7th European Conference on Industrial Engineering and Operations Management
Augsburg, Germany, July 16-18, 2024
Publisher: IEOM Society International, USA DOI: 10.46254/EU07.20240183
Published: July 16, 2024

A Causal Analytics Approach for Monetary Performance Analysis of SMEs under the Implementation of Supply Chain Sustainability Regulations

Ardalan Irani and Omid Fatahi Valilai
School of Business, Social & Decision Sciences
Constructor University Bremen
Campus Ring 1, 28759, Bremen, Germany

Abstract

This paper delves into the amalgamation of Green Supply Chain Management (GSCM) practices and enforcement of German LkSG (Lieferkettensorgfaltspflichtengesetz) environmental regulations in small and medium-sized enterprises (SMEs) operating within supply chains. Incorporating literature across multiple studies, a majority have shown to be vital factors critically affecting the economic, environmental, operational, and GSCM domains. The paper has investigated the application of machine learning methods to promote the direction and strength of these factors' influences on one another. The findings are presented in terms of SEM frameworks or models previously employed by other researchers that enable easy establishment of correlations as well as feedback loops through CLD representation. Such an inclusive approach brings new insight into regulatory adjustment dynamics among SMEs and their financial performance. Seven feedback loops explain how GSCM principles interact with regulatory compliance to produce financial results. The objective for this study is to enlighten policy makers both locally and internationally about this scenario so that they can better enforce policies that will help businesses to operate more sustainably while minimizing risks related with non-compliance.

Keywords
Supply Chain, Sustainability, LkSG environmental regulations, System dynamics, Causal Machine Learning.

1. Introduction

Unlike many other metamorphoses in Germany that traditionally consume a hefty amount of time to be legislated and implemented, the rules regarding the environment preservation are supposed to come to effect immediately and the non-abiding parties in supply chains will incur heavy penalties by the governing authorities. According to The Economist (The Economist, 2023), from the beginning of the year 2024, German enterprises with more than 1000 workers are forced by law to put their suppliers across the whole supply network under surveillance, so that they will not infract from humanitarian or environmental standards. Otherwise, they will be penalized at least 8.6 million euros. Therefore, not only companies across supply chains have the ethical burden of complying with strict environmental standards, but also infractions could even jeopardize the financial thriving of the company. Since measures need to be immediately taken into action, companies are faced with challenges adjusting their processes with new regulations and educating their employees with the amendments they made to their work procedures (Olad et al., 2020).

Aside from the challenge of making changes in a short period of time, another or perhaps the bigger challenge for the SMEs (Small and medium-sized enterprises) is the costs of these changes regarding technology adoption (Radmanesh et al., 2021; 2023). Making procedures or technology equipment much more efficient and less energy intensive over a short course of time will be challenging for companies, especially those with smaller scales. Since mostly one of the cardinal levers for companies in order to remain competitive in the market is keeping the prices to an affordable threshold, and by considering the inevitable costs, companies will face serious challenges for remaining on the positive side. This study tries firstly to identify challenging factors and the level of effect by performing a causality study using system dynamics (SD). Subsequently, this paper will try to quantify the study using machine learning (ML) techniques to assess how effective those factors are on companies' profit and make a sensitivity analysis among those factors. The reason why there should be a focus on causal machine learning is that performing a machine learning without having done a causality study may sometimes bring about false or misguiding results or cannot always strongly depict the roots of a phenomenon due to the problems of overfitting in a large covariate space of a supply chain (Strittmatter, 2023).

1.1 Objectives

This study tries to find answers to the following objectives:

- Which factors would change for SMEs active in supply chains regarding the new environmental regulations?
- What measures can be considered to counteract the negative effect of the aforementioned factors?
- Among the changing factors, which of those have the most negative effect on companies' revenues?
- Among the counteracting measures, which has the most neutralizing effect on profit-shrinking changes?

Since all major role players in the German 4.2 billion Euros economy are affected by this law and they need to bring the principles of the LkSG (Lieferkettensorgfaltspflichtengesetz) into their procedures, operations, and suppliers as well, the paper will analyze the dynamics of remaining solvent in a more restricted business environment. In this section, it will describe how the structure of this study will be formed, and which materials will be presented in the proceeding sections. Next, the related literature of this field will be summarized, and the paper will clarify the state-of-the-art solutions presented by other researcher studies, structures their findings and methods, and describes the research gap. In section three, the methodology chosen by the author to address the research problem will be explored, with emphasis placed on the reasons behind its selection. This methodology, selected for its relevance and effectiveness in addressing the research question, serves as a strategic framework. Through this discussion, insight into the rationale driving the selection will be provided, enhancing understanding of its applicability and alignment with the study's objectives. Having clarified the methodology, the paper will discuss the results of the study and how they could be interpreted in the proceeding step, in section 4. Next, the restrictions of this study and the room for future expansions will be discussed. Finally, in the conclusion section, the paper will summarize the reasons for choosing this topic, the gap identified in the literature, the methodology chosen to tackle the issue, and the results.

