Proceedings of the 2022 Winter Simulation Conference
B. Feng, G. Pedrielli, Y. Peng, S. Shashaani, E. Song, C.G. Corlu, L.H. Lee, E.P. Chew, T. Roeder, and P. Lendermann, eds.

CARBON POLICIES IN NETWORK DISTRIBUTION: A SIMULATION APPROACH FOR SUSTAINABLE SUPPLY CHAINS

Marina Meireles Pereira Mafia
Elias Ribeiro da Silva
Arne Bilberg

Department of Technology and Innovation
University of Southern Denmark
Alsion 2
Sønderborg, DK-6400, DENMARK

ABSTRACT

New carbon policies are being introduced by many countries due to stricter sustainability targets. However, the existing research lacks investigation on how carbon policies influence supply chain distribution networks. In this paper, we investigate how different network policies would influence the supply chain carbon footprint and costs while analyzing how different strategies to minimize the total emissions potentially influence the network distribution operation. A simulation approach is used to investigate the impact of carbon policies in a retail company. The case study results show that adopting a carbon emission policy represents a small increase in transportation costs despite affecting omni-channel distribution network strategies to reduce transportation carbon emissions. This research is expected to be useful to support companies with a new approach for a more data-driven decision-making process toward sustainable distribution networks.

1 INTRODUCTION

Several sectors of the economy have been suffering negative impacts worldwide driven by climate change, while the accelerating economic growth and industrialization have posed significant challenges to global carbon mitigation efforts and climate change responses (Rahman et al. 2022). Therefore, governments are looking for measures to minimize the impact caused by industrialization.

The COP26 summit brought parties together to accelerate action towards the goals of the Paris Agreement and the United Nations Framework Convention on Climate Change. The Glasgow Climate Pact presented a range of items, including strengthened efforts to build resilience to climate change and curb greenhouse gas emissions (UNFCCC 2021). The document also states that rapid, deep, and sustained reductions in global greenhouse gas (GHGs) emissions are needed to limit global warming, including reducing global carbon dioxide (CO_2) emissions by 45 percent by 2030 relative to the 2010 level.

Thus, with the pressure from governments due to new sustainability targets, companies are under pressure to adopt more sustainable policies. According to the Climate Change 2022 report (IPCC 2022) the transport sector account for 23% of global energy-related CO_2 emissions, of which 70% of direct transport emissions came from road vehicles. Therefore, in order to minimize emissions, CO_2 policies have been introduced by many countries, but many others are still analyzing how to implement or are under consideration (World Bank Group 2022). Consequently, many companies are struggling to understand how these new carbon pricing policies will impact their operations.

978-1-6654-7661-4/22/$31.00 ©2022 IEEE

This difficulty has been more evident in omni-channel operations since their distribution network contains several possibilities for delivering the product to the end customer. Omni-channel operations imply a supply-demand synchronization to manage fully integrated channels (Pereira et al. 2018; Pereira and Frazzon 2019). Therefore, consumers are able to shop by interacting with different fulfillment concepts without noticing the different channels operating in the background (Hübner et al. 2022). With the integration of the online and offline channels distribution operations, there was an expansion of the possibilities of product distribution and new fulfillment categories (Hübner et al. 2016), allowing online customers to choose the way they want to receive the product. With this, we have a distribution network with multiple sources to multiple delivery locations. Rout et al. (2021) also sustain that, due to the multiple delivery locations, the vehicle type largely affects the transportation service and should be analyzed to improve the supply chain performance.

Many studies have been adding CO_2 emissions from logistics operations into their supply chain analysis on sustainability, but only a few of them address the CO_2 emission cost. In the context of the omni-channel retail supply chain that aims to reduce CO_2 emissions, we can highlight the paper by (İzmirli et al. 2021), which states that by using a well-designed inventory policy, an omni-channel network can benefit from decreased transportation cost and consequently contribute to CO_2 emission reduction. However, the authors did not include the CO_2 cost in their analyzes, just assuming that reducing the transportation cost would consequently reduce the CO_2 cost.

Thus, it is still unclear how emission costs due to carbon taxes adopted by various countries influence the total cost of distribution and the supply chain operationalization, especially omni-channel supply chains. Besides, it remains unclear how organizations can structure themselves to consider this new metric in their cost analysis and transportation choices.

Therefore, the objective of this paper is to investigate how including the variable air pollutant emissions into the total logistics costs influences the network distribution.

