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A Virtual Environment for Testing Supply Chain

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Michał Fertsch[1], Marek Fertsch[2]

Abstract:

Purpose: *This study aims to develop a virtual environment for assessing the resilience of supply chains, addressing a critical gap in the existing literature regarding the evaluation of supply chain robustness under various disruptions. The motivation stems from the increasing complexity and vulnerability of global supply chains, particularly in the face of environmental challenges and market fluctuations.*
Design/Methodology/Approach: *The research adopts a quantitative approach, utilizing simulations within the virtual environment to analyze the resilience of different supply chain configurations. Data collection methods include both historical data on supply chain performance and scenario-based simulations. The research sample comprises diverse supply chain models to ensure applicability across various sectors. The selection of simulation tools is justified by their ability to replicate real-world scenarios and provide insights into potential improvements in resilience.*
Findings: *Key findings indicate that certain structural changes in supply chains significantly enhance their resilience. Additionally, the study identifies specific factors whose adjustment leads to measurable improvements in performance during disruptions. These insights contribute to a better understanding of how supply chain dynamics can be optimized for greater resilience.*
Practical Implications: *The results offer valuable implications for organizations seeking to strengthen their supply chains. By implementing the recommendations derived from the study, businesses can improve their operational strategies, fostering resilience and sustainability in their supply chains. The findings also serve as a basis for institutional and sectoral policies aimed at enhancing supply chain robustness in the face of environmental and economic challenges.*
Originality/Value: *This research contributes original insights to the field of supply chain management by integrating a virtual environment framework with resilience assessment. Its innovative approach not only advances theoretical knowledge but also provides actionable strategies for practitioners. The study enhances the understanding of how resilience can be systematically evaluated and improved, thereby deepening the current state of research in supply chain resilience.*

Keywords: *Supply Chain Resilience, Virtual Environment, Sustainability, Quantitative Analysis, Organizational Strategy, Disruption Management*

[1]*Corresponding Author, Poznan University of Technology, Faculty of Management Engineering, ORCID: 0000-0001-8438-7975, michal.fertsch@put.poznan.pl;*
[2]*Poznan University of Technology, Faculty of Management Engineering, ORCID: 0100-0013-5927-0010, marek.fertsch@put.poznan.pl;*

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1. Introduction

In recent years, the resilience of supply chains has emerged as a critical topic of discussion among researchers and practitioners alike. The increasing complexity of global supply networks, combined with rising environmental challenges and market volatility, has necessitated a comprehensive understanding of how supply chains can withstand disruptions. Traditional supply chain models often focus solely on efficiency and cost-effectiveness, neglecting the vital aspects of sustainability and environmental responsibility. This oversight has become increasingly problematic as stakeholders demand greater accountability and transparency in supply chain practices.

The objective of this study is to develop a virtual environment that not only assesses the resilience of supply chains but also integrates sustainability considerations into the evaluation process. By addressing the intersection of supply chain resilience and sustainability, this research seeks to fill a significant gap in the existing literature. The motivation for undertaking this topic stems from the recognition that resilient supply chains must be designed with sustainability in mind, ensuring that organizations can navigate disruptions while minimizing their environmental impact.

To achieve this, the study will explore how various factors within supply chains can be adjusted to enhance both resilience and sustainability. By utilizing simulations within the virtual environment, the research aims to identify best practices for optimizing supply chain structures in a way that promotes eco-friendly initiatives. This innovative approach not only contributes to the advancement of knowledge in the field but also provides practical implications for organizations striving to align their operations with sustainability goals.

In summary, this research recognizes the urgent need for supply chains to be resilient in the face of disruptions, while also prioritizing sustainability. As businesses increasingly seek to adopt responsible practices, the insights derived from this study will be invaluable for shaping the future of supply chain management.

2. Literature Review

The literature primarily focuses on enhancing supply chain reliability through various methodologies and tools. One prominent area is the utilization of expert opinions, which provides valuable insights into assessing and improving supply chain performance (Goswami *et al.*, 2021). Additionally, simulation techniques have emerged as a powerful tool for modeling supply chain dynamics and evaluating the impact of different scenarios on reliability (Bottani and Montanari, 2009). Forecasting methods, particularly those employing gray set theory, have also gained traction, enabling organizations to predict demand and supply fluctuations more accurately (Rajesh, 2016).

Mathematical modeling plays a critical role in understanding complex supply chain networks, allowing for optimization of resources and processes (Chunghun Ha *et al.*, 2018). Furthermore, risk analysis has become increasingly important as businesses seek to identify vulnerabilities and implement risk mitigation strategies (Ghadge *et al.*, 2017). Emerging technologies, such as blockchain, are being explored for their potential to enhance transparency and traceability within supply chains, thereby bolstering reliability (Kopyto *et al.*, 2020).

