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Carbon pricing versus emissions trading: A supply chain planning perspective

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ABSTRACT

Carbon pricing (taxes) and carbon emissions trading are two globally practiced carbon regulatory policy schemes. This paper presents an analytical supply chain planning model that can be used to examine the supply chain performance at the tactical/operational planning level under these two policy schemes. Model implementation and analyses are completed using actual data from a company operating in Australia, where these environmental regulatory policies are practiced. Numerical results provide important managerial and practical implications and policy insights. In particular, the results show that there are inflection points where both carbon pricing and trading schemes could influence costs or emissions reductions. An erratic nonlinear emissions reduction trend is observed in a carbon pricing scheme as the carbon price increases steadily; whereas emissions reduction in a carbon trading scheme follows a relatively linear trend with a nonlinear cost increase. Overall, a carbon trading mechanism, although imperfect, appears to result in better supply chain performance in terms of emissions generation, cost, and service level; even though a carbon tax may be more worthwhile from an uncertainty perspective as emissions trading costs depend on numerous uncertain market conditions.

1. Introduction

Environmentally sustainable supply chain (SC) planning, also termed green SC planning, aims to develop unified design, planning and optimization models in which economic goals such as profit maximization and cost minimization are integrated with environmental goals such as carbon and greenhouse gas emissions minimization (Sundarakani et al., 2010; Varsei et al., 2014). The adoption of green SC planning efforts is greatly influenced by two widely-practiced regulatory efforts including carbon pricing (taxing) and carbon trading schemes (Schaltegger and Csutora, 2012).

SC planning and optimization on its own is a relatively intricate process with numerous variables and constraints to be taken into consideration and the incorporation of environmental dimensions adds to its complexity (Fahimnia et al., 2014a). Organizations facing these complex decision environments can find utility in tools for planning and managing their SCs. The development of SC modeling tools that have effectively integrated and evaluated environmental issues, alongside economic and business concerns, have only started to receive significant interest (Benjaafar et al., 2013; Brandenburg et al., 2014; Seuring, 2013; Tang and Zhou, 2012). Many of these modeling efforts focus on strategic planning levels of analysis such as the design of SC networks, while challenges at the tactical and operational planning levels are less explored (Seuring, 2013). In fact, the developments in some areas such as reverse logistics have dominated the early and recent green SC modeling literature (Srivastava, 2007).

Motivated by actual regulatory climate change pressures that are evolving in Australia, we develop and apply an analytical planning model to explore how organizations can manage their SCs under two carbon regulatory schemes. Not only are practical implications associated with the modeling effort presented, but research implications including further model development and investigations of additional outcomes are thoroughly discussed in this paper. The primary objective of this work focuses on the development and analysis of SC planning under emergent regulatory regimes. The proposed SC planning model contributes to the green SC modeling literature through helping organizations, policymakers, and even NGO's evaluate the tactical and operational implications from broad-based regulatory policy decisions.

The remainder of the paper is organized as follows. We begin in Section 2 with some background on environmental regulatory policies and organizational responses to these policies. Green SC management modeling efforts specifically those with a clear focus

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on managing carbon emissions are also reviewed in this section. This background sets the stage for further identifying the need for research we are presenting in this paper. The mathematical optimization model is then presented in Section 3. We utilize practical data from an actual SC for model implementation and analyses in Section 4. Discussions are presented on evaluation of the numerical results and potential implications for organizations and policymakers. The paper concludes by providing a summary of findings, limitations of the study, and directions for future research in Section 5.

2. Carbon regulatory schemes and green SC models

Australia has been under domestic and international pressures to transition into a low-carbon economy. To help meet the goals of a low-carbon economy, Australian regulators have decided to implement a two-stage set of regulatory environmental policy mechanisms. At the first stage, organizations need to respond to a carbon taxation (pricing) scheme initiated in July 2012 (Fahimnia et al., 2013a; Jotzo, 2012). A tonne of carbon pollution is priced at $23 in 2012 rising by 5% per year. At the second stage, after three years of fixed-price period, the scheme is expected to convert into a full emissions trading scheme in 2015. That is, a fixed carbon tax will change to a floating price which means that open trading will set the market carbon price. The trading scheme caps the amount of permits issued and is guided by the overall national commitment (Jotzo and Betz, 2009).

The *carbon pricing scheme* aims to control emissions by taxing the generated carbon. Each greenhouse gas emitter is charged a tax proportional to the size of the emissions generated. A carbon charge is meant to encourage companies to reduce their emissions using various practices and technologies whose managerial and implementation cost is less than the charge. The primary challenge with this mechanism is how to price carbon so that maximum emissions reduction can be achieved while ensuring that the economy is not significantly hurt. Some initial investigations of the cost implications and carbon reduction potentials of the carbon pricing scheme in Australia have been preliminarily posited in logistics and SC settings (Fahimnia et al., 2013a; Fahimnia et al., 2014a) and reverse operations (Fahimnia et al., 2013b). The findings of these studies have shown that the proposed carbon tax of $23 per tonne of emissions is unlikely to add considerably to the overall SC costs and has a minor impact on changing the industry behavior for running greener logistics and SCs.

In a *carbon trading scheme* (also known as a cap-and-trade mechanism), a limited number of tradable emissions allowances, the cap, is created for distribution among the players in an economy. Companies generating more emissions than the allocated allowances receive significant fines or purchase emissions allowances off the market from those generating fewer than the allowed emissions. The scheme creates both pressures (significant fines for over-polluting) and incentives (financial reward for selling surplus allowances) to encourage appropriate environmental initiatives. The goal is to either have companies purchase market-priced credits/allowances or invest in practices and technology to reduce or eliminate greenhouse gas emissions (Sarkis et al., 2010).

