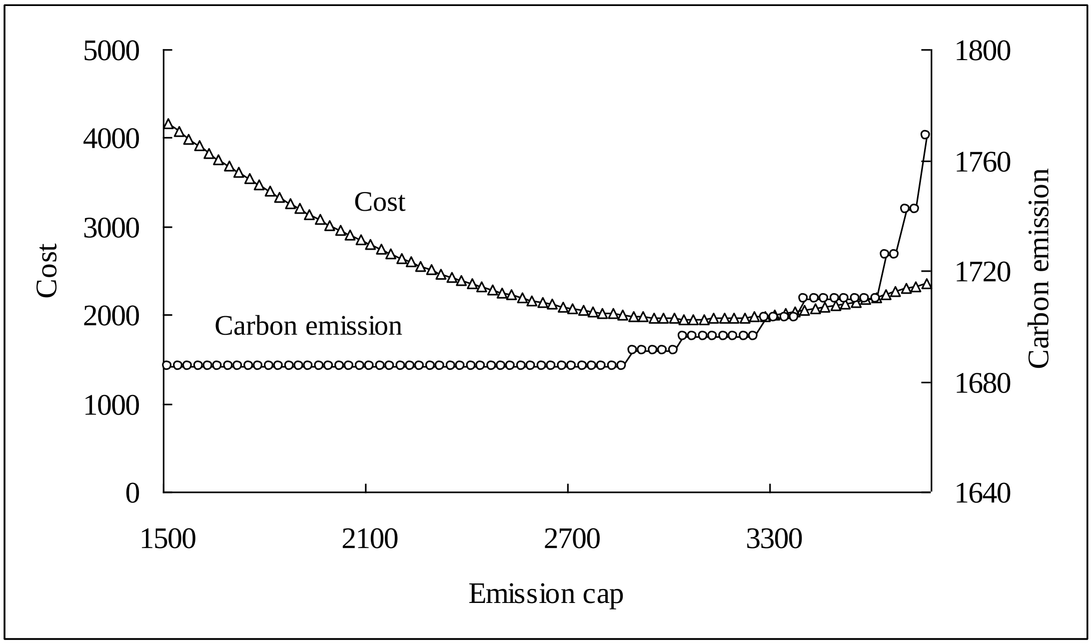

Figure 6: The effect of emission cap on cost and carbon emission under cap and trade when carbon price is dependent on the emission cap