2. Literature Review

2.1 Supply Chain Environmental Performance

The paper has explored the literature for frameworks which are used for supply chain performance evaluation and assessment of environmental effects especially with the focus on importance of globalization and digital transformation over supply chain (Akbaripour et al., 2015; Caraveo et al., 2023). Most of the research studies in this field mainly focus on discovering the relationship between GSCM (Green Supply Chain Management) practices and companies environmental and financial performances. In addition, they have mostly utilized questionnaires in their studies rather than relying on historical data of members in a supply chain. (Mumtaz et al., 2018) used linear regression for testing eight hypotheses about the impacts of 4 green measures on operational costs and environmental pollution. Their results indicate that implementing GSCM practices in Pakistani businesses contributed to the reduction of both environmental pollutions and operational costs. (Farooqi et al., 2023) have also tested seven hypotheses using structural least squared method to investigate the moderating effect of institutional pressure on environmental performance. Implementing the same method of structural equation modeling (SEM), (Al-Sheyadi et al., 2019) investigated and confirmed the complementarity of four GSCM practices, namely eco-design, external environmental practices, environmental management systems, and source reduction. Their results also demonstrate the strong and positive impact of combined GSCM practices on the environment. (Stefanelli et al., 2014) have used the SmartPLS© software to analyze the data from 80 different-sized suppliers in Brazilian bioenergy sector and have confirmed a positive correlation between employing GSCM approach and improvement in the environment performance.

Feng et al., (2018), also by using a hypothesis testing framework, have analyzed the data for 126 Chinese automakers in order to establish a connection among GSCM, environmental performance, operational performance, and financial performance. The results of this study confirm a positive relationship among the implementation of GSCM as an integral approach and environmental and operational performance improvement. The improvement in the latter sectors will lead to improvement in financial performance as well, according to this study. Using SEM, (Abu Seman et al., 2019) proved a positive correlation among GSCM practices (internal environmental management, green purchasing, customer environmental cooperation, reverse logistics), green innovation (green product, process, and management),

and environmental performance. Having identified the drivers of green practices and categorizing them into two main groups of customer drivers and cost drivers, (Wang et al., 2018) have tested hypotheses about the dynamics of effectiveness of those factors on both external and internal green practices, and eventually the environmental performance. In order to differentiate their work with the existing literature and to be able to generalize the results, the authors have used data from multiple companies active in different businesses throughout the world. They also studied the effect on large, medium, and small-sized enterprises. The results reveal a large correlation between environmental performance and both the cost and customer drivers. (Somjai et al., 2019) have used SEM in order to evaluate the impact of green supply chain practices on an organization’s economic and environmental performance.
In the literature, there are also studies that, instead of hypotheses testing to find out the relationship between GSCM and companies’ performance, focus on other aspects. (Benzidia et al., 2021) have studied how benefitting from big data analytics (BDA) and artificial intelligence (AI) would contribute to environmental process integration and green supply chain collaboration (GSCC) and consequently, to the environmental performance of the organization. The results indicate the moderating effect of digital learning in the relationship between BDA-AI and GSCC.

2.2 Causal Machine Learning

Philosophy, mathematics, and principles of experimental design are the mainstay of causal reasoning in its early years. These considerations have laid the conceptual foundation for further developments in integrating topics such as causal reasoning into machine learning. The Scottish philosopher David Hume is best known for his fundamental investigations into causation. He explored the concept of causality in his philosophical works "A Treatise of Human Nature" (Hume, 1896) and "An Inquiry Concerning Human Understanding" (Hume, 2007). Hume's ideas laid the philosophical foundation for subsequent debates on causality. In addition to Hume’s writings, another prominent figure in experimental design and mathematical theory is the British mathematician and geneticist Ronald A. Fisher. Author of the seminal work "Statistical Methods for Research Workers" (Fisher, 1992) that contributed greatly to the development of causal inference in the statistical process, Fisher's research emphasized how important experimental design and the concept of randomization were. The book supports these hypotheses and lays the foundation for the controlled experiments needed to establish causal relationships. Deep statistical methods were also introduced for data analysis, which is necessary to account for cause and effect.