According to the Intergovernmental Panel on Climate Change (IPCC 2022) transport-related emissions in developing regions of the world have increased more rapidly than in Europe or North America. For such, this paper conducts a case study based on real data from an omni-channel retail company in Brazil. Since Brazil still does not have a CO_2 policy (currently under consideration), we will investigate how policies adopted by various other countries would influence the total logistics costs for the company. We also investigate whether it would potentially influence the type of trucks used.

The remaining of the article is organized as follows: Section 2 presents a background of sustainable supply chains and carbon policies in transportation. Next, Section 3 describes the research design, including data collection, modeling parameters, and experiments. Section 4 presents and discusses the results of the what-if scenarios, while Section 5 highlights the implications, contributions, and final remarks.

2 THEORETICAL BACKGROUND

2.1 Sustainable supply chains

Nowadays, there is an increasing awareness of the problems of supply chains in industry, and pressure from society toward sustainable development has steadily increased (Durán-Romero et al. 2020; Geissdoerfer et al. 2018; Jamali and Rasti-Barzoki 2019). As a result, the triple bottom line concept has been used to describe the comprehensiveness of sustainability approaches, including ecological, economic, and ethical/social sustainability (Elkington 1997). Carter and Rogers (2008) define sustainable supply chains as a strategic, transparent integration and achievement of an organization's social, environmental, and economic goals in the systemic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its supply chains.

Firms are focusing on developing their core business to maintain competition in supply chains, meet their global needs in the economic environment, and respect the goal of creating sustainable supply chains (Jamali and Rasti-Barzoki 2019). Nowadays, the selection and management of transportation is a significant factor in creating a more green supply chain. Therefore, corporations are expected to improve their performance indicators to decrease unfavorable external factors of their own logistics activities, such as carbon emissions (Zhu et al. 2008).

Supply chain and logistics activities, including transportation, consumption, production, and storage, accelerate the GHG emission, accounting for nearly 50%–70% of the total emissions (Rout et al. 2020; Hanifan et al. 2012). Moreover, logistics is one of the areas recognized to be primarily responsible for GHG emissions. According to the World Economic Forum (2016), around 13% of the GHG emissions globally are due to the logistics industry. Next, we explore the current background of carbon policies in transportation.

2.2 Carbon policies in transportation

Transportation is a major factor in greenhouse gas emissions and the main cause of air pollution in cities. However, the transport sector has not seen the same gradual decline in emissions as other sectors. Road transport is by far the biggest emitter within this sector, accounting for more than 70% of all GHG emissions from transport in 2014 (European Commission 2016). Road transport emits mainly CO_2, NOx, CO, and NMVOCs, and a small source of N_2O, CH_4, and NH_3. However, the only major direct greenhouse gas emission is CO_2 (Eggleston 1998). Therefore, although other gases are emitted during transportation, most policies are carbon-related.

Emissions of CO_2 are directly related to the amount of fuel used (Eggleston 1998). However, a recent study from the European Union demonstrated that the emissions across different truck subgroups oscillate and variate even more than consumption. For instance, to determine and regulate CO2 emissions from trucks, the European Commission segments the truck market into vehicle groups according to their technical characteristics. In general, trucks from subgroups with a higher average payload across all mission profiles show lower CO_2 emissions due to the metric used (g/t-km). Additionally, the relative share of different test cycles also greatly influences CO_2 emissions. For instance, at similar weights and payloads, subgroups certified with a higher share of urban driving show much higher emissions than subgroups with a higher share of motorway operations (Ragon and Rodríguez 2021).

The use of carbon pricing as a crucial climate policy instrument has received broad support in the economic literature and policymakers, and has now been implemented as a key policy instrument for climate change mitigation in many countries globally. Besides, recent studies indicate that carbon pricing needs to be part of a policy package to secure both rapid mitigation and long-term decarbonization (Khan and Johansson 2022). Supply chain network design has mostly incorporated four policies to integrate environmental issues: carbon cap, carbon offset, cap-and-trade, and carbon tax. All four policies contributed to emission reductions with a slight increase in total cost, mainly by configuring the supply chain to use lower-emitting resources (Eskandarpour et al. 2021; Waltho et al. 2019).

Efforts to use carbon policies for modeling sustainable supply chain networks have gained momentum over the last few years. However, the existing literature mostly deals with the minimization of carbon emissions being carried out through minimization of the overall operational and emission cost or maximization of the total profit (Rout et al. 2021). Specifically, most of these studies focus only on using the carbon emission costs to reduce transportation or total costs (Wanke et al. 2015; Sun et al. 2020; Pak et al. 2022). Just a few studies use carbon minimization as a variable in their objective function (Goodarzian et al. 2021; Yu and Khan 2022; Mogale et al. 2022), but the literature still lacks studies of how a major focus on the minimization of the transportation carbon footprint even when hurting costs or service level to a certain acceptable point would influence strategies for distribution networks. Therefore, this paper intends to contribute to the field by demonstrating how organizations can consider these new metrics in their cost analysis and transportation choices.