The two primary challenges with a carbon trading mechanism include (1) how to identify a method by which to allocate the initial allowances to each company, and (2) how should the fine be evaluated for companies going over allocated allowances, if they do not wish to purchase allowances. Some emissions allocation methods have been proposed and investigated (Böhringer and Lange, 2005; Burtraw et al., 2001; Cramton and Kerr, 2002). In the most widely used allocation method, emissions allowances are grandfathered (allocated) according to the available historical emission data (Böhringer and Lange, 2005). In a *grandfathering emissions allocation method*, an annual emissions reduction goal is set, relying on historical data, to determine what allowances are allocated to the players in a way to achieve the agreed upon goal.

The published green SC models can be classified into three categories. The first category includes modeling efforts with no specific focus on the regulatory schemes, but only trying to minimize the SC environmental impacts including carbon emissions. For example, Diabat and Simchi-Levi (2009) formulated carbon emissions in production, storage and distribution and studied the impact of different emission caps on the SC's economic performance. Mallidis et al. (2012) have considered carbon and particulate matters emissions in a network design problem. Emissions are incorporated for different transportation modes as well as the dedicated or shared use of warehouses. A robust multi-objective model is also presented by Validi et al. (2014) for design of a capacitated network for the distribution of dairy products in Ireland. Harris et al. (2014) present an evolutionary multi-objective optimization approach for solving a large location–allocation problem with capacitated facilities. Emissions generated in depots and through transportation operations are incorporated in the environmental objective function.

The focus of papers in the second category is on SC modeling in a carbon pricing environment. For example, Fahimnia et al. (2014b) and Fahimnia et al. (2014a) present tactical/operational logistics and SC optimization models to examine the potential cost and emissions reduction impacts of the Australian carbon tax on selected case companies. Fahimnia et al. (2013b) investigate a closed-loop SC operating in a carbon pricing environment.

The third category comprises a larger number of published articles with specific focus on SC modeling and performance analysis in a carbon trading environment. Emission factors including the carbon trading price and carbon cap are important players in these models. For example, Ramudhin et al. (2010) present an integrated bi-objective model for the simultaneous minimization of logistics costs and greenhouse gas emissions. Carbon dioxide equivalent (tCO_2e) emissions generated in transportation and manufacturing processes is used as the environmental metric. Chaabane et al. (2012) adds reverse SC operations to this model and presents a life cycle assessment (LCA) analysis to examine the impact of carbon trading price on the SC configuration decisions. More recent modeling efforts in this context have tried to assess the impact of carbon price and carbon cap variations on SC decisions (Abdallah et al., 2012; Bojarski et al., 2009; Diabat et al., 2013). There are also studies focusing on modeling uncertainty in carbon related parameters. For example, emissions costs are expressed stochastically in Chaabane et al. (2012), Giarola et al. (2012) and Pishvaee et al. (2012).

To the best of our knowledge, a study that focuses on comparing the economic and carbon emissions performance of the SC under 'carbon pricing' and 'carbon trading' schemes is non-existent, especially a study with a clear focus on organizational SC planning dimensions. This paper aims to address this research gap by investigating the impacts of these carbon regulatory schemes on an actual SC operating in Australia, where these environmental regulatory policies are being practiced. In addition to contribution to the existing academic literature, the findings of this study can be of significant value for industry practitioners (from an investment perspective) and policymakers (a policy definition and setting perspective).

3. Mathematical model

In the SC under investigation, a set of $\boldsymbol{I}$ product types (indexed by i) are produced on $\boldsymbol{J}$ machine centers (indexed by j) in $\boldsymbol{M}$ manufacturing plants (indexed by m). Production costs and carbon emissions rates may vary from one machine center to another based on the processing times, equipment age and manufacturing technology used. Manufactured products are distributed from manufacturing plants to ***C*** customer zones (indexed by c) either directly or through ***W*** warehouses (indexed by w). A range of ***V*** transportation modes (indexed by v) may be available each with its own shipment cost and emissions generation per item. Storage costs and emissions generations may also vary from one plant or warehouse to another. The aim is to develop a SC planning model focusing on economic and environmental aspects for planning horizon ***T*** (comprising t time periods).

Primary modeling assumptions include the following:

- Variety of product types to be produced is known.
- Number, location, and capacity of manufacturing plants and warehouses are known.
- Number and location of customer zones are known.
- Aggregate demand for all product types is known for all periods of the next planning horizon.
- Backordering the demand of a certain product type is allowed in all periods except for the closing planning period. The forecasted demand for each product type has to be satisfied, sooner or later, before the end of the planning horizon.
- A warehouse or customer zone may be supplied from more than one manufacturing plant.
- Capacity hours of machine centers, capacity of raw material supply, storage capacity of warehouses and plants, and distribution capacities are known.
- Transportation costs and emissions rates are proportional to distances traveled.
- End-users are the locations where products are delivered to the final customers with no product holding capacity.

Input parameters include the following:

d_{ict}	Forecasted demand for i in c at t
f_{mt}	Fixed costs for m to operate at t
f'_{wt}	Fixed costs for w to operate at t
h_{imt}	Unit holding cost for i in m at t
h'_{iwt}	Unit holding cost for i in w at t
hc_{imt}	Holding capacity in m for i at t
hc'_{iwt}	Holding capacity in w for i at t
p_{ijmt}	Processing time (hours) to produce a unit of i on j in m at t
l_{ijmt}	Labor/hour cost for the production of i on j in m at t
r_{imt}	Cost of raw material for producing a unit of i in m at t
v_{imt}	Variable overhead cost for the production of i in m at t
sh_{ict}	Unit backordering/shortage cost for i in c at t
$s^{max}{}_{ict}$	Maximum backordering/shortage allowed for i in c at t
α_{ijmt}	Capacity hours for the production of i on j in m at t
β_{imt}	Capacity units of raw material supply for i in m at t
τ_{imwvt}	Unit transportation cost of i from m to w through v at t
τ'_{iwcvt}	Unit transportation cost of i from w to c through v at t
τ''_{imcvt}	Unit transportation cost of i from m to c through v at t
$\mu_{1imwvt^{max}}$	Maximum transportation capacity of i from m to w through v at t
$\mu_{2^{max}_{iwcvt}}$	Maximum transportation capacity of i from w to c through v at t
$\mu_{3^{max}_{imcvt}}$	Maximum transportation capacity of i from m to c through v at t
$\gamma_{1_{im}}$	Inventory level of i in m at the start of planning horizon (t=0)
$\gamma'_{1_{im}}$	Inventory level of i in m at the end of planning horizon (t=T)
$\gamma_{2_{iw}}$	Inventory level of i in w at the start of planning horizon (t=0)
$\gamma'_{2_{iw}}$	Inventory level of i in w at the end of planning horizon (t=T)
c_{ijmt}	Estimated carbon emissions to produce a unit of i on j in m at t
a_{imwvt}	Estimated carbon emissions for the shipment of i from m to w through v at t
a'_{iwcvt}	Estimated carbon emissions for the shipment of i from w to c through v at t
a''_{imcvt}	Estimated carbon emissions for the shipment of i from m to c through v at t
b_{iwt}	Estimated carbon emissions for holding one unit of i in w at t
b'_{imt}	Estimated carbon emissions for holding one unit of i in m at t
C_{max}	Maximum allowed carbon emissions (carbon cap)
π	Proposed carbon price
L	A very large number

Decision variables include the following:

I_{imt}	Quantity of i produced in m at t
J_{imwvt}	Quantity of i shipped from m to w through v during t
J'_{iwcvt}	Quantity of i shipped from w to c through v during t
J''_{imcvt}	Quantity of i shipped directly from m to c through v during t
X_{imt}	Inventory amount of i in m at the end of t
Y_{iwt}	Inventory amount of i in w at the end of t
S_{ict}	Quantity of i backordered in c at the end of t

$$G_{mt} = \begin{cases} 1, & \text{if } m \text{ operates in } t \\ 0, & \text{Otherwise} \end{cases}$$

$$G'_{wt} = \begin{cases} 1, & \text{if } w \text{ is open in } t \\ 0, & \text{Otherwise} \end{cases}$$

With these parameters and decision variables, the two objective functions, cost and emission functions, can be formulated using mixed-integer linear programming (MILP). Objective function 1 (cost function), presented in Eq. (1), formulates the overall SC costs in planning horizon T, excluding the cost of carbon emission. Eq. (1) consists of nine components: fixed costs of opening plants and warehouses (components 1 and 2), production cost (component 3), inventory holding costs in plants and warehouses (components 4 and 5), transportation costs (components 6–8) and backordering/shortage costs (component 9).

$$\begin{aligned} Z_1 = &\sum_m \sum_t f_{mt}\, G_{mt} + \sum_w \sum_t f'_{wt}\, G'_{wt} + \sum_i \sum_m \sum_t \left[I_{imt} \left(\sum_j p_{ijmt}\ l_{ijmt} + r_{imt} + v_{imt}\right)\right] \\ &+ \sum_i \sum_m \sum_t h_{imt}\ X_{imt} + \sum_i \sum_w \sum_t h'_{iwt}\, Y_{iwt} + \sum_i \sum_m \sum_w \sum_v \sum_t J_{imwvt}\, \tau_{imwvt} \\ &+ \sum_i \sum_w \sum_c \sum_v \sum_t J'_{iwcvt}\, \tau'_{iwcvt} + \sum_i \sum_m \sum_c \sum_v \sum_t J''_{imcvt}\, \tau''_{imcvt} + \sum_i \sum_c \sum_t S_{ict}\, sh_{ict} \end{aligned} \tag{1}$$

Objective function 2 (emission function) is formulated in Eq. (2) representing the overall SC carbon emissions (tonnes of carbon-equivalent emission). Eq. (2) consists of 6 components: manufacturing emission (component 1), transportation emissions (components 2–4), and storage emissions in plants and warehouses (components

5 and 6).

$$Z_2=\sum_i\sum_j\sum_m I_{imt}\,p_{ijmt}\,c_{ijmt}+\sum_i\sum_m\sum_w\sum_v J_{imwvt}\,a_{imwvt}+\sum_i\sum_w\sum_c\sum_v J'_{iwcvt}\,a'_{iwcvt}$$
$$+\sum_i\sum_m\sum_c\sum_v J''_{imcvt}\,a''_{imcvt}+\sum_i\sum_w Y_{iwt}\,b_{iwt}+\sum_i\sum_m X_{imt}\,b'_{imt} \quad (2)$$

Regardless of the environmental regulations in place, the goal is to minimize the overall SC cost. The SC costs are obviously formulated differently depending on the policy instrument used. Considering the two objective functions, cost function in Eq. (1) and emission function in Eq. (2), the minimization of the overall SC cost when operating under carbon pricing scheme and carbon trading scheme can be formulated in Eqs. (3) and (4) respectively.

$$\text{Goal of carbon pricing scheme}: \quad \text{Minimize } Z_1+\pi\ Z_2 \quad (3)$$

$$\text{Goal of carbon trading scheme}: \quad \text{Minimize } Z_1+\pi\ (Z_2-C_{max}) \quad (4)$$

Eq. (3) charges a carbon tax of π corresponding to the amount of emissions generated in a carbon pricing situation. In a carbon trading environment, companies who generate more emissions than the allocated allowances ($Z_2>C_{max}$) can purchase allowances or permits off the market at a price of π (Eq. (4)). Companies generating fewer emissions than the allowed emissions allowances ($Z_2<C_{max}$) can sell their surplus allowances to those who may be polluting above their limits. In the latter case, ($Z_2<C_{max}$) would be a negative number turning carbon trading into a source of income that can help reduce the overall SC costs. The price of the tradable carbon allowances, the value of π, is determined by the supply and demand of the allowances in the market.