Fisher's theorems have long influenced statistics and continue to be used to inform contemporary approaches to causal reasoning, making them a central component of causal reasoning in statistical learning. Besides the fundamental contributions of David Hume and Ronald A. Fisher towards the understanding of causality, Judea Pearl's work on Causal Bayesian Networks has made the subject of causal inference in statistical learning a great jump forward. Using his never-ending research, mainly in his book "Causality" (Pearl, 2009), Pearl was able to create the graphical models called Bayesian Networks that are used for the analysis and representation of causal relationships. These networks help researchers to recognize and measure the effects of cause-and-effect relationships in complicated systems by providing an orderly way of presenting the dependencies and causal links between variables. Pearl presents the formal structure of the observation and recording of the causal information using Causal Bayesian Networks, which are the product of Hume's philosophical ideas and Fisher's stress on the experiment’s imperative. They offer an orderly approach to simulating causation; hence, researchers can infer causal connections besides delineating the linkages between variables. This way, one can easily understand and predict the chain of events and their impacts in a more systematic and data-oriented way. The reason why one should understand the causality in the modern statistical research is that the field has the ability to investigate and evaluate the causal relationships in the various fields like healthcare or social sciences, through the use of the graphical models in statistical learning (Bodendorf et al., 2023).
As already stated, that causality inference is significantly prominent, and this is especially true when it comes to complex systems that are affected by many different things. Since supply chains are normally complex systems with many parts that also are complex systems, which cause the uncertainty throughout the network, before using machine learning algorithms in statistical model, a causality study needs to be carried out in order to avoid the inclusion of unnecessary or misleading predictors. Thus, system dynamics (SD) as main tool for analysing the causality will be adopted.

2.3 Research Gap Analysis

The literature is briefly summarized in Table 1. As explained in the table above, most research in this field mainly focus on discovering the relationship between the GSCM practices and companies environmental and financial performances. This thesis works in the following gaps in the above-mentioned measures:

Firstly, most of the research use structural equation modelling (SEM) as their quantitative methodology for analysing the relationships. Although this methodology is useful, it is only capable of revealing the existence of a relationship between two factors and their directions, yet it fails to clarify the dynamics of relationships among variables when other factors vary. Secondly, as observed, studies mostly use questionnaires to obtain data for their quantitative models. Using surveys, although they may seek the consult of the experts to extract criteria, can be biased in some cases. This bias can even be seen in the results of the respondents. In order to tackle this problem, it is tried to utilize historical data from SMEs.

Thirdly, most studies obtain their data from multiple OEMs (Original Equipment Manufacturer) active in a field and do not take their partners into consideration, whereas this study will try to meticulously analyse SMEs active in a supply chain. According to the LkSG regulation, companies are enforced to analyse their direct suppliers in terms of environmental and humanitarian performance.

Table 1. Literature review analysis

Research	Methods & analysis	Data Level: OEM / SME
(Mumtaz et al., 2018)	Linear regression for evaluating organizational and environmental performance	OEM
(Farooqi et al., 2023)	SmartPLS for evaluating GSCM effects on operational, environmental, and financial performance	OEM
(Wang et al., 2018)	Structural Equations Model (SEM) for evaluating customer drivers and cost drivers on environmental performance	OEM
(Stefanelli et al., 2014)	SmartPLS for evaluating GSCM practices on environmental performance	SME
(Feng et al., 2018)	SEM to assess the meddling effect of operational and environmental performance in the connection between GSCM and financial performance	OEM
(Lopes De Sousa Jabbour et al., 2017)	G*Power 3.1 software to study how external GSCM measures would affect the environmental performance	OEM
(Al-Sheyadi et al., 2019)	SEM to analyze how both internal and external GSCM practices affect the environmental performance and costs	OEM
(Benzidia et al., 2021)	SEM to analyze the effects of big data analytics and artificial intelligence on GSCM and environmental performance	OEM
(Abu Seman et al., 2019)	SEM to analyze the meddling effect of green innovation on GSCM and Environmental performance	OEM
(Somjai et al., 2019)	SEM to analyze the effect of sustainable supply chain practices on financial and environmental performance of a company	OEM
This research	Using causal machine learning to find out the drivers, direction of the relations	SME

3. Methodology and Approach

As mentioned in the previous section, most of the studies have developed frameworks to establish relationships between GSCM practices and different aspects of companies' performance, i.e. economic, environmental, operational, etc. This study tries to identify the most important factors in literature and identify the ones that relate to the implementation of LKSG. The identified factors belong to the most important economic, environmental, and operational factors and GSCM practices that we, by using machine learning techniques, try to recognize the direction and the amount of impact that factors have on each other. Having identified the factors and presuming their relationship using the literature, it will be possible to form the following loops and eventually, a causal loop diagram (CLD). This

CLD consists of 19 of the most important factors that are mentioned repeatedly by different studies in literature. The factors are ordered in Table 2.