3 RESEARCH DESIGN

3.1 Use Case and Data Collection

The application case is developed based on a Brazilian retailer presented in (Pereira and Frazzon 2021). The retailer is an omni-channel that operates physical and online stores, selling a wide array of products, including home décor, furniture, kitchen appliances, and electronics.

The demand data used is from 2016 to 2018 in monthly historical sales. The furniture category is chosen since it represents the highest financial impact on the company. The five most representative products are chosen for the simulation in terms of sales volume and financial value. The supply chain distribution network data was also collected in the company's ERP and is represented in the simulation according to the company's current distribution network.

The data of each player in the chain and general information collected and inserted into the simulation are: historical sales, the inventory control policy; sourcing policy (closest dynamic sources); transportation costs, transportation time (real routes are used subject to average truck speeds); fleet capacity; less-than-truckload (LTL) shipments are allowed; fixed facility and inventory holding costs, production time, and product price and cost.

In line with the objectives of this paper, several simulation experiments are conducted to investigate how including the variable air pollutant emissions (primarily CO_2) into the total logistics costs influence the network distribution. The paper also investigates how different policies might influence the total logistics costs for the company. Finally, we also investigate whether different strategies could influence the type of trucks used.

Brazil has not yet implemented CO_2 emission policies, as they are still in the analysis phase, and therefore, to analyze the cost of CO_2, data were collected from the Carbon Pricing Dashboard of the World Bank Group (World Bank Group 2022). Additionally, we used the recent report from The International Council on Clean Transportation (Ragon and Rodríguez 2021) regarding the CO_2 emission parameters by type of truck.

3.2 Simulation Modelling

The simulation model represents an omni-channel retailer supply chain with the following characteristics: one supplier, one central distribution center, three regional distribution centers, sixteen physical stores, and physical and online clients. The supply chain model was run for one year using the simulation tool AnyLogistix Studio Edition 2.15.2

In the current distribution network, customers place orders through the company website or buy the products directly at physical stores. After the orders arrive, the physical stores analyze whether they have the product in stock to make the sale. Next, orders from the online channel are sent to the central distribution center, currently the agent responsible for distributing the online orders. After supplying the demands, each player in the simulation analyzes the number of products in stock and, if necessary, places an order to the previous supply chain tier.

The analyzed supply chain is composed of 5 tiers, being the supplier ( ) as tier 5, the central distribution center as tier 4 ( ), the regional distribution center as tier 3 ( ), the stores being tier 2 ( ), and tier 1 the customers (physical and online). In this way, the material distribution flow goes from the supplier to the central distribution center (CDC), then to the regional distribution centers (RDC), and finally to the stores. Physical customers are only fulfilled by stores, while online customers currently can only be fulfilled by the CDC. The agents and their geographical positions can be seen in Figure 1.

Figure 1: Geographical location of agents.

We use a regular month as a base scenario for our simulation model. However, parameters must be assessed holistically to analyze the impact of different carbon policies in the company supply chain. Hence, the following data have been used, and assumptions have been made:

- **Cost calculation policy**: we use the cost calculation policy "Distance-based with fixed cost". The variable distance-based costs relate to fuel, labor, tiers, maintenance, and repair. The fixed costs relate to equipment, licenses and taxes, insurance, and management.
- **Carbon policy**: although four different carbon policies are successfully used worldwide, in this paper, we consider only the carbon tax policy due to its ample use in different countries and data availability.
- **Vehicle type**: we use three types of trucks from three different categories that cover more than 75% of regulated trucks sold in Europe over the last years (Ragon and Rodríguez 2021) and also reflect the actual company's fleet vehicle types. The truck's sub-categories used are: 10-LH (tractor 6x2 axle), 5-LH (tractor 4x2 axle), 4-RD (rigid 4x2 axle). In line with common industry practices (Hübner et al. 2019; Hübner and Ostermeier 2019), it is assumed that heavy-duty trucks (e.g., 10-LH) are employed for deliveries between the supplier and central/regional distribution centers, avoiding operations inside cities, while medium-duty trucks (e.g., 5-LH) and light-duty vehicles (e.g., 4-RD) can be used in all routes accordingly to the needs in terms of volume capacity and payload.
- **Products**: 5 SKUs with different volumes are considered
- **Trip distance**: The distances are calculated based on real routes through the GIS map available in Anylogistix software
- **Inventory policy**: All tiers have limited and specific inventory capacity following a min-max policy for each SKU and location, including the supplier (Tier 5).
- **Replenishment**: Since the company's historical data is available monthly, replenishment is also calculated on a monthly basis. The processing lead time is set for one day.

