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Review

The Design of Green Supply Chains under Carbon Policies: A Literature Review of Quantitative Models

Zhitao Xu [1], Adel Elomri [2], Shaligram Pokharel [3,*] and Fatih Mutlu [4]

1 College of Economics and Management, Nanjing University of Aeronautics and Astronautics, 29 Jiangjun Avenue, Nanjing 211106, China; gerard_butler@sjtu.edu.cn
2 Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, Doha, Qatar; aelomri@hbku.edu.qa
3 Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, Doha, Qatar
4 ICRON Technologies, Istanbul 34467, Turkey; Fatih.mutlu@icrontech.com
* Correspondence: shaligram@qu.edu.qa

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Abstract: Carbon footprinting of products and services is getting increasing attention due to the growing emphasis on carbon related policies in many countries. As a result, many enterprises are focusing on the design of green supply chains (GSCs) with research on supply chains (SCs) focused not only on cost efficiency, but also on its environmental consequences. The review presented in this paper focuses on the implications of carbon policies on SCs. The concept of content analysis is used to retrieve and analyze the information regarding drivers (carbon policies), actors (for example, manufacturers and retailers), methodologies (mathematical modeling techniques), decision-making contexts (such as, facility location and order quantity), and emission reduction opportunities. The review shows a lack of emissions analysis of SCs that face carbon policies in different countries. The research also focuses on the design of carbon policies for emissions reduction in different operating situations. Some possible research directions are also discussed at the end of this review.

Keywords: supply chain management; carbon policy; carbon emission; sustainability; green supply chains

1. Introduction

Carbon emission is considered one of the main contributors to global warming. As industries are assumed to be one of the major contributors to these emissions, their processes, and supply chains (SC) are increasingly subjected to various carbon policies [1].

Five major carbon policies generally considered by governments are the carbon cap, carbon tax, carbon cap-and-trade, carbon subsidy, and carbon offset policies. The carbon cap policy provides a specific limit on carbon emissions for industries [2]. The carbon tax policy requires industries to pay a unit fee for their emissions [3,4]. The cap-and-trade policy, also called carbon trading policy, allows the industry to sell or purchase emissions in a trading market [5,6]. A carbon subsidy policy allows industries to get a rebate for a unit reduction in carbon emission [7,8], and finally, a carbon offset policy allows industries to provide investments to projects that offsets their higher carbon emissions [3,9]. Although these are the basic carbon policies, some of countries have experimented with hybrid policies, such as the combination of carbon tax and carbon offset, as reported by Wang-Helmreich and Kreibich [10]. Due to the increasing adoption of carbon policies by governments, industries are also focusing on carbon issues in their SCs [11–13].

Carbon emissions are also associated with product life cycles and are referred to as the carbon footprint [11,14], essentially prompting a reduction of carbon emissions at different stages of the product life cycle [15–17]. Since emissions reduction tends to increase the cost of a supply system [18], both government and industry should also evaluate the economic impact of such a reduction. Zhou and Wen [19] mention that a firm's behaviour changes when carbon constraints are imposed on its business processes. This type of change can help the decision makers to understand the implications carbon policies in businesses. Schaltegger and Csutora [20] mention the accounting of emissions in order to promote sustainability. Kolk, et al. [21] mention the importance of establishing a clear mechanism to disclose emissions. Herold and Lee [22] mention that both internal and external carbon management practices of a firm influence the carbon disclosure strategies. However, correct assessments and evaluation can provide an opportunity to develop sustainable and green supply chains (GSCs). Daryanto, et al. [23] have also emphasized the development of a global GSC.

Various quantitative models are developed to assess costs and emissions in a SC. Govindan, et al. [24] review multi-criteria approaches for green SC analysis and selection. The analysis of SCs concerning the voluntary emission reduction is well developed [20,25–27], however, research on holistic perspectives of carbon policies in the GSCs are not adequate. Three research questions emerge for review: (1) What modelling techniques are adopted to assess the impacts of various carbon policies on SCs? (2) What are the differential impacts of the widely employed carbon polices on SCs, in terms of cost and emissions reductions? (3) What are future research directions for evaluating the effectiveness and the efficiency of the carbon polices with a SC perspective? This review addresses these questions by highlighting the development and trends in GSCs under different carbon policies. The review uses the content analysis method as discussed in Section 2. This method is used to scrutinize the research in terms of the drivers, actors, methods, decisions and the opportunities that help in the design and implementation of GSCs. The result of the review is presented in Section 3. In Section 4, conclusions and possible research directions are discussed.

2. Review Methodology

The content analysis method prompts for a systematic search of the factors in the given research context [28]. Authors mention that the content analysis method assists in evaluating the symbolic content of the literature available in various databases Pokharel and Mutha [29], Caunhye, et al. [30]. Content analysis is used here to search for information primarily from electronic databases such as ScienceDirect, EmeraldInsight, Taylor and Francis, and Inderscience. Keyword-based and phrase-based searches are also advised by Kondracki et al. [31] to collect the information. For this review, keywords including carbon emission, closed-loop supply chain, carbon policy, carbon tax, cap-and-trade, carbon offset, carbon cap, green supply chain, and sustainable supply chain are used. Literature was streamed to quantitative models under carbon policies. The selected literature is then segregated to a set of five content categories, as shown in Figure 1.