Table 2. The identified factors

Row	Research	Factor
1	(McIntyre et al., 1998)	Total CO_2 emissions
2	(Al-Sheyadi et al., 2019), (McIntyre et al., 1998)	Energy and resource management
3	This research	Waste of excess production
4	(Farooqi et al., 2023), (Wang et al., 2018), (Al-Sheyadi et al., 2019), (Abu Seman et al., 2019)	Green logistics
5	(Farooqi et al., 2023), (Wang et al., 2018), (Al-Sheyadi et al., 2019), (Abu Seman et al., 2019)	Green supplier selection
6	(McIntyre et al., 1998)	Adoption of ISO 14001
7	This research	Recycling Process
8	This research	Waste reduction
9	This research	Pressure for commitment to LkSG
10	(Benzidia et al., 2021)	AI and BDA-enabled infrastructure
11	This research	Predictive and corrective measures
12	This research	Risk management and analysis
13	(Benzidia et al., 2021)	Transparency of operations and information
14	This research	LkSG infraction penalties
15	This research	Waste water recycling
16	This research	Precise demand planning
17	(Farooqi et al., 2023), (Mumtaz et al., 2018)	Total costs of company
18	(Farooqi et al., 2023), (Mumtaz et al., 2018)	Total Profit of the company
19	This research	Optimal warehouse sizing

This research establishes the connections between them based on the results of previous studies. In those studies, as mentioned in the previous section, authors have analyzed the relationship among those factors using different methodologies, such as structural equation modeling, and have gathered their data through connoisseurs via questionnaires. The result is juxtaposing those results of the separate connections between variables, draw the inferences, and form feedback loops. This is what, to the best of knowledge, has not yet been carried out in the literature. This can contribute to easier understanding of the dynamics for the policy makers to make correct decisions to adapt their businesses with the new regulations in a way that they will not incur losses, whether by infraction penalties or by false alterations in the way they operate their business. Figure 1 depicts the CLD.