The objective functions in Eqs. (3) and (4) are subject to the following constraints:

Raw material supply restriction

$$I_{imt}\le\beta_{imt} \qquad \forall\ i,m,t \quad (5)$$

Machine center capacity limitation:

$$I_{imt}p_{ijmt}\le\alpha_{ijmt} \qquad \forall\ i,j,m,t \quad (6)$$

Storage capacity restriction in plants (Eq. (7)) and warehouses (Eq. (8))

$$X_{imt}\le hc_{imt} \qquad \forall\ i,m,t \quad (7)$$

$$Y_{iwt}\le hc'_{iwt} \qquad \forall\ i,w,t \quad (8)$$

Distribution capacity limits for the shipment of items from the plants to the end-users either directly (Eq. (9)) or indirectly (Eqs. (10) and (11))

$$J''_{imcvt}\le\mu_3^{max}{}_{imcvt} \qquad \forall\ i,m,c,v,t \quad (9)$$

$$J_{imwvt}\le\mu_1^{max}{}_{imwvt} \qquad \forall\ i,m,w,v,t \quad (10)$$

$$J'_{iwcvt}\le\mu_2^{max}{}_{iwcvt} \qquad \forall\ i,w,c,v,t \quad (11)$$

Inventory balance in manufacturing plants (Eq. (12)) and warehouses (Eq. (13))

$$X_{imt}-X_{im(t-1)}=I_{imt}-\sum_w\sum_v J_{imwvt}-\sum_c\sum_v J''_{imcvt} \qquad \forall\ i,m,t \quad (12)$$

$$Y_{iwt}-Y_{iw(t-1)}=\sum_m\sum_v J_{imwvt}-\sum_c\sum_v J'_{iwcvt} \qquad \forall\ i,w,t \quad (13)$$

Inventory balance at the customer zones

$$\sum_w\sum_v J'_{iwcvt}+\sum_m\sum_v J''_{imcvt}=d_{ict}-S_{ict}+S_{ic(t-1)} \qquad \forall\ i,c,t \quad (14)$$

Demand satisfaction constraint

$$\sum_m\sum_t I_{imt}=\sum_c\sum_t d_{ict}+\sum_m\gamma'_{1\ im}-\sum_m\gamma_{1\ im}+\sum_w\gamma'_{2\ iw}-\sum_w\gamma_{2\ iw} \qquad \forall\ i \quad (15)$$

Backordering restriction

$$S_{ict}\le S_{ict}^{max} \qquad \forall\ i,c,t \quad (16)$$

Inventory levels at the start and end of the planning horizon in plants (Eq. (17)) and warehouses (Eq. (18)):

$$X_{im0}=\gamma_{1\ im}\quad\text{and}\quad X_{imT}=\gamma'_{1\ im} \qquad \forall\ i,m \quad (17)$$

$$Y_{iw0}=\gamma_{2\ iw}\quad\text{and}\quad Y_{iwT}=\gamma'_{2\ iw} \qquad \forall\ i,w \quad (18)$$

Restrictions on decision variables

$$0\le I_{imt}\le G_{mt}L \qquad \forall\ i,m,t \quad (19)$$

$$0\le J_{imwvt}\le G_{mt}\ L\ \text{and}\ 0\le J_{imwvt}\le G'_{wt}\ L \qquad \forall\ i,m,w,v,t \quad (20)$$

$$0\le J'_{iwcvt}\le G'_{wt}\ L \qquad \forall\ i,w,c,v,t \quad (21)$$

$$0\le J''_{imcvt}\le G_{mt}L \qquad \forall\ i,m,c,v,t \quad (22)$$

$$0\le X_{imt}\quad\text{and}\quad 0\le Y_{imt} \qquad \forall\ i,m,t \quad (23)$$

$$0\le S_{ict} \qquad \forall\ i,c,t \quad (24)$$

4. Model implementation: a case study

4.1. Case company data

The case company, referred to as ABC, is engaged in the production and distribution of a broad range of outdoor dining and recreational furniture in Australia. The case study presented here focuses on the production and distribution of three popular types of aluminum-made powder-coat finish dining furniture at ABC. Two manufacturing plants in Adelaide and Melbourne are each equipped with six machine centers to produce the concerned products for distribution to five customer zones in Adelaide, Melbourne, Sydney, Perth and Brisbane. Production costs are slightly lower in Adelaide, but more emissions are generated due to older and less efficient machinery and manufacturing technology. ABC owns three warehouses in Adelaide, Melbourne and Sydney. There are additional rental warehouses in other cities which are not part of our analysis. The available transport modes differ from one route to another with various per-item transportation costs and emissions rates. Rail and truck transportations are available in most routes, but ocean transportation is available in few routes only.

Data collection was performed in two stages. Production data such as processing times, labor costs, and equipment emissions rates, were collected by the research team directly from the manufacturing sites. Logistics data was obtained from the available third-party logistics providers. The latter could include transportation costs and emissions rates for each transport mode at each road as well as the holding costs and emissions rates at the warehouses. The estimated demand data for 2014 was provided by the sales and marketing department.

According to the new environmental legislation in Australia, carbon is priced at $23 per tonne in 2012 (with no cap limit) rising by 5% each year until converting to full emissions trading scheme at the end of a three-year fixed-price period. Using the proposed SC planning model, we aim to compare the overall impacts of the proposed carbon pricing scheme and the projected carbon trading scheme on the economic and carbon emissions performance of ABC over a one year tactical planning horizon. The SC structure and related operations at ABC represents a broad range of Australian businesses in the discrete, durable parts manufacturing sector. The insights that will be gained from our comparative analysis can hence be valuable from both an investment perspective for organizations and a policy setting perspective for policymakers.

Table 1
Numerical results for scenario 1 (carbon pricing scenario).