- **Fleet capacity**: The capacity of each type of truck is limited and varies (see Table 1). There are unlimited trucks available.

3.3 Model Assumptions and Limitations

During the modeling process, several assumptions are made that involve the following limitations:

1. An average t-km emission was used based on the type of products carried. However, these numbers might vary depending on the type of products or operation conditions (e.g., room vs. refrigerated products; delivery in flat vs. hilly area).
2. Since the historical sales data is provided monthly rather than daily, the consolidation and replenishment in our simulation occur on the first days of each month, which limits in-depth analysis of inventory costs, max lead time, and max number of trucks used since shipments barely occur by the end of each month.
3. We assume the same costs and emissions per km for fully loaded, partially loaded, and empty trucks. Besides, only transportation emissions are considered, while emissions from loading/unloading operations are not.
4. We assume all online orders from the same city in a given month are dispatched to the same location. Therefore, here we assume that each online customer acts as a consolidation center from where all the online orders are served.

3.4 Design of Experiments

Three analyzes are proposed for this case study. Firstly, we analyze how carbon pricing adopted by different countries might influence the company's transportation costs. Secondly, we analyze whether different strategies would lead to different choices in fleet composition. Thirdly, we analyze how different omni-channel distribution strategies might influence emissions, traveled distances, transportation costs, and inventory.

Experiment 1: To analyze how different carbon pricing might influence the company's transportation costs, we run experiments as described in Table 2. Carbon prices are stated in USD per tonne of carbon dioxide equivalent (tCO2e), the global standard for carbon emission pricing comparison. Our baseline scenario is the current scenario at the company, in which no carbon policy is in effect. To cover all current carbon prices in effect worldwide (World Bank Group 2022), we run experiments from \$0 to \$150 USD at intervals of \$15 USD.

Table 2: Table captions.

Parameter	Value
Baseline	No carbon pricing policy
Range	\$0 - \$150 (USD)
Steps	\$15 (USD)

Experiment 2: We compare the fleet composition (number of each type of truck) for all scenarios created and analyzed during Experiment 1. Our focus is to analyze whether (i) the number of trucks will change to optimize the distribution network given the new emission costs, and (ii) the types of trucks used will change since each type of truck has different capacities, operating costs, and emission levels, which also leads to different emission costs. We test all scenarios with the three types of trucks described in Section 3.2.

Experiment 3: We investigate different strategies for sustainable omni-channel distribution networks. Our focus is to evaluate if different omni-channel distribution network strategies could reduce the carbon emission cost.

We use the current distribution strategy as the baseline scenario, which is delivering products to online customers only via the CDC. In alternative scenarios, online customers can also be supplied by different agents in the supply chain (i.e., RDCs and stores). Therefore, we compare the alternative strategies to the baseline in percentage. All scenarios analyzed are presented in Table 3.

Table 3: Online customer sourcing strategies.

Scenarios	Strategies
Scenario 1	CDC (Baseline)
Scenario 2	CDC and RDC
Scenario 3	CDC and Stores
Scenario 4	CDC, RDC and Stores
Scenario 5	RDC and Stores
Scenario 6	Stores

As Brazil still does not have a carbon emission pricing policy, a carbon emission price of $5 USD was adopted for this analysis since this is the value currently adopted by all South American countries with an already implemented carbon price policy. The Key Performance Indicators (KPI) used for this analysis are: total cost, traveled distance, number of shipped vehicles, carbon cost emission, and inventory cost.

4 RESULTS

4.1 Carbon Policies Analyses

Carbon pricing can take different forms and shapes. In the State and Trends of Carbon Pricing series, carbon pricing refers to initiatives that put an explicit price on GHG emissions, i.e. a price expressed as a value per ton of carbon dioxide equivalent (tCO2e) (World Bank Group 2022). Figure 2 shows how different carbon pricing adopted by different countries and regions worldwide would impact the total transportation cost, both in percentage and in total value.