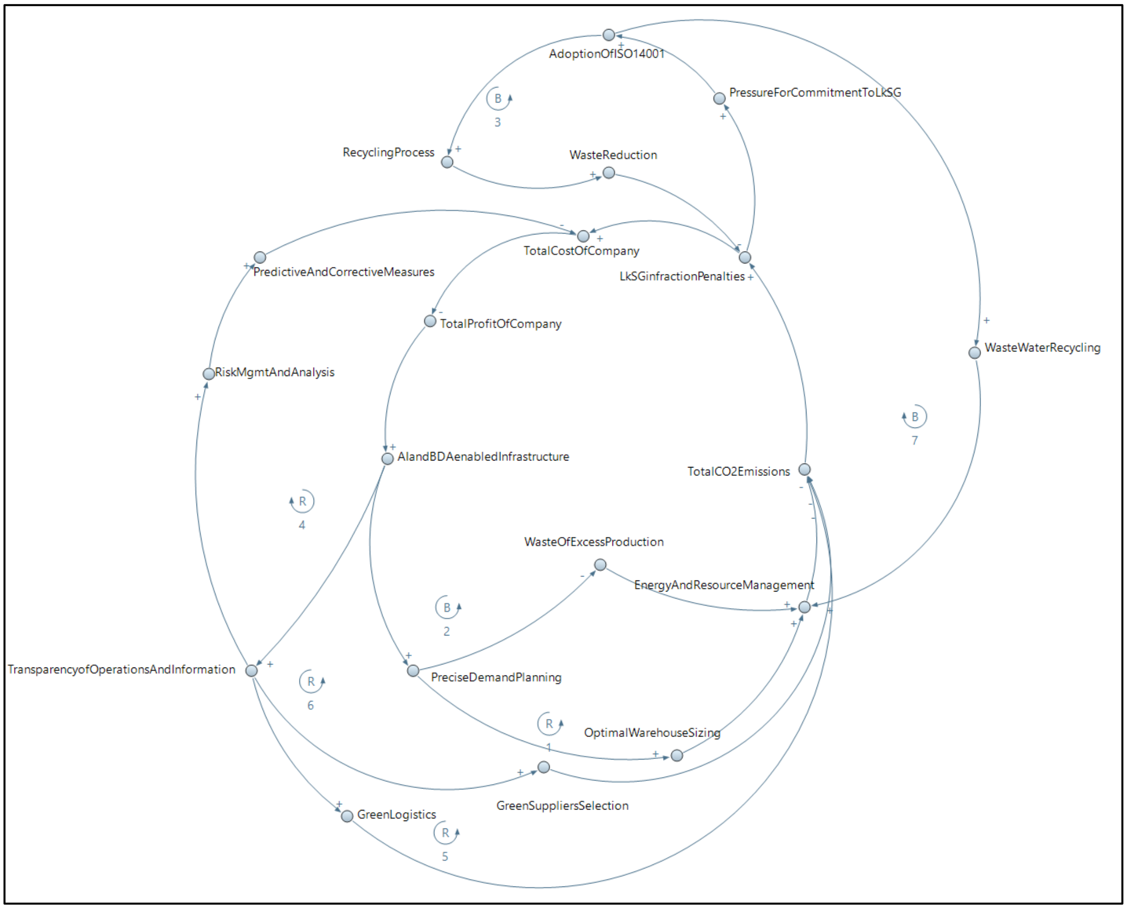

Figure 1. Causal Loop Diagram of the identified factors

As it can be observed in the Figure 1, seven feedback loops have been elaborated that together shape the dynamics of how taking GSCM principles and making alterations in business to act within the LkSG framework could affect the SMEs' financial performance.

3.1 Feedback Loops Clarification

To shed light on how the CLD works, the paper will analyze each loop separately. In this system, seven separate feedback loops work together to shape the dynamics of the system, three of which are balancing and four are reinforcing. For better clarity, each loop will be exemplified with a conceptual scenario.

Loop 1: Effect of IT and Industry 4.0 on Precision; Reinforcing

Total costs of company > - Total profit of company > + AI and BDA-enabled infrastructure > + Precise demand planning > + Optimal warehouse sizing > + Energy and resource management > - Total CO2 emissions > + LkSG infraction penalties > + Total costs of company

Example scenario:

Imagine a circumstance under which the costs of the company would increase. When costs increase, the profit will automatically decrease, therefore they are conversely correlated. When the company makes less profit and will have less budget to provide an AI and BDA-enabled infrastructure. Therefore, their relationship is straightforward. Under this scenario, the demand planning of the business will be reduced. The less precise the demand is forecasted, the more safety stock and as a result, a bigger warehouse are required. A bigger warehouse means larger energy consumption and that could bring about a bigger CO_2 footprint for the business. This whole scenario could lead to incurring a penalty, that leads to an increase in the costs. In that sense, this is a reinforcing feedback loop.

Loop 2: Effect of IT and Industry 4.0 on Waste Prevention; Balancing

Total costs of company > - Total profit of company > + AI and BDA-enabled infrastructure > + Precise demand planning > - Waste of excessive production > + Energy and resource management > - Total CO_2 emissions >+ LkSG infraction penalties > + Total costs of company

Example scenario:

Assuming the identical scenario as in loop 1, it can be assumed that a more precise forecast of the demand will cut the excessive production. Therefore, their correlation is negative. When the company's production is more adaptive to the actual demand, the waste due to excessive production will be reduced. It follows the same logic as in the previous example.

Loop 3: ISO 14001 as a Measure of Waste Recycling; Balancing

LkSG infraction penalties > + Pressure for commitment to LkSG > + Adoption of ISO 14001 > + Recycling process > + Waste reduction > - LkSG infraction penalties

Example scenario:

The bigger the penalties are, the more pressure the companies feel to conform the regulations. This pressure can drive businesses to adopt the ISO 14001 principles in order to remain on the safe side. Since one of the principles of ISO 14001 is about the recycling, the one companies who adopt this standard will need to employ recycling methods. The latter is harmonic with the waste reduction, which will lessen the probability of being fined for environmental reasons.

Loop 4: Role of IT and Industry 4.0 on Risk Management; Reinforcing

Total costs of company > - Total profit of company > + AI and BDA-enabled infrastructure > + Transparency of operations and information > + Risk management and analysis > + Predictive and corrective measures > - Total costs of the company

Example scenario:

Following the same scenario as in loop 1, a company that has been able to provide itself with AI and BDA-enabled infrastructures is better prepared to monitor the operations and the flow of internal and external information. That enables the business to well analyze and manage the risks and take predictive and corrective measures on time. That eventually brings about a reduction in costs.