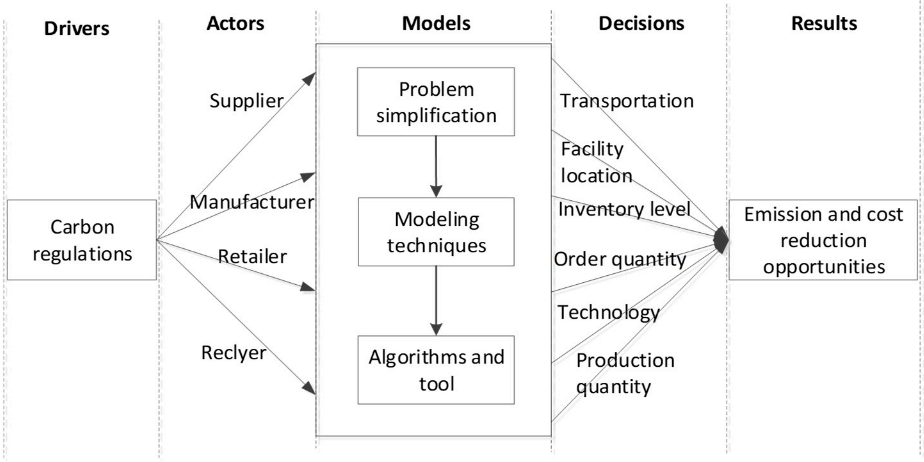

Figure 1. Framework for literature analysis.

As shown in Figure 1, carbon regulations (policies) are considered as the drivers for the design or redesign of SCs. The implementation of these policies involves various actors within a SC. In a SC, the actors can include a combination of two or more of the supplier, manufacturer, third party logistics provider (3PL), retailer, and the recycler. A two-echelon SC contains two actors, generally the manufacturer and the supplier, or the manufacturer and the retailer. In this case, the materials and the products flow in the forward direction. A multi-echelon SC contains three or more actors, for example, supplier, manufacturer, 3PL, and retailer. Similar to a two echelon SC, products and flows are also considered in a multi-echelon SC. A multi-echelon SC can contain both forward and the reverse flows of materials and products, called a closed loop supply chain (CLSC).

The analysis of SCs can be done in terms of problem simplification, established modeling techniques, or algorithms. The model outcomes can be in terms of one or more of the following: transportation mode selection, facility location, inventory level, order quantity, technology, and production quantity.

From all the collected literature, 85 were found to be closely related to this study. The literature is grouped for different levels and policies as shown in Figure 2. The columns in Figure 2 represent the number of papers under each group, for example, a discussion on taxation for different SCs (the first column). It is noted that the column labelled others refers to policies such as subsidies and carbon offsets. The number of papers is double-counted if a study discusses two or more policies. The depth of the color in the columns shows the research intensity at a particular level. The review shows that most of the literature focuses on multi-echelon SCs. Similarly, cap and trade and carbon tax are the most researched carbon policies. Additional literature is used for highlighting the importance of policies and emissions.

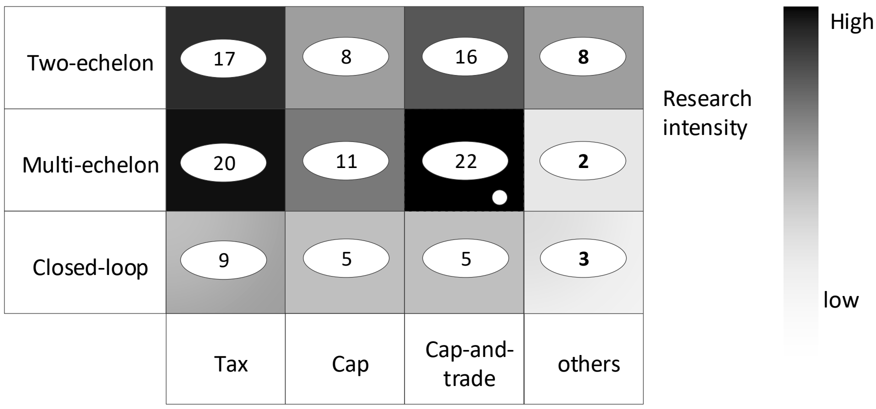

Figure 2. Research intensity for supply chains (SCs) under carbon regulations.

3. Results of the Literature Review

In this section, selected articles are grouped in different subsections in order to answer the research questions stated in Section 1. The review focuses on different aspects of GSC as shown in Figure 1. The insight developed for each of these related aspects is given below.

3.1. Drivers and Actors

The review shows that cap-and-trade and carbon tax policies are the most important drivers followed by carbon cap schemes. For example, the carbon tax policy is adopted in Japan, Austria, Denmark, Finland, Ireland, and the cap-and-trade policy is adopted in Europe and China. Economists and policymakers favor the carbon tax as it requires lesser administration in its implementation [13,32]. The cap-and-trade policy offers the opportunity for firms to share the benefits of low-emission activities by carbon trading [33]. The review shows that most of the research focuses on the activities associated with the forward flows in a supply system, only a few studies have explored the decisions for CLSCs.

3.2. Models and Decisions

3.2.1. Two-Echelon Level

Research on two-echelon not only focuses on the manufacturing processes, but also on the emissions generated during inventory [34–38] and transportation [36,37,39]. Table 1 illustrates the SC models according to their carbon policies, modeling techniques, SC actors, and decisions. Most of the models consider cap-and-trade policy, followed by a carbon tax policy. Some of these models are discussed below.