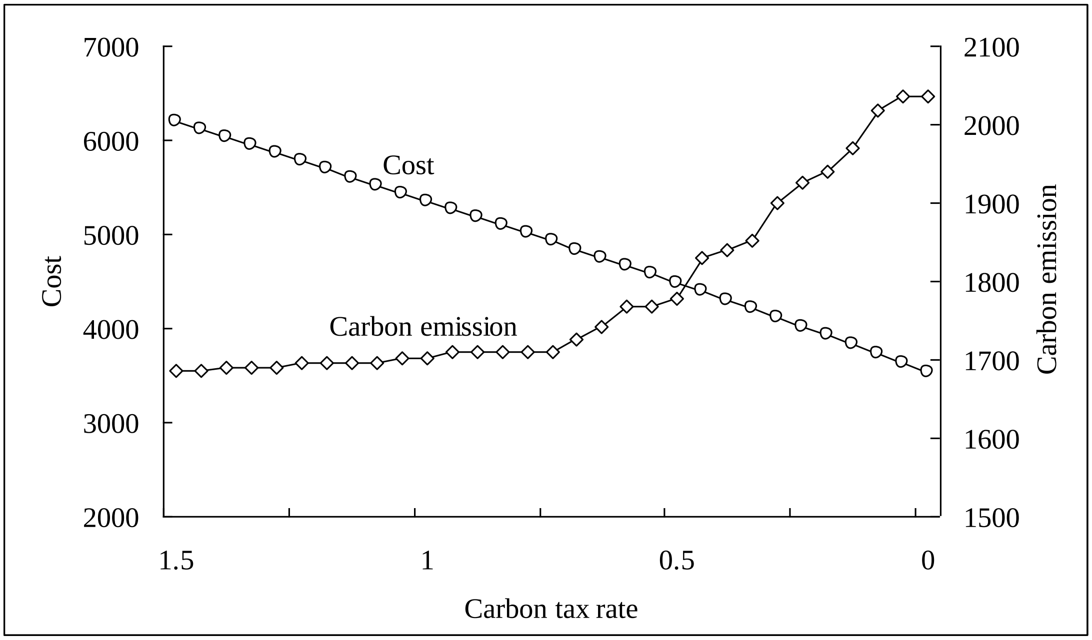

Figure 7: The effect of the carbon tax rate on cost and carbon emission

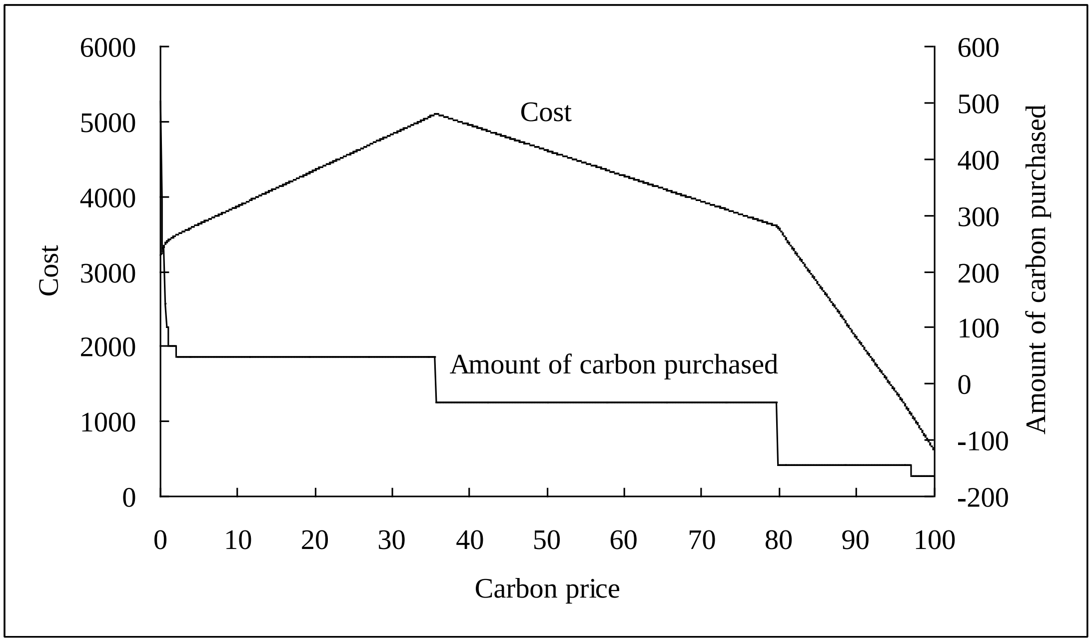

Figure 8: The effect of carbon price on cost and the amount of carbon purchased (a negative amount corresponds to carbon sold)