Carbon price	Emission components (Tonnes)			Overall emission (Tonnes)	Cost components ($)					Overall SC cost ($)
	Production	Transportation	Storage		Production	Transportation	Storage	Shortage	Emission	
0	4547.6	4794.1	48.2	9390	4,478,517	2,304,180	144,252	69,627	0	6,996,576
5	4547.6	4467.3	48.2	9063	4,478,517	2,304,180	144,252	69,627	45,316	7,041,892
10	4547.6	4467.3	48.2	9063	4,478,517	2,304,180	144,252	69,627	90,631	7,087,207
15	4547.6	4467.3	48.2	9063	4,478,517	2,304,180	144,252	69,627	135,947	7,132,523
20	4547.6	4467.3	48.2	9063	4,478,517	2,304,180	144,252	69,627	181,263	7,177,839
25	4547.6	4467.3	48.2	9063	4,478,517	2,304,180	144,252	69,627	226,578	7,223,154
30	4544.0	4462.8	45.7	9053	4,479,015	2,304,480	138,627	69,627	271,576	7,263,326
35	4544.0	4462.8	45.7	9053	4,479,015	2,304,480	138,627	69,627	316,839	7,308,589
40	4544.0	4432.6	45.7	9022	4,479,015	2,305,632	138,627	69,627	360,897	7,353,798
45	4544.0	4432.6	45.7	9022	4,479,015	2,305,632	138,627	69,627	406,009	7,398,910
50	4531.5	4333.3	46.3	8911	4,480,777	2,307,488	156,563	69,627	445,551	7,460,006
55	4519.6	4290.6	50.9	8861	4,482,439	2,306,318	188,516	62,500	487,359	7,527,132
60	4519.6	4290.6	50.9	8861	4,482,439	2,306,318	188,516	62,500	531,664	7,571,438
65	4519.6	4290.6	50.9	8861	4,482,439	2,306,318	188,516	62,500	575,969	7,615,743
70	4519.6	4290.6	50.9	8861	4,482,439	2,306,318	188,516	62,500	620,275	7,660,048
75	4519.6	4112.4	50.9	8683	4,482,439	2,319,382	188,516	62,500	651,215	7,704,053
80	4517.7	3856.9	50.9	8425	4,482,705	2,339,030	188,516	66,500	674,039	7,750,790

4.2. Decision scenarios and numerical results

The MILP model presented in Section 3 was coded in CPLEX 12.3 using Excel spreadsheets for both populating the input parameters with real data and analyzing the numerical results. For the sake of comparative analysis, the proposed model is run in two scenarios based on the type of environmental policy instrument adopted:

Scenario 1 (*Carbon pricing scenario*): Using Eq. (3) as the SC planning objective, we monitor the value of the overall SC cost (i.e. $Z_1+\pi\,Z_2$) and its components (Eqs. (1) and (2)) while varying the carbon price (π) over a small and realistic range of $0–$80 per tonne of emission, given the history of these types of policy instrument schemes in other nations and regions of the world.

Scenario 2 (*Carbon trading scenario*): Using the grandfathering concept, we adopt Eq. (4) as the model goal to monitor the value of the overall SC cost (i.e. $Z_1+\pi\,(Z_2-C_{max})$) and its components (Eqs. (1) and (2)). The percentage carbon cap, and grandfathered amount, ranges from 100% with no emissions reduction to the maximum possible SC emissions reduction—given the available SC design, equipment, and infrastructure. Through trial-and-error, the model determines the desired carbon price at which ABC is forced to reduce its emissions below the carbon cap goal (percentage grandfathering goal).

Numerical results for Scenarios 1 and 2 are presented in Tables 1 and 2 respectively. In Scenario 1, the model outputs are shown for different carbon prices ranging from $0 to $80 per tonne of emissions in intervals of $5. Each row in Table 1 represents a different fixed price. The numerical results in this scenario include the overall emissions generated (fourth column) and overall SC cost (final column) and their constituting components. For the emission components, there are three SC operations causing emissions, production, transportation and storage. For example, at the carbon price of $0, the overall emissions generation is 9390 tonnes; while no emission costs are incurred from these emissions since the carbon price is assumed to be $0 per tonne (see the final cost component in Table 1).

Similarly, Table 2 summarizes the numerical results for the carbon trading scenario. The emission and SC costs are shown for a range of percentage grandfathering (shown in the first column) or target carbon caps (shown in the second column). The starting, baseline, maximum emissions generation is 9390 tonnes, when no emissions control regulatory instrument is in place (refer to the first row in Tables 1 and 2). A percentage grandfathering goal of 98% (see the second row) indicates that ABC should reduce its overall carbon generation from 9390 tonnes to 9202 tonnes (0.98×9390), a new carbon cap for ABC. Given the current SC design, technologies, equipment and infrastructure, the lowest possible emissions generation is 6197 tonnes, equal to 66% grandfathering.

There are three additional columns in Table 2 that require some explanation. The 'desired carbon price' column is determined by fixing the model at various carbon caps. The desired carbon price is the required price that makes the company reduces its emissions below a set carbon cap. Thus, a trial-and-error approach, using $1 carbon price increments, is used until the required emission level is reached. The number of allowances traded is also determined by the model and indicates the number of allowances that can be sold at the carbon market when the carbon emission is kept below the required emission level. Obviously, the number of allowances traded is calculated by taking the carbon cap (C_{max}) from overall emissions generated (Z_2). Negative numbers in Table 2 reflect the revenue that can be generated through trading allowances.

4.3. Analysis of the numerical results

Fig. 1 illustrates the SC cost and emissions reduction performance over the range of the carbon prices when a carbon pricing scheme is in place. The *y*-axis values in the figure represent the SC cost percentage increase and emission percentage reduction at each carbon price when compared to the $0 price. This perspective allows for evaluating the scheme effectiveness over a range of carbon prices. Fig. 1 shows that the SC cost increases steadily and relatively linearly as the carbon price increases. There is however a very erratic, nonlinear result to the emissions reductions. As can be seen there is a rapid decrease in carbon emissions which occurs at the very low carbon prices of $0–5 per tonne. After this point, emissions improvement remains unchanged until carbon prices reach $50 per tonne, when there is another slight jump in emissions reductions. The next significant improvement in emissions reductions occurs at a carbon price of over $75 per tonne.