Stackelberg Game (SG) models are also used by the researchers to optimize the two-echelon SCs for carbon price [40–42], and product price Xia and Zhi [11], Hafezalkotob [43], Ren, et al. [44], Qi, et al. [45]. In these models, the government is mostly considered as the leader and the organization with the SCs is considered as the follower. Between the manufacturer and retailer, the former is usually considered as the leader for SC. Xu, et al. [46] provide a SC coordination model under cap-and-trade regulations in a make-to-order SC with wholesale prices and cost-sharing contracts. Hafezalkotob [43] introduces a tariff policy in the coordination model and shows different impacts on centralized and decentralized SCs. In an uncoordinated SC, the environmental impact would be different. For both the centralized and decentralized SCs, raising tariff rates can lead to an increase in demand for greener products, thus reducing the emissions Madani and Rasti-Barzoki [47]. Wang, et al. [48] examine the carbon tax policy for a decentralized SC by using a three-stage SG model and centralized SC by using a two-stage SG model. The authors show that both the cost and emission of a SC can be reduced if the actors have a distributed pricing power. Yang, et al. [49] considered two competitive SCs under the cap-and-trade scheme. In the vertical direction, the manufacturer and retailer are the leader and follower of a SG, respectively. In the horizontal direction, there is a Nash game about the emission reduction decisions between manufacturers. Their analysis shows that vertical cooperation leads to higher emissions reduction and lower retail prices. Yi and Li [42] establish a SG model with a manufacturer and a retailer with incentives (subsidies) and carbon tax. It was revealed that a subsidy policy can always drive energy saving and emissions reductions, while the effectiveness of the carbon tax policy relies on the initial emissions level and the exact carbon tax. The first observation in Yi and Li [42] is also highlighted by Yuan, Gu, Guo, Xia and Xu [38]. The problem with multiple competing retailers in the SG game is discussed by Li [50], Qi, Wang and Bai [45], and Zhou, et al. [51,52]. Zhou, Hu and Zhou [51] treat the carbon policy parameter as the decision variable and recommend that the government should tighten the carbon tax if the market has intensive retail competition.

Table 1. Models and decisions at the two-echelon level.

Author	Carbon Regulations	Modeling Techniques	Actors	Decisions
Hua, Cheng and Wang [35]	Cap-and-trade	E-EOQ	Single manufacturer-retailer	Order quantity
Barari, Agarwal, Zhang, Mahanty and Tiwari [9]	Tax	Evolutionary game theory	Single supplier-manufacturer	Emission cost and marketing cost
Choi [53]	Tax	Integral equation	Single manufacturer-retailer	Order quantity
Du, Zhu, Liang and Ma [40]	Cap-and-trade	SG	Single emission permit supplier and single emission-dependent manufacturer	Production quantity and carbon price
Jaber, et al. [54]	Tax, cap-and-trade	NLP	Single manufacturer-retailer	Production rate and joint lot size
Xia and Zhi [11]	Cap-and-trade	SG	Single manufacturer-retailer	Retailer's promotion level, emission reduction of per unit product
Yang, et al. [55]	Tax, cap, cap-and-trade	SG	Single manufacturer-retailer	Order quantity
Hafezalkotob [43]	Joint tax and subsidy	SG	Single manufacturer-retailer	Retail price, tariff for products
He, Zhao and Xia [15]	Tax	SG	Single supplier-manufacturer	Emission decrements
Hovelaque and Bironneau [34]	Tax	E-EOQ	Single supplier-manufacturer	Order quantity
Bazan, Jaber and Zanoni [36]	Tax, cap	Classical coordination model and VMI-CS	Single manufacturer-retailer	Production rate, number and size of shipments(truck)
Li [50]	Tax	NLP	Single distributor, multiple retailers	Delivery cycle, vehicle type
Ren, Bian, Xu and He [44]	Cap	SG	Single manufacturer-retailer	Wholesale price, retail price, quota allocation
Jiang, et al. [56]	Cap-and-trade	E-EOQ	Single supplier-manufacturer	Order quantity
Qi, Wang and Bai [45]	Cap	SG	Single manufacturer, two retailers	Retail and wholesale prices
Li, Su and Ma [39]	Joint tax and cap-and-trade	E-EOQ	Single manufacturer-retailer	Production rate, order quantity and number of shipments(truck)
Qiu, Qiao and Pardalos [37]	Cap-and-trade	MIP	Single manufacturer, multiple retailers	Production quantity, inventory, vehicle route, customer satisfaction
Xu, He, Xu and Zhang [46]	Cap-and-trade	SG	Single supplier-manufacturer	Wholesale price, order quantities
Xu, et al. [57]	Cap-and-trade	SG	Single manufacturer-retailer	Wholesale prices, production quantities
Ghosh, et al. [58]	Cap	E-EOQ	Single manufacturer-retailer	Order quantity, reorder point, number of shipments
Ji, et al. [59]	Cap-and-trade	SG	Single manufacturer-retailer	Wholesale price, marginal profit, promotion degree, emission reduction rate
Hafezalkotob [60]	tariff	SG	Single manufacturer-retailer	Wholesale price, retail price, tariff
Yang, Zhang and Ji [49]	Cap-and-trade	SG	Single manufacturer-retailer	Wholesale price, retail price
Yi and Li [42]	Joint tax and subsidy	SG	Single manufacturer-retailer	Wholesale price, retail price, energy-saving level, carbon-emission level
Zhou, Hu and Zhou [51]	Tax	Dynamic game model	Single manufacturer, multiple retailers	Retail price, wholesale price, carbon tax
Yuan, Gu, Guo, Xia and Xu [38]	Cap-and-trade	SG	Single manufacturer-retailer	Wholesale price, order quantities
Yuyin and Jinxi [8]	Joint tax and subsidy	SG	Single manufacturer-retailer	Wholesale price, retail price, energy-saving level
Bai, Gong, Jin and Xu [52]	Cap-and-trade	SG	Single manufacturer, multiple retailers	Wholesale price, retail price, green technology level

In a SC with two single actors, the enhanced economic order quantity (E-EOQ) model is used to obtain the optimal order quantity for the manufacturers [34,35,56] under a carbon policy. The E-EOQ model is adapted to determine the order quantity under the carbon tax [26] and the cap-and-trade policy [35]. Bazan, Jaber and Zanoni [36] analyzed the total SC costs through two different models. The authors concluded that the vendor managed inventory (VMI) with consignment stock agreement policy yields fewer SC costs compared to a classically coordinated SC. Jaber, Glock and El Saadany [54] discuss an integrated carbon tax and cap-and-trade policy by considering a penalty cost for exceeding the allowed emissions limit. The authors used a non-linear programming (NLP) model for the analysis and showed that penalties can be more effective in promoting GSCs than the coordinated policy for individual actors (the manufacturer and the retailer). Li, Su and Ma [39] adopt the E-EOQ model to examine production jointly with transportation outsourcing, and show that such a model can provide emissions reduction that is higher than that obtained through the cap-and-trade policy. The authors also mention that with the increase in the carbon price, emissions reduction also becomes smoother. Chen and Chen [32] developed an input-output model with standard emissions per unit of the product. The authors mention that the adoption of emissions standards can lead to a reduction in emissions and costs over the long term.