Loop 5 and 6: Reinforcing

Loop 5: Transparency of Information and Green Supplier Selection

AI and BDA-enabled infrastructure > + Transparency of operations and information > + Green supplier selection > - Total CO_2 emissions > + LkSG infraction penalties > + Total costs of company > - Total profit of company > + AI and BDA-enabled infrastructure

Loop 6: Transparency of Information and Green Logistics Selection

AI and BDA-enabled infrastructure > + Transparency of operations and information > + Green logistics > - Total CO_2 emissions > + LkSG infraction penalties > + Total costs of company > - Total profit of company > + AI and BDA-enabled infrastructure.

Example scenario:

The transparency of operations and information leads to two great capabilities for businesses. Those two are "Green supplier selection" and "Green logistics and transportation", which form the reinforcing loops of 5 and 6. In loop 5, the transparency and comparison capability that is brought about by the infrastructure enables businesses to monitor their suppliers from different environmental aspects and choose the ones that comply with the LkSG regulations. The same happens in loop 6, where transparency allows the companies to choose the method of logistics and transportation which leaves the least carbon footprint.

Loop 7: ISO 14001 as a Measure of Water Recycling; Balancing
LkSG infraction penalties > + Pressure for commitment to LkSG > + Adoption of ISO 14001 > + Wastewater recycling > + Energy and resource management > - Total CO2 emissions > + LkSG infraction penalties
Example scenario:
Another principle in ISO 14001 is the recycling of wastewater. Businesses that adopt that standard will require to recycle their wastewater, which leads to better management of energy and resources.

3.2 Variables Quantification Process

So far, the paper has identified the most important variables of this context through studying the literature and brainstorming with experts, establish connections between them using the results of other studies in the literature, and form causal loops that represent the dynamics of how taking environmental regulations could affect an SME in terms profitability. In order to be able to validate the causality and verify the relationships between the variables, it is required that data from the real world to build a machine learning model and complete the causality study. Since some of those variables are qualitative, it is a challenging task to be able to quantify all of them. In addition, for some of the variables it is needed to develop specific questionnaires and use the experts' opinions and viewpoints. This process will be done in a future study, but this study has broken down the variables into two categories, the ones for which quantitative data exist, and the ones that require to undergo a quantification process before the can be put into a machine learning model. The separation of variables is explained in Table 3.

Table 3. Variables with and without currently existing quantitative data

Row	Variables with existing quantitative data	Variables without existing quantitative data
1	Total CO_2 emissions	Energy and resource management
2	Green logistics and transportation	Waste of excess production
3	Adoption of ISO 14001	Green supplier selection
4	AI and BDA enabled infrastructure	Waste reduction
5	LkSG infraction penalties	Pressure for commitment to LkSG
6	Waste water recycling	Predictive and corrective measures
7	Total Costs of company	Risk management and analysis
8	Total profit of company	Transparency of operations and information
9	-	Precise demand planning
10	-	Optimal warehouse sizing
11	-	Recycling Process

4. Conclusions and Discussions

This paper tries to revolve around the solvency of active businesses in supply chains, specifically the SMEs, under the implementation of the new strict environmental regulations in the European Union (EU) and in specific, the German LkSG. For first objective for factors which change for SMEs active in supply chains regarding the new environmental regulations, The paper has studied all the related and state-of-the-art literature in this context. Nineteen of the most important factors mentioned in Table 2 have been defined. In the literature, most studies have analysed the correlation of the variables bilaterally using methods such as SEM and stated the direction of the correlation. The paper has elaborated the results and has created formed causal loops that depict the dynamics those variables working together as illustrated in Figure 1. For second objective for determining the measures that can be considered to counteract the negative effect of the aforementioned factors, in Table 2, in addition to the challenging factors, the counteracting measures have been explained. For example, adoption of ISO 14001 and green logistics and transportation. However, what discriminates this study from other studies that exist in the literature, is the CLD in Figure 1, which enables the decision-makers to scrutinize the cause-and-effect under varying scenarios.

For the third objective to determine the changing factors with the most negative effect on companies' revenues and the fourth objective for finding the counteracting measures which have the most neutralizing effect on profit-shrinking changes, the paper has offered the application of machine learning (ML) methods using real-world data. This will enable firstly the verification of the direction of the cause-and-effect and then, analyze the magnitude of the correlation. In that case, we will be able to test the most challenging situations and analyze how strong each of the challenges and their counter measures are.