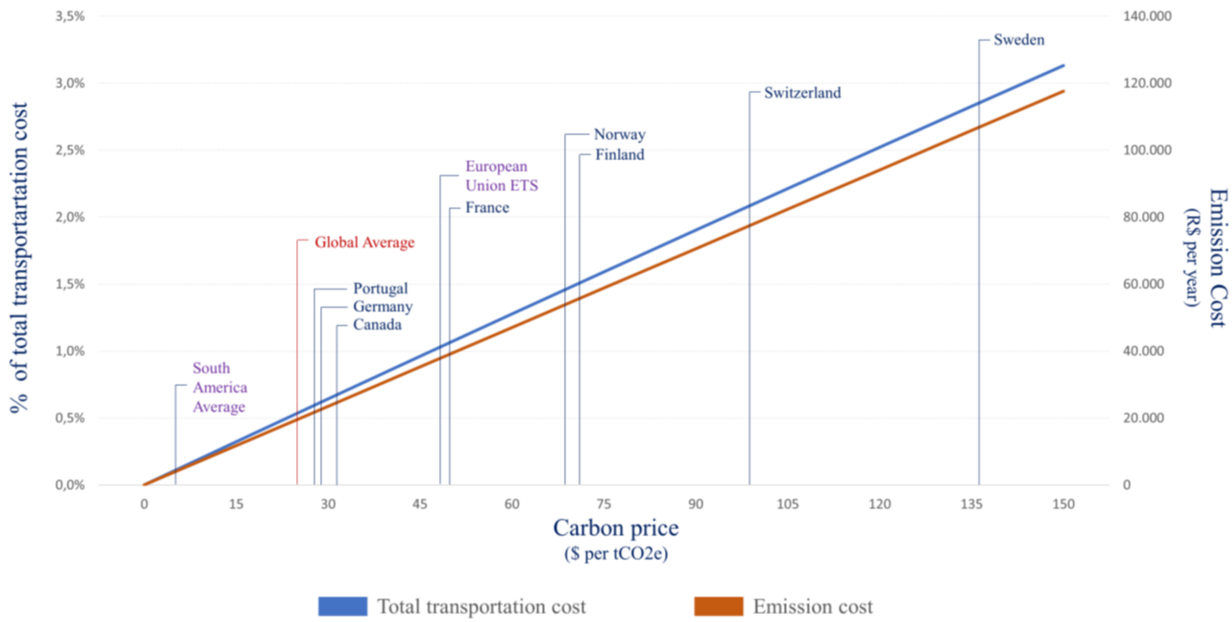

Figure 2: The left y-axis shows the percentage increase in the total transportation cost depending on the adopted carbon price. The right y-axis shows the emission costs depending on the carbon price. The emission costs are presented in BRL, the base currency for the company analyzed. The x-axis states the carbon price in USD per tonne of carbon dioxide equivalent (tCO2e). To allow comparison, a sample of countries is presented accordingly to their current carbon price initiatives.

Results show an almost linear relationship between carbon emission cost and total transportation cost since the emission cost would represent a small percentage of the total transportation cost. For the company analyzed, it would range from 0.30 to 0.32 percentage points (p.p.) increase in the total transportation cost for each $15 USD increase in carbon emission price. Although it seems a small percentage increase in cost, it might become challenging for companies such as transportation companies that operate with low margins. Therefore, next we analyze the fleet composition to identify potential improvements in truck choices due to emission costs.

4.2 Fleet Composition Analyses

The fleet composition is described in theory as an important component for cost optimization in a distribution network. We therefore analyze whether different emission price policies would lead to changes in the choice of vehicles to operationalize the company distribution. For such, both the number of vehicles used in each distribution path presented in Figure 2, as well as the types of vehicles utilized are analyzed.

The results showed that neither the number of vehicles nor fleet composition changed due to different emission prices. This is because the impact of emission costs on the total transportation cost is lower than 3% in all analyzed scenarios, even considering the current highest emission price (i.e., $137,24/tCO2e in Sweden), which was not shown to substantially alter the choice of vehicles used.

4.3 Alternative Strategies for The Omni-Channel Distribution Network

Omni-channel distribution networks allow different strategies for customer fulfillment. Therefore, we determine and analyze various distribution network strategies capable of minimizing carbon emissions and consequently enabling supply chains to adopt more sustainable practices.

Figure 3 presents the omni-channel supply chain KPI for the five alternative strategies previously described in Section 3.4. The y-axis represents the percentage of each KPI compared to Scenario 1, which was used as a baseline, which justifies all KPIs being 100% for this scenario. The values for Scenarios 2-6 are the relative KPI change expressed as a percentage compared to Scenario 1.