The emissions from transportation depends on the truck type [39,50] and the vehicle route [32], freight volume, and the delivery strategy. A probability model is used by Li [50] to model the delivery strategy for the distributors. The energy consumption as a function of freight volume for E-EOQ is considered by Li, Su and Ma [39]. Chen and Chen [32] combined the orders and transportation of the goods by using differential equations and NLP. The authors concluded that a joint policy of cap-and-trade and carbon tax can result in to a higher emissions reduction when the carbon prices are small.

All of the models surveyed here, except for the models in [38,40,58], consider a single period and a deterministic demand. When the market is emissions sensitive, any reduction in emissions would lead to a higher production cost and the demand quantities for the products follow an inverse function [41]. Du, Zhu, Liang and Ma [40] propose a coordination model under the cap-and-trade policy with the supplier having an emissions permit, and a manufacturer that is emission-dependent. Ghosh, Jha and Sarmah [58] analyze the policy of a strict carbon cap to develop a mathematical model for a two echelon SC that faces stochastic demand and partial back orders. The carbon constraint is used in the model to optimize costs and order quantity. The reorder point, as well as the number of optimum shipments, is also obtained from the model. Yuan, Gu, Guo, Xia and Xu [38] consider a cap-and-trade policy with known probability density function of the demand and information asymmetry in a SC. Jaber, Glock and El Saadany [54] investigated the cap-and-trade scheme in an environment with environment-concerned consumers, while Li [50] derived the optimal delivery strategies considering the time-dependent demands under the carbon tax policy.

3.2.2. Multi-Echelon Level

Some authors [61–63] discuss that the cost-based SC design and emissions based SC designs are different. Therefore, the relationship between carbon policies and multi-echelon SC decisions should be studied carefully. Table 2 provides constraints, modeling techniques, algorithms and tools, and the decisions associated with models for multi-echelon SC design and planning.

Table 2. Models and decisions at the multi-echelon level.

Author	Carbon Regulations	Constraints	Modeling Techniques	Decisions
Nagurney, et al. [64]	Tax	/	Variational inequality theory	Carbon tax rate
Ramudhin, Chaabane and Paquet [26]	Cap-and-trade	Handling capacity, BOM	MILP	Logistics, facility location, supplier selection, transportation mode
Giarola, et al. [65]	Cap-and-trade	Handling capacity	MILP	Selecting the best biomass and technologies options
Abdallah, et al. [66]	Cap-and-trade	Handling capacity, Material supply	MILP	Logistics, facility location, supplier selection
Ortiz-Gutiérrez, et al. [67]	Cap-and-trade	Handling capacity	MILP	Logistics, manufacturing technology, facility location
Jin, et al. [68]	Tax, cap, cap-and-trade	/	MILP	Logistics, transportation mode
He, et al. [69]	Tax and cap	/	Input-output	Inventory level, production quantity
Luo and Tang [70]	Cap-and-trade	Changeover variable	MILP model	Inventory level, production quantity
Palak, Ekşioğlu and Geunes [3]	Tax, cap, cap-and-trade, offset		MILP, E-EOQ	Logistics, supplier selection, transport modes
Tseng and Hung [71]	Tax	Handling capacity	MILP	Logistics, transport modes
Osmani and Zhang [72]	Tax	Handling capacity	Stochastic MILP	Logistics, technology, inventory level, facility capacity
Fahimnia, et al. [73]	Tax, cap-and-trade	Handling capacity	MINLP model	Logistics, inventory level
Hammami, et al. [74]	Cap, tax	Handling capacity, lead time	Production-inventory	Logistics, facility location
Ni and Shu [75]	Cap, tax	Storage capacity, service level	MINLP	Bounds of service time
Martí, et al. [76]	Tax, cap	/	E-EOQ	Facility location, customer allocation, transport modes
Fahimnia, et al. [77]	Tax	Handling capacity	MINLP	Logistics, vehicle speed
Wu, et al. [78]	Tax	Handling capacity, transmission constraints	SG	Carbon tax rate
Zakeri, Dehghanian, Fahimnia and Sarkis [5]	Offset	Material supply, capacity	MILP	Logistics, inventory level, facility location
Shaw, et al. [79]	Cap-and-trade	Handling capacity	chance constrained programming theory	Logistics, facility location
Moon, Jeong and Saha [62]	Cap-and-trade	Material supply, capacity	MILP	Logistics, facility location, inventory level
Sarkar, et al. [80]	multi-level trade credit	/	NLP	Logistics
Zhou, et al. [81]	Tariff	Handling capacity	Stochastic MINLP	Logistics, facility location, transport modes
Ma, Ho, Ji and Talluri [13]	Tax	Inventory capacity	SG	Sales price and production rate
Saxena, Jain and Sharma [4]	Tax	Handling capacity	Fuzzy goal programming	Logistics, facility location

The review presented in Table 2 shows that in multi-echelon SCs, logistics and facility location are the most important business decisions, followed by the selection of suppliers and transportation modes. Other researchers incorporate the technology options [65,67,72] and inventory level controls [13,62,70,73]. Beside the capacity limit, the material supply constraint [5,62,66], the customer service level constraint [6], the bill of material constraint [26], and the changeover constraint in sintering for the steel industry [70] are also considered for a multi-level SC design.

Table 2 also shows that mixed integer linear programming (MILP) is the most used approach in GSC design. Abdallah, Farhat, Diabat and Kennedy [66] consider green procurement and propose a MILP model to minimize the emissions in a SC. Their case study indicates that if the cap-and-trade policy were adopted in heavy manufacturing industries, the adoption of green technology and transportation would become more important. Fahimnia, Sarkis, Boland, Reisi and Goh [77] link the carbon tax with the fuel price in determining flows and truck speed in GSC design. They highlight that a reduction in fuel cost can be balanced by an increase in carbon price per ton.