In conclusion, this research has investigated the complex and multi-faceted relationship between new environmental legislation, namely the German LkSG, and the intrinsic operations of small and medium-sized enterprises (SMEs) in supply chains. Building on an extensive literature review, a total of 19 critical factors expected have been defined and studied to evolve under the auspices of the legislation. By using a combination of structural equation modeling (SEM) and distilling a selection of findings into causal loop diagrams, study has enriched the understanding of the associations and feedback mechanisms of the relevant factors. The paper has thereby provided a holistic framework for managers to navigate the broader implications of environmental regulation for SMEs while attending the operations of their core business. This research has brought out a challenge-based view of the factors awaiting significant changes and has outlined ways SME operators and decision-makers could minimize or resolve their impacts. The paper has discussed the options of securing ISO 14001 certification, deployed green logistics and transportation measures, and proposed the most relevant route for adoption in the form of a tool kit. Subsequent to this, the paper has melded all the insights into a causal loop diagram, providing a comprehensive view of the causal relationships across multiple scenarios in every factor. In terms of future research, the paper proposes integrating machine learning (ML) techniques to delve deeper into the financial repercussions for supply chain SMEs. In particular, it is recommended for exerting negative influences on profits and the countervailing strategies adopted by SME operators to offset their profit-shrinking impacts. By integrating causality, feedback mechanisms and learning models, this research seeks to provide a more unified view of environmental regulatory compliance and cost implications. This would be very useful to help more informed decisions related to compliance with new regulations while ensuring the survival and sustainability of SMEs going forward in fast-evolving business climates.

Future research could use the principles of ISO 14044 to advance understanding of the environmental impact on SMEs in the supply chain. By following established life cycle assessment (LCA) methods, researchers can delve deeper into the environmental footprint of materials and processes. This allows a comparison between the mitigation strategies proposed in this study, leading to a robust decision-making process. Furthermore, incorporating a social perspective into broader sustainability strategies in SMEs can enhance their environmental performance when considering socio-economic factors. Specifically, the benefits of ISO 14044 principles provide a structured framework for LCA, which facilitates informed decision-making and facilitates the transition to sustainable business practices in the SMEs' supply chains.

References

Abu Seman, N. A., Govindan, K., Mardani, A., Zakuan, N., Mat Saman, M. Z., Hooker, R. E. and Ozkul, S., The Mediating Effect of Green Innovation on the Relationship between Green Supply Chain Management and Environmental Performance, *Journal of Cleaner Production*, vol. **229**, pp. 115–27, 2019. DOI: 10.1016/j.jclepro.2019.03.211

Akbaripour, H., Houshmand, M. and Fatahi Valilai, O., Cloud-Based Global Supply Chain: A Conceptual Model and Multilayer Architecture, *Journal of Manufacturing Science and Engineering*, vol. **137**, no. 4, accessed July 12, 2022, from https://doi.org/10.1115/1.4030887, August 1, 2015. DOI: 10.1115/1.4030887

Al-Sheyadi, A., Muyldermans, L. and Kauppi, K., The Complementarity of Green Supply Chain Management Practices and the Impact on Environmental Performance, *Journal of Environmental Management*, vol. **242**, pp. 186–98, 2019. DOI: 10.1016/j.jenvman.2019.04.078

Benzidia, S., Makaoui, N. and Bentahar, O., The Impact of Big Data Analytics and Artificial Intelligence on Green Supply Chain Process Integration and Hospital Environmental Performance, *Technological Forecasting and Social Change*, vol. **165**, p. 120557, 2021. DOI: 10.1016/j.techfore.2020.120557

Bodendorf, F., Sauter, M. and Franke, J., A Mixed Methods Approach to Analyze and Predict Supply Disruptions by Combining Causal Inference and Deep Learning, *International Journal of Production Economics*, vol. **256**, p. 108708, February 1, 2023. DOI: 10.1016/j.ijpe.2022.108708

Caraveo, A., Krishnamoorthy, S., Lawas, J. M., Periaswamy, P., Sodachi, M., and Fatahi Valilai, O., Mutual Resiliency and Lean Analysis for Supply Chain Management in a COVID-19 Ventilator Production Case

Study, *Advances in System-Integrated Intelligence*, Cham: Springer International Publishing, pp. 299–309, 2023.

Farooqi, R., Iqbal, A., Shaikh, M. A., Iqbal, M. S. and Athar, A., Effect of Green Supply Chain Management On Financial Performance: Moderating Effect of Institutional Pressure, *Journal of Business Studies and Economic Research*, vol. **1**, no. 1, pp. 1–20, 2023.

Feng, M., Yu, W., Wang, X., Wong, C. Y., Xu, M. and Xiao, Z., Green Supply Chain Management and Financial Performance: The Mediating Roles of Operational and Environmental Performance, *Business Strategy and the Environment*, vol. **27**, no. 7, pp. 811–24, 2018. DOI: 10.1002/bse.2033

Fisher, R. A., Statistical Methods for Research Workers, in *Breakthroughs in Statistics: Methodology and Distribution*, S. Kotz and N. L. Johnson, Eds., New York, NY: Springer, accessed October 22, 2023, from https://doi.org/10.1007/978-1-4612-4380-9_6, pp. 66–70, 1992.