Interestingly, the SC performance for ABC shows that the current carbon price of $23 per tonne has no more emissions improvements when compared to a $5 per tonne carbon price. In the price range of $5–$50, it is only the SC cost that increases due to the increased cost of emission, with no considerable improvement in emissions generation. Whether these types of characteristics are true for other

Table 2
Numerical results for scenario 2 (carbon trading scenario).

Percentage grandfathering	Carbon cap (Cmax)	Desired carbon price ($)	Emission components (Tonnes)			Overall emission (Tonnes)	Number of allowances traded	Cost Components ($)					Overall SC cost ($)
			Production	Transportation	Storage			Production	Transportation	Storage	Shortage	Allowance trading	
100	9390	0	4548	4794	24	9366	0	4,478,517	2,304,180	144,252	69,627	0	6,996,576
98	9202	1	4548	4467	24	9039	−163.2	4,478,517	2,304,180	144,252	69,627	−163	6,996,413
96	9014	48	4544	4372	23	8939	−75.1	4,479,015	2,308,512	138,627	69,627	−3606	6,992,176
94	8827	72	4520	4245	25	8790	−36.9	4,482,439	2,309,582	188,516	62,500	−2655	7,040,383
92	8639	80	4518	3857	25	8400	−238.8	4,482,705	2,339,030	188,516	66,500	−19,101	7,057,651
90	8451	80	4518	3857	25	8400	−51.0	4,482,705	2,339,030	188,516	66,500	−4077	7,072,675
88	8263	89	4507	3692	30	8230	−33.4	4,484,168	2,348,091	235,504	67,884	−2969	7,132,677
86	8075	93	4503	3495	30	8028	−47.9	4,484,833	2,366,121	235,504	67,884	−4452	7,149,889
84	7888	95	4503	3248	30	7781	−106.6	4,484,833	2,389,491	235,504	67,884	−10,123	7,167,589
82	7700	99	4493	2831	30	7354	−346.0	4,486,162	2,430,291	235,504	67,884	−34,253	7,185,588
80	7512	99	4493	2831	30	7354	−158.2	4,486,162	2,430,291	235,504	67,884	−15,661	7,204,180
78	7324	106	4471	2798	39	7307	−16.9	4,489,287	2,425,008	313,687	67,504	−1790	7,293,696
76	7136	112	4469	2567	39	7074	−62.1	4,489,553	2,447,700	313,687	95,007	−6953	7,338,994
74	6949	124	4469	2433	45	6947	−1.9	4,489,553	2,451,831	352,687	173,007	−237	7,466,840
72	6761	367	4393	2299	67	6759	−1.6	4,463,984	2,499,184	561,658	315,106	−582	7,839,350
70	6573	535	4349	2147	76	6571	−1.8	4,470,308	2,579,401	639,082	333,804	−946	8,021,649
68	6385	632	4331	1965	80	6376	−9.2	4,472,160	2,654,337	648,610	432,002	−5797	8,201,311
66	6197	6000	4303	1793	86	6182	−15.6	4,474,188	2,804,413	666,578	648,421	−93,300	8,500,300

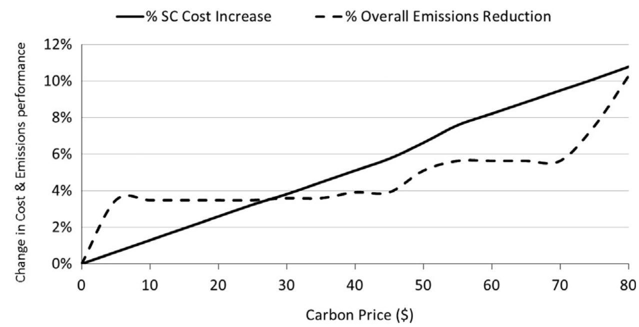

Fig. 1. Cost increase and emissions reduction performance in the carbon pricing scenario.

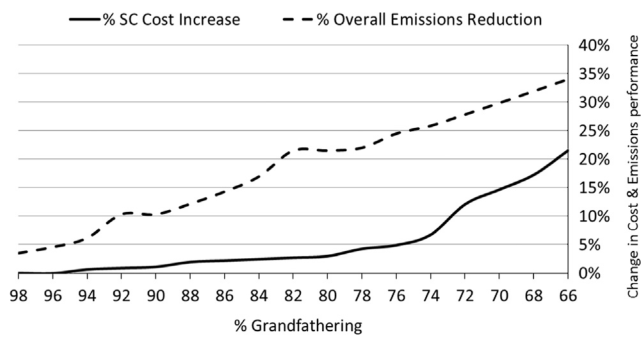

Fig. 2. Cost increase and emissions reduction performance in the carbon trading scenario.

companies and industries overall, should be carefully evaluated. The ultimate purpose of setting this price is to have some substantial emissions reduction, but if the increased costs do not cause organizations to decrease their emissions further, then the effectiveness of setting a particular price comes into question. Overall, the increase in carbon price does cause emissions reduction. The best situation, if the only goal is for effective carbon emissions reduction, for the organizations and the policymakers would be carbon pricing at the beginning of the portions when reductions remain unchanged, in this case at $5 and $55.