Palak, Ekşioğlu and Geunes [3] analyze the impact of carbon policies on the selection of the supplier and transportation mode for a biofuel SC. Osmani and Zhang [72] develop a stochastic model with MILP formulation by considering a SC design for biofuel. The dynamic evolution of a bioethanol SC is studied through a multi-period and multi-objective MILP by Ortiz-Gutiérrez, Giarola and Bezzo [67]. The authors used the ε-constraint method for their analysis. Multiple objective MILP optimization models are proposed by Moon, Jeong and Saha [62] to minimize the shortages of raw materials and maximize the profit in a SC over the chosen multiple periods, and Ramudhin, Chaabane and Paquet [26] for analyzing the emissions and logistics costs for a SC.

Research is usually focused on the linear relationship between variables and the goals of the model, specifically for operational decisions like inventory level given in [75] and transportation mode given in [81]. Li, et al. [82] mention another impact, a change in product configuration due to carbon policies.

Ni and Shu [75] use mixed integer non-linear programming (MINLP) model to analyze carbon emissions and service time trade-off under the carbon cap and carbon tax policies. Their study reveals that under carbon policies, the cost of the SC becomes lower when there is a larger safety stock holding capacity. For transportation related research, the impact of carbon tariffs on the SC design is considered. However, authors like Hafezalkotob [43], Madani and Rasti-Barzoki [47], Hafezalkotob [60], and Zhou, Gong, Huang and Peters [81] mention that carbon tariffs can be administered as a tax by a country to the production system based in another country. Such a tax may help in the coordination of carbon pricing across the supply chain [83].

Some authors have used game theory to develop optimal strategies for individual actors in a decentralized GSC. The authors mention that taxes can have a detrimental effect on the profit levels and therefore, incentives are useful to implement methods and technologies to reduce emissions. Wu et al. [68] investigate carbon taxes in a decentralized SC in order to maximize multiple actors' profits. Similarly, Nagurney, Liu and Woolley [64] propose a model based on variational inequality theory in the context of the electric power supply chain under the carbon tax. Using a two-stage game model, Ma, Ho, Ji and Talluri [13] analyze a coordinated pricing problem subjected to the carbon tax. The authors develop pricing game models through two equilibrium models, the open loop and Markovian Nash. Sarkar, Ahmed and Kim [80] introduce a multi-level trade credit policy that serves as financial assistance for SC actors. The authors proved that this carbon policy is able to improve the economic and environmental performance of a three-echelon supply chain. Daryanto, Wee and Astanti [23] consider the emissions costs and its impact on single and multiple echelons. The authors mention that in order to avoid asymmetric power of a player, a game theory type of model may be more suitable in SC analysis.

One of the important aspects of GSCs is the uncertainty in demand over the long term. Demand uncertainty has been considered by He, Xu and Niu [69], Osmani and Zhang [72] through a probability density function based on an input-output model for carbon policy and the loss of profit for the firms. Shaw, Irfan, Shankar and Yadav [79] incorporate the uncertainties in capacities of the supplier, manufacturer and warehouse, and demand in order to develop a chance-constrained model of a GSC network. Their analysis shows a direct correlation between the number of manufacturing plants and the carbon price. It also shows that a higher demand variation results in higher carbon emissions. Osmani and Zhang [72] developed a stochastic MILP model considering multi-period and two-stage for a dual-feedstock lignocellulosic-based bioethanol supply chain design.

Santibanez-Gonzalez [84] use the multi-period two-stage model to analyze the GSC for carbon dioxide capture and storage in geological reservoirs. The authors consider uncertainty in the reservoir capacity in order to develop a MILP stochastic model for the analysis of cost and capacity in the SC. Saxena, Jain and Sharma [4] investigate the impact of supply and demand uncertainty and carbon tax policies. The authors obtain results for the number and location of new plants or extension of capacities for the planning period considered for remanufacturing.

3.2.3. Closed-Loop Level

The modeling techniques, constraints, decisions, and the algorithms of the models developed for CLSCs are given in Table 3. Unlike the study at other SC levels, the cap-and-trade is discussed more explicitly in CLSCs. Once the return and recycling of products are incorporated, the impact of carbon policies on CLSC and the relationship between the firms get more complex. Shu, et al. [85] analyze carbon tax and carbon subsidies to develop a two-stage SG model by considering the manufacturers, retailers, and the consumers as the entities of the SC. The authors show that subsidies should be used on carbon tax in order to obtain profit and to reduce emissions.

Some researchers use operational variables in their models, such as the batch size in manufacturing and shipment [86], inventory levels [87–89], technologies [87], product prices [7,88,89], and transportation modes [16,33,90]. The cost and emissions generated from both manufacturing and remanufacturing activities are also studied based on the variational inequality formula theory [88,89] and the game theory [7]. Li, Du, Yang and Hua [7] mention that, for the reduction in emissions, the subsidy should depend on the recycling price range. Bazan, Jaber and Zanoni [86] compare the classical model and the vendor-managed inventory with consignment stock agreement (VMI-CS) model for a CLSC with a manufacturer and a retailer with a facility for remanufacturing. They observed that the VMI-CS model outperforms the classical model in terms of cost reduction for a wide range of manufacturing rates, but not necessarily a more environmentally responsible choice.

Table 3. Models and decisions on the closed-loop level.