Hume, D., *A Treatise of Human Nature*, Clarendon Press, pp. 748, 1896.

Hume, D. Ed., *An Enquiry Concerning Human Understanding and Other Writings*, New York: Cambridge University Press, 2007.

Lopes De Sousa Jabbour, A. B., Vazquez-Brust, D., Jose Chiappetta Jabbour, C. and Latan, H., Green Supply Chain Practices and Environmental Performance in Brazil: Survey, Case Studies, and Implications for B2B, *Industrial Marketing Management*, vol. **66**, pp. 13–28, 2017. DOI: 10.1016/j.indmarman.2017.05.003

McIntyre, K., Smith, H., Henham, A. and Pretlove, J., Environmental Performance Indicators for Integrated Supply Chains: The Case of Xerox Ltd, *Supply Chain Management: An International Journal*, vol. **3**, no. 3, pp. 149–56, 1998. DOI: 10.1108/13598549810230877

Mumtaz, U., Ali, Y. and Petrillo, A., A Linear Regression Approach to Evaluate the Green Supply Chain Management Impact on Industrial Organizational Performance, *Science of The Total Environment*, vol. 624, pp. 162–69, 2018. DOI: 10.1016/j.scitotenv.2017.12.089

Olad, A. A., and FatahiValilai, O., Using of Social Media Data Analytics for Applying Digital Twins in Product Development, *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, *2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, pp. 319–23, 2020.

Pearl, J., *Causality*, Cambridge University Press, pp. 487, 2009.

Radmanesh, S.-A., Haji, A. and Fatahi Valilai, O., Blockchain-Based Architecture for a Sustainable Supply Chain in Cloud Architecture, *Sustainability*, vol. **15**, no. 11, p. 9072, 2023. DOI: 10.3390/su15119072

Radmanesh, S.-A., Haji, A. and Valilai, O. F., Blockchain-Based Cloud Manufacturing Platforms: A Novel Idea for Service Composition in XaaS Paradigm, *PeerJ Computer Science*, vol. **7**, p. e743, 2021. DOI: 10.7717/peerj-cs.743

Somjai, S. and Jermsittiparsert, K., The Trade-off between Cost and Environmental Performance in the Presence of Sustainable Supply Chain, vol. **8**, pp. 237–47, 2019.

Stefanelli, N. O., Jabbour, C. J. C. and Jabbour, A. B. L. D. S., Green Supply Chain Management and Environmental Performance of Firms in the Bioenergy Sector in Brazil: An Exploratory Survey, *Energy Policy*, vol. **75**, pp. 312–15, 2014. DOI: 10.1016/j.enpol.2014.06.019

Strittmatter, A., What Is the Value Added by Using Causal Machine Learning Methods in a Welfare Experiment Evaluation?, *Labour Economics*, vol. **84**, p. 102412, 2023. DOI: 10.1016/j.labeco.2023.102412

The Economist, German Companies Fret about a New Supply-Chain Law, *The Economist*, 2023.

Wang, Z., Wang, Q., Zhang, S. and Zhao, X., Effects of Customer and Cost Drivers on Green Supply Chain Management Practices and Environmental Performance, *Journal of Cleaner Production*, vol. **189**, pp. 673–82, 2018. DOI: 10.1016/j.jclepro.2018.04.071

Biographies

Ardalan Irani is a M.Sc. graduate in Supply Chain Management from Constructor University Bremen. He also holds a M.Sc. in Industrial Engineering from University of Tehran. His research area includes machine learning and supply chain management and applied operations research. His studies include analysis of green supply chain management with focus on SME roles.

Dr. Omid Fatahi Valilai has received his B.Sc., M.Sc and Ph.D from Sharif University of technology, Tehran, Iran in 2007, 2009 and 2012. From 2013 to 2019, he was an Assistant and then Associate professor at the Department of Industrial Engineering manufacturing, Sharif University Tehran, Iran. He is currently a distinguished lecturer of Industrial Engineering in the School of Business, Social & Decisions Sciences at Constructor University Bremen, Germany. His research interest includes Computer Integrated Manufacturing (CIM), Manufacturing Systems, Integrated and Collaborative Manufacturing Process Design, New Product Development Integration with Manufacturing Processes, System Analysis and Design and blockchain technology. He has more than 100 research papers in conferences and journal publications.