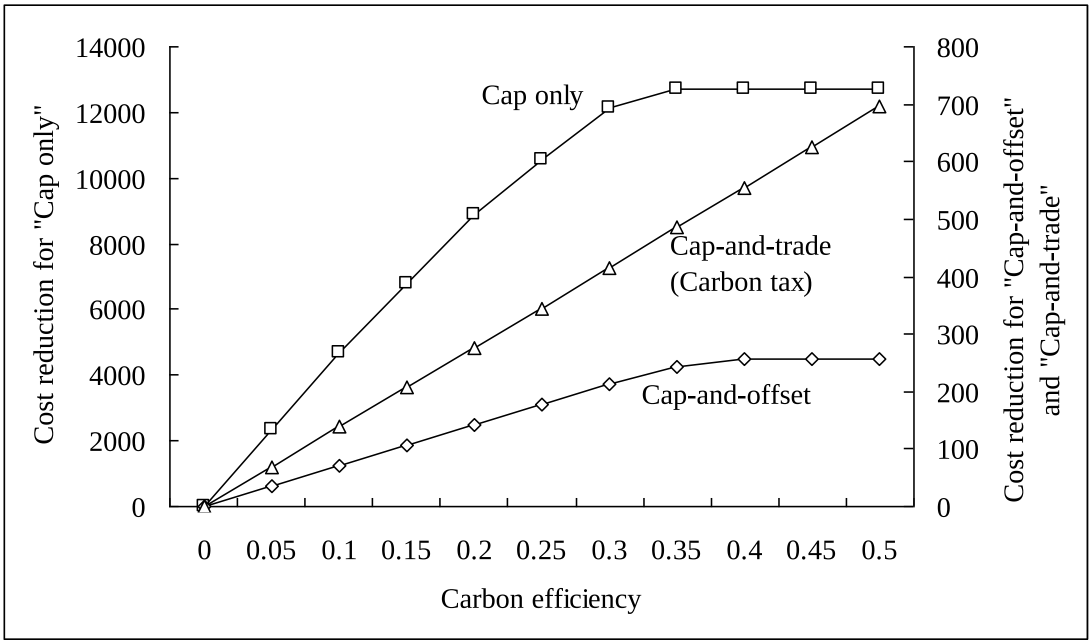

Figure 9: The benefit of carbon efficient technologies under different policy mechanisms (the benefit is measured by the cost reduction relative the base case of technology with zero carbon efficiency)

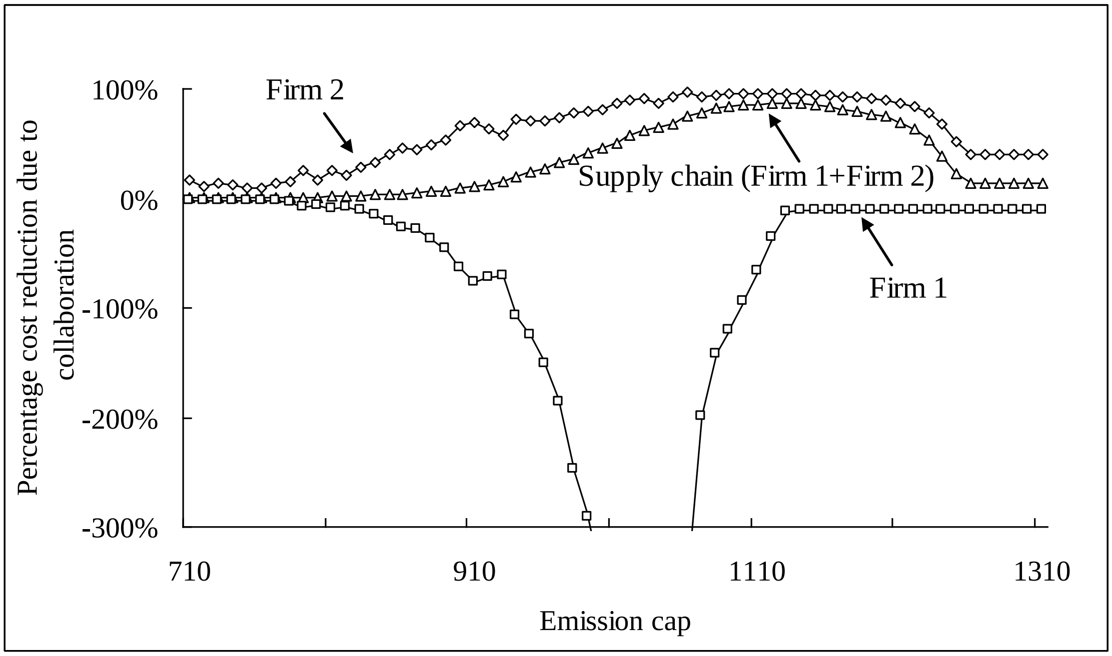

Figure 10: The impact of collaboration on cost when individual caps are imposed on each firm (a negative percentage corresponds to a cost increase; at its lowest point, which is not shown, the percentage reduction for firm 1 is approximately -400% for a cap of 1030)