Author	Carbon Regulations	Constraints	Modeling Techniques	Algorithms and Tool	Decisions
Chaabane, Ramudhin and Paquet [87]	Cap-and-trade	Capacity, number of facilities	MILP	LINGO/LINDO	Logistics, inventory level, facility location, technology
Fahimnia, Sarkis, Dehghanian, Banihashemi and Rahman [2]	Tax	Capacity	MILP	AMPL/CPLEX	Logistics, facility location
Gao and Ryan [90]	Tax, cap-and-trade	Capacity	Stochastic MILP	Gams/CPLEX	Logistics, facility location, transportation mode
Li, Du, Yang and Hua [7]	Carbon subsidy	/	Game theory	/	Price of raw materials, wholesale and retail price of unit product
Zhang, Sun, Hu and Dai [88]	Cap, tax	/	Variational inequality formula theory	Modified project contraction algorithm	Logistics, inventory level, product price
Choudhary, Sarkar, Settur and Tiwari [12]	Tax, cap, cap-and-trade	Capacity	MILP	Forest data structure algorithm	Logistics, facility location
Bing, et al. [91]	Cap-and-trade	Capacity enhancement	MILP	LamaSoft/Xpress	Logistics, emission quota, facility location
Tao, Guang, Hao and Song [89]	Cap, tax	Periodic and global carbon emission constraint	Variational inequality and complement theory	Modified projection and contraction algorithm	Logistics, inventory level, product price
Mohammed, et al. [92]	Tax, cap, cap-and-trade, offset	Capacity	Stochastic MILP	Gams/CPLEX	Logistics, facility location, transportation mode
Entezaminia, Heidari and Rahmani [33]	Tax, cap, cap-and-trade, offset	Capacity, technology	MILP	CPLEX	Logistics, facility location, transportation mode, inventory level
Xu, et al. [93]	Tax, cap, cap-and-trade	Capacity, number of facilities	MILP	CPLEX	Logistics, facility location
Bazan, Jaber and Zanoni [86]	Tax and cap	Capacity	NLP	/	Batch size for shipment and manufacturing
Xu, Elomri, Pokharel, Zhang, Ming and Liu [17]	cap	Capacity, number of facilities	Robust MILP	CPLEX	Logistics, facility location
Haddadsisakht and Ryan [16]	Tax	Capacity	Hybrid robust/stochastic model	CPLEX	Logistics, facility location

A CLSC network coordination is also widely researched area. Most of the papers on CLSCs under carbon regulations have focused on a centralized system. Xu, Pokharel, Elomri and Mutlu [93] compare the effects of the carbon cap, carbon tax, and carbon cap-and-trade on hybrid and dedicated facilities for CLSCs. Their results show that under a cap-and-trade policy, dedicated CLSCs can have better emissions reductions. Similarly, cost efficiency is achieved for dedicated CLSCs under carbon cap policies, and emissions reduction is achieved in a hybrid CLSC under carbon tax policy.

The research on the decentralized CLSCs is also considered in the literature for optimizing the product price. Zhang, Sun, Hu and Dai [88] use variational inequality formula theory and studied the CLSC network equilibrium problem with the carbon tax policy and the carbon cap policy in order to optimize the prices of raw materials and the product. Tao, Guang, Hao and Song [89] consider the periodic emission and global emission constraints in a CLSC network equilibrium. The authors use variational inequality and complement theory for the equilibrium model and show that when carbon constraints are imposed, the profit levels for SC entities in a CLSC decrease.

Some authors have studied uncertainty in demand and product return in a CLSC. Mohammed, Selim, Hassan and Syed [92] use multiple scenarios to propose a stochastic model in order to design and plan a multiple product CLSC for multiple periods facing uncertain demand and returns. Bing, Bloemhof-Ruwaard, Chaabane and van der Vorst [91] consider carbon trading for a global plastic waste reverse SC redesign. The investigation shows that in order to reduce costs and emissions, the relocation of re-processors of the used products may be necessary. Uncertainties in demand and product returns are discussed by Gao and Ryan [90] by considering the emissions released during transportation. Haddadsisakht and Ryan [16] use a hybrid robust/stochastic model under volatile carbon tax rate and show that carbon tax does not directly influence the number of facilities. The number depends more on the use of the transportation modes.

Xu, Elomri, Pokharel, Zhang, Ming and Liu [17] investigate uncertainties related to global solid waste recycling. The uncertainties could be due to foreign exchange, the quantity of waste collected, and/or the cost of transportation. Their analysis shows that if there is a carbon cap, it is better to recycle the waste in the generating countries rather than in the waste importing countries.

For a CLSC, almost all of the selected literature focuses on the reduction of the effect of carbon regulations by using optimization on logistics in the SC. With regards to facility locations in the CLSC network design, the most popular techniques are the Stochastic MILP [90,92] and robust MILP [17].

3.3. Effect of the Carbon Policies

3.3.1. Carbon Tax Policy

A stream of research is focused on emission reduction under the carbon tax policy. This tax policy provides more flexibility, but compared to the other three carbon policies, it can impose a bigger financial burden to reach certain emission targets [33,85]. Some authors have mentioned that reduction in emissions is possible without a substantial increase in the cost [18,94]. However, both the cost and the emissions would decrease if a co-option strategy is used by the firms under the cap-and-trade policy [95]. A co-option strategy refers to the coexistence of collaboration and competition mechanisms in a system. Cachon [96] investigates the emission reduction opportunities for the retailer by considering the emissions generated by the consumers. The research shows that carbon emissions are reduced more with an increase in fuel efficiency than with carbon tax. However, in a two-echelon SC, if subsidy and carbon tax policies are promoted simultaneously, both the manufacturer and the retailer would be encouraged to focus on the efficiency [42]. The same conclusion is also obtained by Shu, Huang, Chen, Wang and Lai [85] in trade-old-for-remanufactured CLSC. Olsen, et al. [97] mention that if a carbon tax is implemented through proper analysis of their impact, it can support government investments in projects that reduce emissions. With good pricing, companies may also be attracted to invest in carbon sequestration. Carbon tax is an important policy as it not only assists to generate funds and reduce emissions, it can also assist in developing a comprehensive policy on climate reform [98].