Our next analysis focuses on the carbon trading scheme. Corresponding to each grandfathering goal, Fig. 2 shows ABC's performance in terms of SC cost increase and emissions reduction. The baseline for this analysis is the situation when there is a 100% cap which implies a $0 credit price (i.e. no need for purchasing any allowances). In this scenario, emissions reduction follows a relatively linear and upward trend, similar to the behavior of SC cost increase in the carbon pricing scenario (Fig. 1). Two significant insights can be obtained from these results. Firstly, an increase in carbon prices from one stage to another in scenario 1 (carbon pricing) may not necessarily lead to improved emissions levels. Secondly, lowering percentage grandfathering can *continuously* result in greater emissions reductions (in the event the desired carbon prices are practicable) until a point when SC costs may become impractical. In case of ABC, the best environmental performance—given the current system design, equipment, and infrastructure—is obtained at the 66% grandfathering level (i.e. a 34% emissions reduction) that causes a 26.72% increase in SC cost. But careful analysis of the SC cost trend shows that there is a relatively stable, and albeit relatively small, slope increase in Scenario 2 as the cap tightens from 100% to 74%. This small steady SC cost increase inflects upward at the 74% grandfathering cap. Thus, the marginal benefit of emissions reduction for a given SC cost increase lessens after this point and becomes even worse after the 68% level. Careful investigation by ABC and policymakers are needed to determine these inflection points and the marginal

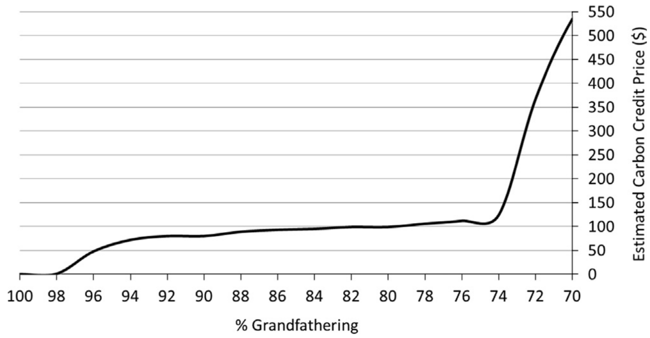

Fig. 3. Estimated carbon price to achieve grandfathering goals in the carbon trading scenario.

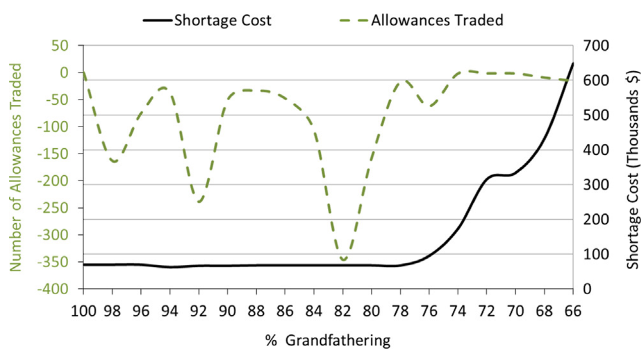

Fig. 4. Traded allowances against shortage cost in the carbon trading scenario.

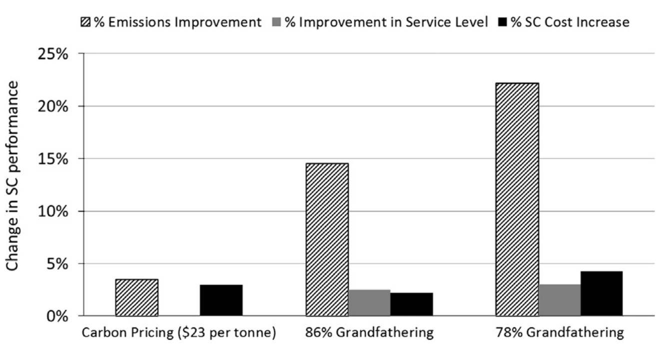

Fig. 5. SC performance under carbon pricing and carbon trading schemes.

benefits associated with the grandfathering level, especially when facing the nonlinear and erratic behavior of optimal cost solutions based on emissions reductions.

Using the fix carbon price trial-and-error procedure defined in Section 4.2, Fig. 3 shows the carbon prices required to achieve certain grandfathering goals. For instance, a carbon allowance price of $80 per tonne is required to force ABC to optimally reduce its carbon emission by 10% (i.e. a 90% grandfathering goal). It should be noted that the actual price of carbon allowances will be determined by the supply and demand for allowances in the market. The values in Fig. 3 are the estimated prices a company should be charged to keep its carbon emissions below the target grandfathering amounts. The actual market carbon price may be highly dependent on the performance of the other companies trading their allowances (i.e. how many surplus allowances are being sold and how many additional allowances are being purchased by affected companies). Governments and policymakers may also have influences on the actual carbon price through decisions on the provision of subsidies as well as the effective carbon cap setup. Fig. 3 shows that a 4% to 26% cap reduction from the baseline results in a slow, steady increase for the best price. But a cap of over a 26% reduction (grandfathering lower than 74%) will cause a very large carbon price increase and significant SC cost increase. It is at this stage that ABC should definitely consider investment in carbon emissions mitigation of its SC activities, either through SC restructuring or technology investment decisions. This result may not be true for all companies but a similar analysis can be completed for different cases.

One important policy question in a carbon trading environment can be how to determine the best percentage for the grandfathering level at which the actual market prices are close to the companies' estimated carbon credit price. It can be argued that carbon price estimations are more accurate if the number of allowances sold and the estimated revenue generated by a company is closer to zero. This level would have the minimal impact of the trading prices on SC performance. Fig. 4 shows a clear illustration of the number of traded allowances at each grandfathering level (the dashed line in Fig. 4). It can be seen that in some instances the number of allowances sold is close to the zero trading line, see for instance the 78% and 74–70% grandfathering levels. In another observation, when comparing the trends in traded allowances in Fig. 4 with numerical results in Table 2, we observe that the sharp decreases in the number of allowances traded at percentage grandfathering of 82% and 92% coincide with major reductions in transport emissions at these points through the use of greener transportation modes. These however occur in conjunction with increased transportation costs at these points.