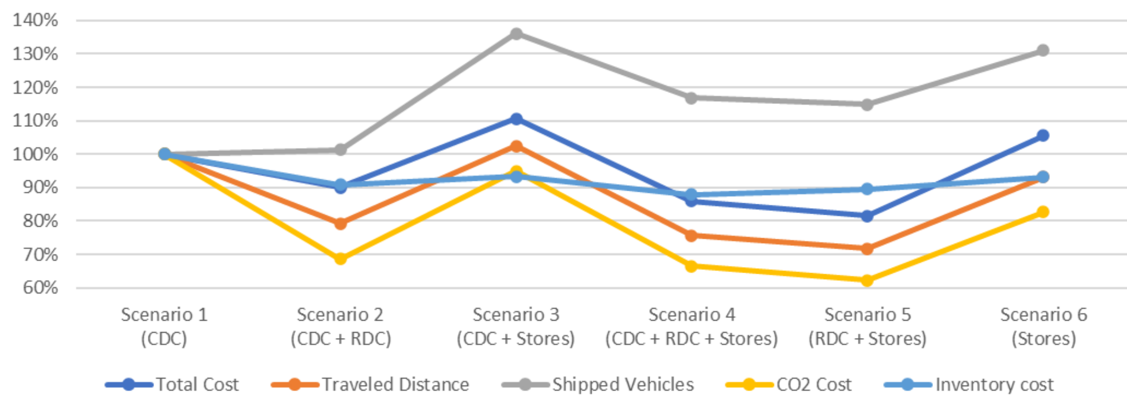

Figure 3: Omni-channel distribution network scenarios.

The results show that Scenario 5 (RDC+Stores) accounts for the lowest carbon emission costs, in which the regional distribution center and stores are responsible for delivering the products to the online customers. The lowest emission cost can be explained by the fact that one of the RDCs is located in a place with no physical stores closeby, thus reducing the distance between delivery points and consumers. The geographical closeness can also be seen with the reduced traveled distance KPI.

The "RDC + Store" scenario presented the second lowest inventory cost value, as it managed to make better use of the stock at the end of the chain since the sourcing policy adopted selects the sourcing point for the products by proximity based on the stock availability. Despite using a greater amount of trucks, when compared to the scenarios in which the CDC makes the delivery (Scenario 1), the insertion of the RDC as a delivery point allowed a better consolidation of the loads when compared to the scenarios in which product deliveries are carried out also by the stores (Scenario 3 and 6) and in the scenario where all tiers deliver the products (Scenario 4).

5 DISCUSSION AND CONCLUSIONS

This study investigated how carbon policies might affect distribution networks while discussing their influence on transportation costs in omni-channel operations. Unlike several studies, we used real carbon emission costs for analysis and discussed their influence on supply chain operationalization, expanding the work developed by İzmirli et al. (2021).

The case study results in a Brazilian distribution network showed that although implementing a carbon policy increases the transportation variable costs, the marginal difference among the types of trucks analyzed was not substantial enough to influence a change in the vehicle fleet composition. The findings also show that targeting carbon prices per t-km (tonne-kilometer) similarly to developed countries will increase significantly operating costs for transportation. Therefore, as we see, rather than targeting similar carbon prices per tCO2e in different conditions, a carbon policy that leads to a similar percentage of the total variable cost of transportation among countries might be an appropriate strategy that contributes to a more green supply chain while does not create threats in terms of competitiveness.

The simulation supported identifying a sourcing strategy that provides a 38% reduction in carbon emissions while considering different omni-channel distribution network KPIs. Therefore, it was possible to identify the best strategy for this omni-channel without changing the fleet composition. Besides, it is still possible to argue the need to find a balance for the trade-off between distance from consumers and the consolidation of loads to reduce carbon emissions toward a sustainable supply chain.

Therefore, our study contributes to the literature by extending previous studies by including new metrics in their cost analysis and transportation choices, while we use simulation modeling to propose new approaches to adapt distribution networks due to upcoming carbon policies. Moreover, our managerial contributions regard proposing a data-driven approach that considers economic and environmental factors for analyzing omni-channel distribution strategies, supporting them in achieving sustainable emission targets proposed by the United Nations.

There are many ways to extend the current study. Three promising and challenging extensions are proposed. First, this study used a limited amount of types of trucks. Therefore, more types of trucks should be included in future analyzes, especially the upcoming electric trucks. However, a direct comparison might be biased if it does not include Scope 2 emissions (e,g,, electricity source), which poses challenges in terms of accurate data for modeling. Second, many companies are targeting emission reductions only related to Scope 1 (direct greenhouse emissions) rather than targets for the overall carbon footprint, which includes Scope 2 and 3 (indirect and value chain emissions). Therefore, a valuable extension would be to include in the simulation other carbon emission sources (e.g., carbon emissions from keeping facilities open, inbound and outbound operations) for a more comprehensive analysis that might influence the distribution network and possible strategies. Third, in this study, we used equal consumptions and emissions for fully loaded, partially loaded, and empty trucks, besides not optimizing the network to aggregate loads from different suppliers to increase truck utilization ratio and decrease the number of trucks utilized. However, in real life, it rarely seems so. Thus, further detailing emissions for different conditions while optimizing the distribution strategy would enable other sustainable indicators analyses.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the Fabrikant Mads Clausen Fond, Denmark, for the project “Simulation Lab – Enabling simulation along the value chain”.