Li [50] mentions that if carbon taxes are not high, distributors adopt frequent delivery strategies, potentially leading to a higher delivery cost. However, if retailers and manufacturers use a wholesale pricing contract or the markdown money contract under a carbon tax policy, it can successfully entice the retailer to source locally [53,99]. Choi [100] mentions that carbon footprint-based taxation may also bring changes in sourcing decisions. The buyer may consider saving through local sourcing, even if production and logistics costs are higher.

Under the carbon tax policy, optimal CLSC designs may involve improvement or deterioration in terms of costs and emissions [2]. Therefore, carbon subsidies can help to reduce emissions, especially when the carbon tax is very high [2]. However, Li, Du, Yang and Hua [7] mention that the recycling price range should be considered while developing a subsidy policy. In a CLSC involving uncertain demand and returns, Gao and Ryan [90] show that if there is a variation in the flow of the product, then both the costs and the emissions for a CLSC would increase. Xu, Elomri, Pokharel, Zhang, Ming and Liu [17] obtained similar results for a global reverse logistics network design with a global carbon cap policy.

Although a reasonable tax rate is required, only a few studies such as Zhou, Hu and Zhou [51], Nagurney, Liu and Woolley [64], Wu, Huang, Hsu, Wang, Lin and Chen [78] treat it as a variable in the models. The most popular approach in the literature is to use sensitivity analysis in evaluating the carbon tax rate in order to promote GSCs.

3.3.2. Carbon Cap Policy

The carbon cap policy can be applied with two principles, that is, grandfathering and benchmarking. Ji, Zhang and Yang [59] mention that the grandfathering principle uses the trend of emissions, but benchmarking focuses on the output based on a common benchmark in the sector. Their analysis shows that the adoption of benchmarked processes can lead to the production of low carbon products. However, the carbon cap policy does not always yield a low cost solution [101] as the carbon cap level is the most important factor for the industries [33]. Therefore, the knowledge on a range of carbon cap becomes important for policymakers to design different levels of carbon cap [45]. Between carbon tax and carbon cap policies, the latter is generally less flexible in terms of emission reduction cost [33] but it usually leads to a lower total cost [69,76].

Some studies have extended the application of the common carbon cap policy to analyze the GSCs. For example, Xu, Elomri, Pokharel, Zhang, Ming and Liu [17] introduce a global carbon cap policy for GSCs by considering the flow of electrical wastes and find when policy changes in different countries the flow of wastes also changes. Some authors (such as [74,88,89]) have considered periodic carbon emission constraints and a global carbon emission constraint on the CLSC. Hammami, Nouira and Frein [74] mention that periodic carbon caps lead to lower emissions, but the per unit emissions may be increased compared to that of the global cap. Zhang, Sun, Hu and Dai [88], however, find that a global carbon cap is better than the periodic carbon cap. Tao et al. [76] mention that the global cap has an advantage when the emission limit is high, while the periodic cap is superior when the emission limit is low. He, Xu and Niu [69] introduce the carbon emission elasticity of profit measure to evaluate the impact of carbon policies and show that the mandatory cap is better than the carbon tax from an industry standpoint. Martí, Tancrez and Seifert [76] mention that the optimal network structure for the carbon tax and carbon cap policies are similar. However, if the service time constraint is considered, the carbon tax policy may have more effect in the SC design [75].

3.3.3. Cap-and-Trade Policy

The cap-and-trade policy has been researched more explicitly than other carbon policies as there are opportunities for income or offsets [5]. With cap-and-trade policy implementation, emissions and costs could decrease simultaneously [15,35,93]). Comparatively, under cap-and-trade policy, firms would not be motivated to adopt green remanufacturing technologies when the customer has an independent demand for remanufactured products [102]. This case is reversed when there is a market for such products [103]. If more customers opt for low-carbon products, the cap-and-trade would be an asset to the manufacturing company [104].

Zakeri, Dehghanian, Fahimnia and Sarkis [5] mention that, in energy intensive industries like aluminum, the carbon-trading policy can result in better emissions reduction than the carbon tax policy. However, for manufacturers aiming to adopt green technology, the profit level decreases with the carbon cap policy than with the cap-and-trade policy [105]. Palak, Ekşioğlu and Geunes [3] mention that a cap-and-trade policy is better than a carbon offset policy. However, for the carbon offset policy, the trading market effect of carbon cap and carbon price pose differential effects on the SC.

Supply chain operations are less responsive to an increase in price versus an increase in the carbon cap [3]. The potential for the reduction in emissions with the carbon cap alone is limited [91,106]. The variation in the carbon cap does not impact the strategies for optimal trade credit or inventory replenishment [106]. It is not always possible to obtain emission or cost reduction through a lower cap level [91]. However, with the carbon cap and the use of heterogeneous transportation modes, both costs and emissions may be reduced [102]. Yenipazarli [102] uses the SG model and finds that a carbon cap either reduces or maintains the emissions level. There is an appropriate threshold of the carbon cap for emission reduction [45], therefore, in an emission-trading environment, a two-threshold policy is used for decision making [57] If the carbon cap is lower than one threshold, emission permits are bought by the manufacturer from the market, however, if the cap is between the two thresholds, the manufacturer becomes indifferent in the purchase or sale of emission permits. A similar finding is also obtained by Yenipazarli [102], Li, et al. [107], and Hafezalkotob [43]. Hence, the carbon cap should be carefully set in order for it to be effective in emissions reduction.

The carbon tax policy may be a more effective option for reducing emissions compared to a carbon cap [6]. Carbon price influences the operational costs and the level of emissions. Therefore, GSC designs should consider logistics as well. This view is proposed by various authors for two-echelon SCs [37], the multi-echelon SCs [39,55], Fahimnia, Sarkis, Boland, Reisi and Goh [77] and the closed-loop SCs [33,93]. Other authors [68,70,87,91,108] have also mentioned the need to use global perspectives on the SC design.