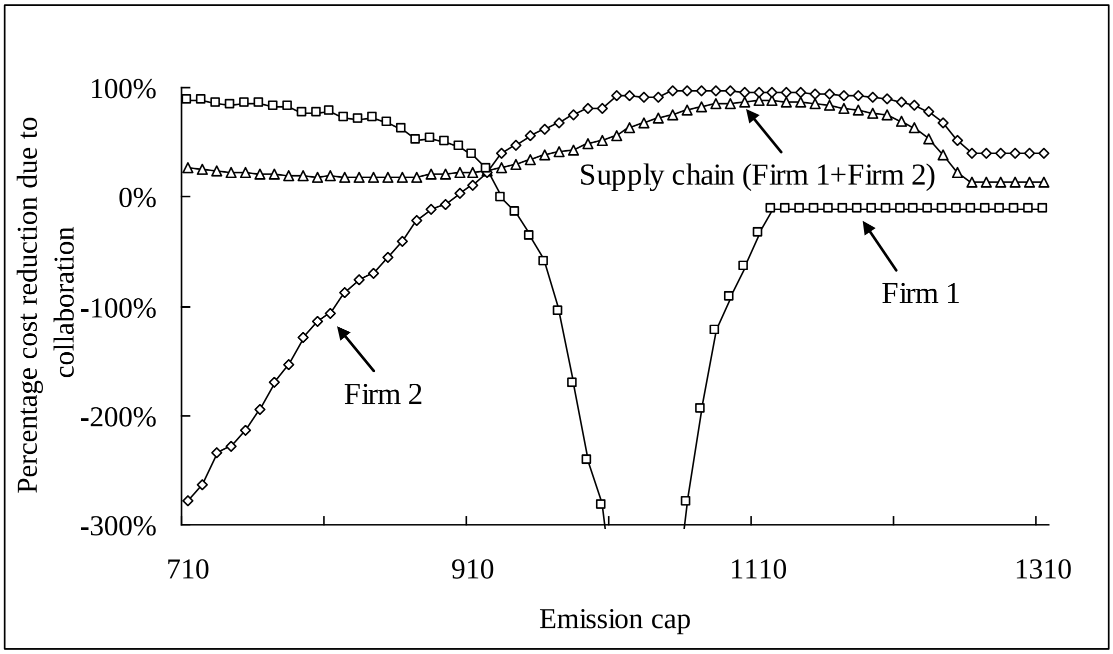

Figure 11: The impact of supply chain collaboration on cost when a shared cap is imposed on the entire supply chain (at its lowest point, which is not shown, the percentage reduction for firm 1 is approximately -500% for a cap of 1030)

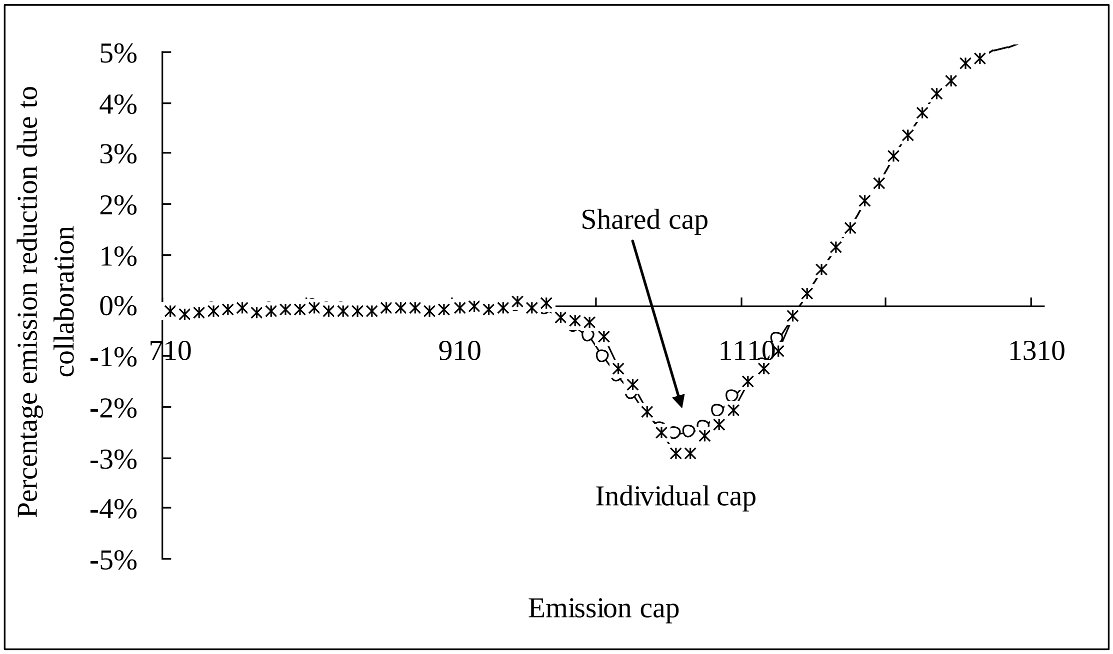

Figure 12: The impact of supply chain collaboration on carbon emissions for the entire supply chain, with and without a shared emission cap (a negative percentage corresponds to emission increases due to collaboration)