REFERENCES

Carter, C. R., and D. S. Rogers. 2008. “A Framework of Sustainable Supply Chain Management: Moving toward New Theory.” *International Journal of Physical Distribution & Logistics Management* 38(5):360–387.

Durán-Romero, G., A. M. López, T. Beliaeva, M. Ferasso, C. Garonne, and P. Jones. 2020. “Bridging the Gap between Circular Economy and Climate Change Mitigation Policies through Eco-Innovations and Quintuple Helix Model.” *Technological Forecasting and Social Change* 160:120246.

Eggleston, S. 1998. Emissions: Energy, Road, Transport https://www.ipcc-ggip.iges.or.jp/public/gp/bgp/2_3_Road_Transport.pdf

Elkington, J. 1997. Cannibals with Forks: The Triple Bottom Line of 21st Century Business. 1st ed. Oxford: Capstone.

Eskandarpour, M., P. Dejax, and O. Péton. 2021. “Multi-Directional Local Search for Sustainable Supply Chain Network Design.” *International Journal of Production Research* 59(2):412–428.

European Commission. 2016. *A European Strategy for Low-Emission Mobility*. Brussels, Belgium.

Geissdoerfer, M., S. N. Morioka, M. M. de Carvalho, and S. Evans. 2018. “Business Models and Supply Chains for the Circular Economy.” *Journal of Cleaner Production* 190:712–721.

Goodarzian, F., V. Kumar, and A. Abraham. 2021. “Hybrid Meta-Heuristic Algorithms for a Supply Chain Network Considering Different Carbon Emission Regulations Using Big Data Characteristics.” *Soft Computing* 25(11):7527–7557.

Hanifan, G. L., A. E. Sharma, and P. Mehta. 2012. “Supply Chain Management: Why a Sustainable Supply Chain Is Good Business.” Outlook: *The Journal of High Performance Business* 3:1–8.

Hübner, A., J. Hense, and C. Dethlefs. 2022. “The Revival of Retail Stores via Omnichannel Operations: A Literature Review and Research Framework.” *European Journal of Operational Research* 302(3):799–818.

Hübner, A., A. Holzapfel, and H. Kuhn. 2016. “Distribution Systems in Omni-Channel Retailing.” *Business Research* 9(2):255–296.

Hübner, A., A. Holzapfel, H. Kuhn, and E. Obermair. 2019. “Distribution in Omnichannel Grocery Retailing: An Analysis of Concepts Realized.” In Operations in an Omnichannel World, 283–310.

Hübner, A., and M. Ostermeier. 2019. “A Multi-Compartment Vehicle Routing Problem with Loading and Unloading Costs.” *Transportation Science* 53(1):282–300.

IPCC, I. P. on C. C. 2022. Climate Change 2022. Mitigation of Climate Change. The Daunting Climate Change.

İzmirli, D., B. Y. Ekren, V. Kumar, and S. Pongsakornrungsilp. 2021. "Omni-Chanel Network Design Towards Circular Economy under Inventory Share Policies." *Sustainability* 13(5):1–24.

Jamali, M.-B., and M. Rasti-Barzoki. 2019. "A Game Theoretic Approach to Investigate the Effects of Third-Party Logistics in a Sustainable Supply Chain by Reducing Delivery Time and Carbon Emissions." *Journal of Cleaner Production* 235:636–652.

Khan, J., and B. Johansson. 2022. "Adoption, Implementation and Design of Carbon Pricing Policy Instruments." *Energy Strategy Reviews* 40:100801.

Mogale, D. G., A. De, A. Ghadge, and E. Aktas. 2022. "Multi-Objective Modelling of Sustainable Closed-Loop Supply Chain Network with Price-Sensitive Demand and Consumer's Incentives." *Computers & Industrial Engineering* 168:108105.

Pak, N., N. Nahavandi, and B. Bagheri. 2022. "Designing a Multi-Objective Green Supply Chain Network for an Automotive Company Using an Improved Meta-Heuristic Algorithm." *International Journal of Environmental Science and Technology* 19(5):3773–3796.