In general, the cap-and-trade policy shows advantages in motivating the industry to pursue GSCs. However, its impact on the supply and consumption of carbon credits in GSCs should be explored further. This review found only two studies [40,41] that focus on SCs with large emissions, such as those from the power plants and paper factories. However, such SCs release emissions for a long time. Therefore, the cap and the volatility in the carbon trading market may affect the level of emissions reduction in such SCs. The review also shows that the research on the SCs at multi-echelon and closed-loop levels across the global network is still absent.

4. Conclusions

This paper focuses on the review of the research on the GSC design. The review shows that research on GSCs has increased since 2012 due to growing worldwide environmental concerns and the tightening enforcement of carbon policies in many countries.

Various quantitative models can be considered for the GSC design. However, the choice of a quantitative model depends mainly on the actors involved, followed by the strategic and the operational SC decisions to be made, rather than solely on the carbon policies. Most of the research on multi-echelon and the CLSC are focused on facility location, flows, the choice of suppliers, and the transportation mode. Some researchers also consider demand uncertainty, multiple period transactions for profit maximization.

The review shows that MILP techniques are the most popular techniques for CLSCs. Although advances in optimization algorithms are making it easier to solve large models; such models have a limited capability for integrating the strategic and multi-period operations.

From the perspective of carbon policy, most studies focus on cap-and-trade, followed by the carbon tax and the mandatory cap. The carbon policy with a mandatory cap is more effective than that without it, but they are not always efficient. The carbon tax policy may be better, but the cost of implementing it might be a lot higher for the firms [38,42,92]. With a lower carbon tax, it is difficult to achieve higher emission reduction [39]. With the cap-and-trade, however, carbon credits available in the market [75,92,94] and among the SC partners [6,80] can help in achieving more economic benefits [6] and emissions reductions. Some studies on subsidy and carbon offset policies are also available. Compared with the former two policies, the subsidy and the offset policies are voluntary, rather than compulsory.

The review shows that carbon policy should be designed and implemented for a given specific situation, and a universal model may not be applicable for both cost and emissions minimization. For instance, a cost-efficient carbon policy for one industry may not be applicable to the other industry due to their inherent cost structures [70]. It is worthy to note that, the integration of different carbon policies (like subsidy and tax or like cap and tax) may be a better option [8,42,85] for the cost and emissions efficiency. Hence, the industry should make a particular response to a specific carbon policy by optimizing its specific SCs. Generally speaking, customized techniques are necessary to assist a firm to pursue low-carbon operations less expensively.

Further Research Directions

Arising from the above, some research directions for consideration are given below.

(1) The current research can be extended to assess the stochastic nature of the carbon policy parameters. Although the uncertainty in the GSC is mentioned in the literature, it is limited to the customer demand aspects [38,40,41,69,72,90,109]. The uncertainties can also be seen in various carbon policies, such as the shift of the carbon tax policy to a carbon trading scheme in Australia [110], and the parameters of a particular carbon policy, such as the unstable carbon price on the market, the carbon tax rate and the carbon price on the carbon market. The increasing variability of the stochastic parameters degrades the financial and environmental performance of a SC Osmani and Zhang [72]. As these unstable parameters are the major causes leading to SC risk, they also influence the GSC design. Therefore, uncertainty factors should be used in GSC design.

(2) The current research lacks a comprehensive analysis of international carbon policies on a SC. The carbon policies along a GSC can vary from one region to another (for example, Europe and Asia) or from one country to another [111]. Therefore, when regions or country-specific policies are not considered, it can even lead to a higher level of emission [81] because of carbon leakage. One possible approach to cope with the carbon leakage problem is to impose innovative carbon policies, like carbon tariffs on the goods from unregulated countries [81] or a global cap policy [17]. Another study [83] mentions that a policy of incrementally increasing carbon taxes may help in the coordination of carbon pricing across a SC (that may involve many nations) and it may support a holistic analysis of carbon policies for a GSC. A possibility of linking carbon policies across nations for a coordinated emissions reduction is also mentioned in Wang-Helmreich and Kreibich [10]. Research can, therefore, be extended to analyze the relation between carbon emissions with different carbon policies and their impact on the GSC design.

(3) Carbon taxes and subsidies can promote remanufacturing [2,7,102] and low-carbon technologies [107]. The carbon offset policy provides the firms with opportunities to achieve carbon-neutral SC by engaging in emissions reduction offset projects [112]. However, only limited studies have mentioned the subsidy, offset, and the pricing policies, and so their extensive effects on different levels of a SC deserve further investigation. Furthermore, the implications of carbon policies are higher in SCs [8,68] as the emission reduction activities involve various firms, government, and customers. Existing studies indicate that the effectiveness of carbon policies relies highly on the thresholds of the carbon policy parameters. Research can be extended to study joint carbon policies [39,54,86] and carbon footprints [32]. Such research can provide valuable insights for policymakers to understand and develop a correct level of subsidies.

(4) Emissions can be affected through coordination [42,112,113],) or through collaboration [9,44]. Firms can affect their partners' emissions by coordination, information sharing, or even simply by leveraging their economic power [38,112]. Most of the studies in a decentralized GSC assume that there is one leader and one follower in decision making. The competition of the actors in a supply system or between different supply systems has also been discussed. However, real-world competition is more complex as it involves multi-faceted actors. For example, two competitors can cooperate in collecting and disposing of the used products. Therefore, the effect of carbon policies on a collaborative GSC design becomes necessary.

(5) The sustainability of SCs under carbon policies is another potential area of research. Sustainability is considered in terms of three main aspects which are economic, environmental and social, and these three aspects are interdependent in the SCs. In particular, it is worthwhile to note that social welfare is not exhaustively considered in existing models. As the relationship between the carbon cost and social welfare also depends on market competition [114], the research can also be extended to the impact of carbon policy on social welfare. In addition, the sustainability of a GSC and customers' willingness to pay for products can also be explored.

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