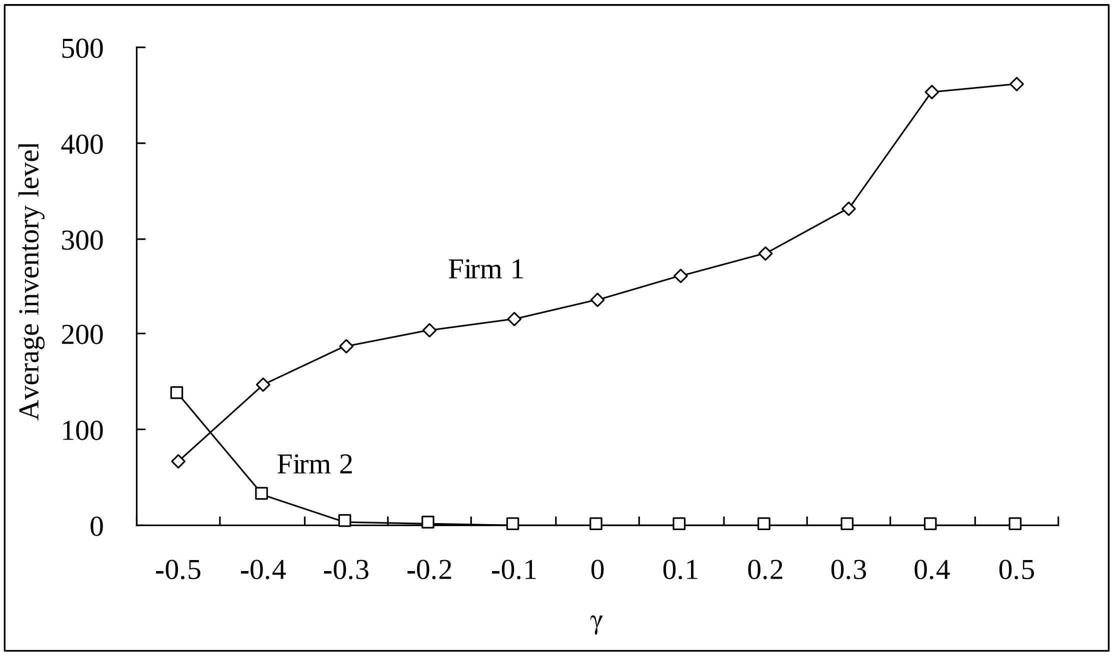

Figure 13: The impact of inventory holding carbon footprint on the average inventory held by the firms in the supply chain ($\hat{h}_1 = 1-\gamma, \hat{h}_2 = 1+\gamma$)