Pereira, M. M., and E. M. Frazzon. 2019. "Towards a Predictive Approach for Omni-channel Retailing Supply Chains." *IFAC-PapersOnLine* 52(13):844–850.

———. 2021. "A Data-Driven Approach to Adaptive Synchronization of Demand and Supply in Omni-Channel Retail Supply Chains." *International Journal of Information Management* 57:102165.

Pereira, M. M., D. L. de Oliveira, P. P. Portela Santos, and E. M. Frazzon. 2018. "Predictive and Adaptive Management Approach for Omnichannel Retailing Supply Chains." *IFAC-PapersOnLine* 51(11):1707–1713.

Ragon, P.-L., and F. Rodríguez. 2021. *CO2 Emissions from Trucks in the EU: An Analysis of the Heavy-Duty CO2 Standards Baseline Data.* International Council on Clean Transportation: San Francisco, CA, USA.

Rahman, M. M., N. Anan, A. H. M. Mashud, M. Hasan, and M. L. Tseng. 2022. "Consumption-Based CO2 Emissions Accounting and Scenario Simulation in Asia and the Pacific Region." *Environmental Science and Pollution Research* 2100(0123456789).

Rout, C., A. Paul, R. S. Kumar, D. Chakraborty, and A. Goswami. 2020. "Cooperative Sustainable Supply Chain for Deteriorating Item and Imperfect Production under Different Carbon Emission Regulations." *Journal of Cleaner Production* 272:122170.

Rout, C., Paul, A., Kumar, R.S., Chakraborty, D. and Goswami, A. 2021. "Integrated Optimization of Inventory, Replenishment and Vehicle Routing for a Sustainable Supply Chain under Carbon Emission Regulations." *Journal of Cleaner Production* 316:128256.

Sun, Y., C. Zhang, and X. Liang. 2020. "An Agent-Based Simulation for Coupling Carbon Trading Behaviors with Distributed Logistics System." *In: Advances in Intelligent Systems and Interactive Applications*, 222–229.

UNFCCC. 2021. COP26 - Glasgow Climate Pact. Cop26.

Waltho, C., S. Elhedhli, and F. Gzara. 2019. "“Green Supply Chain Network Design: A Review Focused on Policy Adoption and Emission Quantification." *International Journal of Production Economics* 208:305–318.

Wanke, P., H. Correa, J. Jacob, and T. Santos. 2015. "Including Carbon Emissions in the Planning of Logistic Networks: A Brazilian Case." *International Journal of Shipping and Transport Logistics* 7(6):655.

World Bank Group. 2022. "Carbon Pricing Dashboard." ETS and Carbon Taxes. https://carbonpricingdashboard.worldbank.org/map_data.

World Economic Forum. 2016. "Digital Transformation of Industries : Digital Enterprise." *World Economic Forum* (January):45.

Yu, Z., and S. A. R. Khan. 2022. "Green Supply Chain Network Optimization Under Random and Fuzzy Environment." *International Journal of Fuzzy Systems* 24(2):1170–1181.

Zhu, Q., J. Sarkis, and K. Lai. 2008. "Green Supply Chain Management Implications for "Closing the Loop"." *Transportation Research Part E: Logistics and Transportation Review* 44(1):1–18.

AUTHOR BIOGRAPHIES

MARINA MEIRELES PEREIRA MAFIA is an Assistant Professor in the Department of Technology and Innovation at University of Southern Denmark. She holds a Ph.D. degree in Industrial Engineering focused on data-driven supply chains. Her current research interests are related to data science, industry 4.0, simulation, logistics, and supply chain management. Her email address is marinapereira@iti.sdu.dk and her homepage is https://portal.findresearcher.sdu.dk/en/persons/marinapereira.

ELIAS RIBEIRO DA SILVA is an Associate Professor in the Department of Technology and Innovation at University of Southern Denmark. He holds a Ph.D. degree in Industrial and Systems Engineering focused on digital manufacturing. His primary research interest is the influence of digital manufacturing technologies on operations and supply chain management. He has been the coordinator of the Supply Chain 4.0 Network since 2020. His email address is elias@iti.sdu.dk and his homepage is https://portal.findresearcher.sdu.dk/en/persons/elias-ribeiro-da-silva.

ARNE BILBERG is an Associate Professor and Head of Unit in the Department of Technology and Innovation at University of Southern Denmark. He holds a Ph.D. degree in Computer Simulation and Computer Integrated Manufacturing from the Technical University of Denmark. His research interests cover lean manufacturing, computer simulation, and digital twins. His email address is abi@iti.sdu.dk and his homepage is https://portal.findresearcher.sdu.dk/da/persons/abi.