This analysis should be examined against SC service level, an important SC performance measure. SC service level can be defined as penalties and compensation paid to customers in case of demand backordering. Fig. 4 indicates that the overall shortage cost at ABC increases dramatically after the 78% grandfathering point. Given the existing SC infrastructure, equipment, and technology, if emissions reduction is to be greater than 22%, ABC needs to either sacrifice its service level or increase its SC costs to a large extent. This type of decision can be examined against investment in alternative emissions mitigation strategies. This situation causes a conflict in the policymaker and industry practitioner perspectives. For example, Fig. 4 shows that the 74%, 72% and 70% grandfathering levels can be an ideal policy situation in terms of the number of allowances traded, with only 2 allowances (rounded up) traded in all cases, with 26%, 28% and 30% emissions reductions, respectively. However, from an organizational perspective, 74%, 72% and 70% grandfathering levels would imply an increase in overall SC cost by 6.72%, 12.07% and 14.65% (Fig. 2) as well as 148%, 353% and 379% poorer service levels respectively (i.e. $173,007, $315,106 and $333,804 shortage costs compared to a baseline of $69,627).

Fig. 5 provides a graphical comparison between the current carbon pricing situation in Australia (a $23 carbon price in Scenario 1) and two optimal points of Scenario 2 (in terms of SC cost, service level and number of allowances traded). Values are shown relative to the baseline situation when there is no carbon pricing or trading scheme in place. For Scenario 1, Fig. 5 shows the numerical results (emissions generation, service level and SC cost) for the current carbon price of $23 per tonne. From Scenario 2, we choose two situations, 86% and 78% grandfathering which have a reasonable SC cost and service level and require a small number of allowance trading, 48 and 17 allowances respectively (see Fig. 4).

ABC performs better in all aspects, emissions, service level, SC cost at the 86% grandfathering point when compared to the current carbon pricing scheme. The SC cost in this case is increased by about 2.2%, while carbon emissions and service level improve by 14% and 2.5% respectively. The 78% grandfathering point is where the environmental performance is improved to a marginally greater extent (i.e. 22% improvement), but the overall SC cost is accordingly increased noticeably (by about 4.25%). This result, if spread across all companies in an industry, may impose considerable impact on the national economy and competitive positioning of firms. Overall, carbon trading may outweigh a carbon pricing scheme, but the carbon cap amount (the percentage grandfathering) is subject to many factors including the carbon reduction goals and the current economic situation. It may also depend on what alternatives exist to help fund new processes technologies, infrastructure, and equipment.

Although there is more flexibility with industry support for a market-based mechanism for carbon trading, a carbon fixed price (carbon tax) may actually be more beneficial from an uncertainty perspective. If companies know that the carbon price will be stable, they can make investments to improve their carbon emissions performance based on certain price data. But, one challenge of a fixed price is determining what price to set. A wrong carbon fixed price may either cause unnecessary burden if it is fixed too high or go in the other extreme and be so low that no reductions are actually made in carbon emissions, which may be the case for ABC. Of course, any revenue generated by the fixed price (tax) can be used to help invest in public efforts to reduce carbon emissions. Our findings show that a market-based carbon trading mechanism may be a more effective way, even though imperfectly, to set the price to achieve the reduction in carbon emissions.

5. Conclusions and future research

Many nations, in response to global climate change caused by greenhouse gas emissions, have introduced carbon reduction regulatory policy schemes. Carbon pricing and emissions trading are the two most widely practiced schemes. Companies will consider their SC operations as carbon emitters and use planning and optimization tools to help evaluate their cost and emissions performance under these carbon regulatory policies. Given this context, in this paper we linked environmental regulatory policies to internal SC planning practices using a tactical SC optimization model. Two scenarios reflecting the two environmental regulatory policies were run using actual company data. Results were analyzed from overall SC cost and emissions reduction perspectives.

The results showed that various planning and policy insights can be gathered with the proposed mathematical programming optimization model. In both circumstances, the carbon pricing and trading schemes, there seemed to be inflection points where certain policies or practices could more meaningfully influence costs or emissions reductions. We have seen erratic nonlinear emissions reduction trends in a carbon pricing scheme as carbon price increases steadily, whereas in a carbon trading scheme, emissions reduction follows a relatively linear trend, but the SC cost increase is rather nonlinear. While a carbon tax may be more beneficial from an uncertainty perspective, we find that a carbon trading mechanism, although imperfect, result in better supply chain performance in terms of emissions generation, cost and service levels. Although the results are for one company and their planning purposes, policymakers can broaden the model to include various industries and company inputs. Whether all industries and companies will have similar characteristics is not known at the time, but the utility of such a model for a single organization is quite clear.

There are certain limitations for this study, but these limitations also provide opportunities for further research. First, extending the model to industry level analyses can be completed, although it may require the incorporation of additional variables, constraints and assumptions. Using broad-based macro-economic input-output analysis may be one way of helping define data that can be used to judge the influences of different prices and policies. Another limitation of the technique was the need to complete a trial-and-error for some price setting determinations. Making carbon price parameter a decision variable, although it might cause some nonlinearities in the resulting models, may allow it to jointly determine the desired price that can force a company to reduce the emissions level below the carbon cap goal. Also, our modeling effort was at the tactical operational planning levels, and hence the infrastructure, technology, equipment choices, and processes were considered fixed. The incorporation of such strategic decisions into the developed model would allow for consideration of when to invest in improvements rather than being completely reactive to just purchasing or selling allowances.

The field of green SC planning and emergent climate change regulatory policy is still evolving. The complexities of the decisions and policy relationships require thoughtful modeling. We have shown the utility of the tactical SC planning model developed in this paper and how advances in thought and practice can be achieved in numerous directions. The common saying is that we can think globally (strategic design and planning to tackle climate change in the long-term), but act locally (tactical and operational planning, harmonized with those strategic goals). This research shows the necessary investigations needed at multiple levels of analysis to help us solve one of the humanity's most pressing concerns.

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