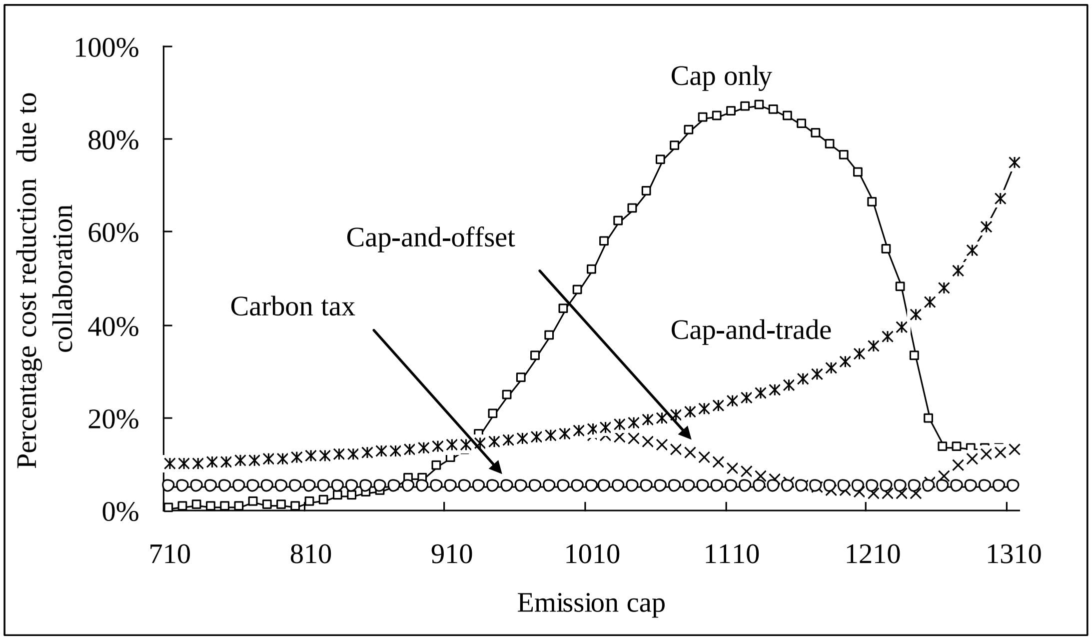

Figure 14: The effect of regulatory policies on the benefit of supply chain collaboration under varying emission cap levels

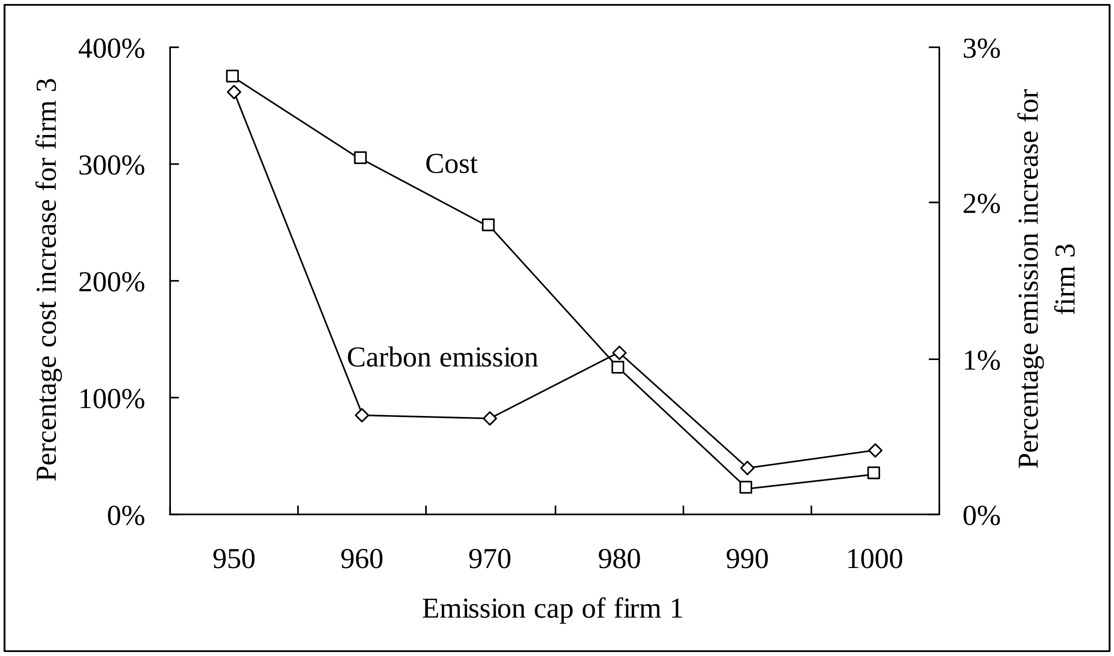

Figure 15: The impact of partial supply chain collaboration on the cost and emission of the firm that does not participate in the collaboration

Appendix: Experimental Setup for the Numerical Results

Unless stated otherwise, Figures 1-15 are based on a set of examples with similar parameter values. In particular, the planning horizon in all cases is 15 periods. End demand in each period is generated independently from a uniform distribution over the interval [20, 70]. Each data point shown in each figure corresponds to the average of 20 different demand series. The same demand series are used for all the figures. In all cases, and unless stated otherwise, cost and carbon footprint parameters are stationary. The parameters are given by the following:

$$h_t = 1;\ f_t = 60;\ c_t = 4;\ b_t = 100;\ \hat{h}_t = 2;\ \hat{f}_t = 20;\ \text{and } \hat{c}_t = 2 \text{ for all } t,$$

in settings with a single firm, and by

$$h_{i,t} = 1;\ f_{i.t} = 30;\ c_{i,t} = 0;\ b_{i,t} = 100;\ \hat{h}_{i,t} = 1;\ \hat{f}_{i,t} = 40;\ \text{and } \hat{c}_{i,t} = 1 \text{ for all } i \text{ and all } t,$$

in settings with multiple firms. All the results were obtained by solving the corresponding optimization problems as specified below. The problems were solved using the commercial solver ILOG CPLEX version 11.1 running on a personal computer workstation with an Intel CPU of 3.2 GHz and 1 GB of memory.

The following is additional information specific to each of the figures.

- Figure 1 is based on model P1.
- Figure 2 is based on model P1 with different plots corresponding to different carbon footprint parameter values. These parameter values are varied by varying i from i = 0 to i = 4 as follows: $\hat{f}_i = 0.95^i \hat{f}_0$, $\hat{c}_i = 0.95^i \hat{c}_0$, and $\hat{h}_i = 0.95^i \hat{h}_0$. where the values $\hat{f}_0 = 20$, $\hat{c}_0 = 2$, and $\hat{h}_0 = 2$ correspond to the base case.
- Figure 3 is based on a modified version of model P1 where constraint (3) is replaced by $\hat{f}_t y_t + \hat{h}_t I_t + \hat{c}_t q_t \le C, \quad \text{for } t = 1,...,T$ (that is a carbon emission cap is imposed on each period instead of the entire planning horizon).
- Figure 4 is based on model P4.
- Figure 5 is based on model P3.
- Figure 6 is based on a modified version of model P3 where the objective function is given by (34) with $p = 4 - 0.0009C$.
- Figure 7 is based on model P2.
- Figure 8 is based on model P3.
- Figure 9 is based on models P1, P2, P3, and P4 (for this figure, the emission cap is set to 1200 for the

policies "cap only," "cap-and-offset," and "cap-and-trade;" similarly, carbon price (or carbon tax) is set to 2 for the policies "cap-and-offset," "cap-and-trade," and "carbon tax;" Carbon efficiency is measured relative to the base case $\hat{f}_t = 20,\ \hat{c}_t = 2,$ and $\hat{h}_t = 2$. For example, an efficiency of 10% means that the new carbon parameters are 10% smaller, i.e. $\hat{f}_0 = 18,\ \hat{c}_0 = 1.8,$ and $\hat{h}_0 = 1.8.$

- Figures 10-12 are based on modified versions of models P5, P6, and P7 involving two firms, firm 1 and 2 with firm 2 serving as the supplier to firm 1. To ensure that firm 2 is always able to fulfill orders from firm 1, in the experiments carried out, we replace constraint (17) with $I_{i,t} = I_{i,t-1} + B_{i,t} + q_{i,t} - q^*_{i-1,t},$ for $t = 1,...,T;$ replace constraint (27) with $I_{i,t} = I_{i,t-1} + B_{i,t} + q_{i,t} - q_{i-1,t},$ for $t = 1,...,T,\ i = 1,...,N;$ add the term $\sum_{t=1}^{T} b_{i,t} B_{i,t}$ to the objective function (16) and the term $\sum_{i=2}^{N} \sum_{t=1}^{T} b_{i,t} B_{i,t}$ to the objective function (25). The variables $B_{i,t}$ correspond here to the amounts of demand fulfilled through other means, such as outsourcing. A unit of demand of demand fulfilled in this fashion incurs the higher fulfillment cost $b_{i,t}$.
- Figure 13 is based on the same modified version of model P7 used to generate Figures 10-12 and by assuming that firms are allowed to share their emission caps.
- Figure 14 is based on the same modified versions of models P5-P7 used to generate figures 10-12; these models are further modified to incorporate policy mechanisms, other than strict caps, as in models P2-P4; the results are for the case where the firms are subject to individual caps; and where the carbon price and the carbon tax factor are both set equal to 2.
- Figure 15 is based on similar models to those used to generate figures 10-12, except that in this case we have three firms (the parameters for all three firms are the same). Firms 1 and 2 collaborate, while firm 3 makes decisions independently. The emission cap of firm 1 is varied as shown in the figure. Emission caps of firm 2 and 3 are C_2=1200 and C_3=950.

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