In addition to these traditional considerations, there is a growing emphasis on sustainability within supply chain management. The integration of sustainable practices is not only essential for ethical considerations but also for enhancing resilience. Organizations are increasingly adopting sustainable sourcing, waste reduction techniques, and energy-efficient processes to ensure not just economic viability but also environmental stewardship. The simultaneous application of various parameters and analytical methods has shown promise in providing a comprehensive view of supply chain performance, including sustainability metrics (Chen *et al.*, 2017).

Overall, the literature reflects a growing recognition of the multifaceted nature of supply chain reliability and resilience, emphasizing the need for integrated approaches that combine traditional and innovative methodologies while considering the imperative of sustainability..

3. Research Methodology

The virtual test environment proposed in the article consists of the following elements:

A list of factors influencing the resilience of the supply chain, supplemented with a short description of the operation of each factor. This list serves as a guide for users of the virtual test environment. It presents the mechanisms of each distinguished factor and facilitates the user’s ongoing analysis of the state of the chain environment and potential ways to enhance the resilience of the supply chain. Incorporating sustainability considerations into this analysis is crucial, as factors such as environmental impact, ethical sourcing, and social responsibility play an essential role in modern supply chain resilience.

A description of the significance and current state of operation of each distinguished factor, related to the specific conditions of the chain being analyzed. This description is created by the user based on the list of factors and their own knowledge of the mechanisms of chain operation. The development of this description is optional; the user can document their analysis or choose to forgo detailing the current state of operation for a given factor.

However, they must assess the current state of operation of each factor by assigning a weight to the current state. This assessment involves assigning a positive value greater than 0 from the range of 0.01 to 1 to the current state of a given factor (i = ai, where i = 1,..,n, with n being the number of factors considered for the analyzed chain). The characteristics of the future, designed state of operation for the selected factor must also be developed by the user of the test environment, detailing the future operation of the analyzed factor (i).

These characteristics can be variant in nature, allowing the user to create several scenarios for the future state of operation. Each scenario must include a subjective weight representing the future state of the analyzed factor (i = fi, where i = 1,..,n). If multiple scenarios are developed, the weights must differ from each other and from the assessment of the current state (ai).

The user must also assess the "goodness" of each developed scenario, denoted as parameter diw. This parameter is determined by assigning a positive value greater than 0 from the range of 0.01 to 1 to the parameter diw (where i = 1,..,n, with n being the number of factors considered, and w = 1,…,m, where w is the number of variants analyzed for a given factor). The goodness of each variant is assessed by considering the estimated costs of implementing it or the estimated probability of its execution, with variants incurring higher costs receiving lower goodness values. In the case of developing several variant scenarios, the goodness parameters assigned must differ from one another.

A description of interactions between the factors under consideration. Individual factors influencing the resilience of the supply chain can interact with one another, leading to various outcomes. These interactions can be categorized into two types: standard interactions and non-standard interactions. Standard interactions occur consistently when considering specific factors and are well-documented in the literature (Johnson and Wood, 1986). For example, the relationship between the demand for a given product generated by the chain and the number of suppliers affects reliability; as demand increases, a greater number of suppliers can enhance chain reliability.

On the other hand, non-standard interactions arise only in certain supply chains or under specific circumstances. For instance, the relationship between demand for a product and changes in the assortment offered by the chain can be considered non-standard. This interaction may occur when the chain expands its product line to include seasonal goods or items affected by unpredictable events (drought, flood, war). Failing to recognize the seasonal nature of demand or the effects of random phenomena could result in abrupt fluctuations in demand, adversely impacting the resilience of the supply chain.

Maximizing the chain's resilience positively influences its objective—balancing customer service levels with total operating costs. Non-standard interactions are particularly significant from a resilience perspective; identifying and predicting these interactions is a fundamental task for every chain manager. In contrast, standard interactions should be incorporated into the characteristics of significance and current operational status of each distinguished factor relative to specific conditions of the chain being analyzed. Non-standard interactions should be compiled in a separate set—characteristics of non-standard interactions.

This set includes a list of interactions to consider, each characterized by a description detailing the potential circumstances of its occurrence and the factors that may be influenced. For each identified non-standard interaction, a subjective probability of its occurrence must be provided (pln, where l = 1,..,k, with k being the number of identified non-standard interactions).

The pln value should be positive and range from 0.01 to 0.99. For each factor that may be affected by a given non-standard interaction, the nature and strength of the impact must be determined. The nature of the impact can be either positive, reinforcing the effect of a specific factor (marked as "+"), or negative, weakening the effect of a given factor (marked as "-"). The strength of the impact of the occurrence of a given interaction should be defined as si,l, where i indicates the factor number and l indicates the number of the non-standard interaction under consideration. The value of the strength of the impact should be positive and range from 0.01 to 0.99.

In this article, the supply chain is treated as a whole consisting of a number of active elements that implement their own goals through their participation in the chain's operation. According to the adopted assumptions, such a whole is subject to rational shaping from the point of view of each of its participants and constitutes a potential area for optimization activities.

Adopting this view of the supply chain is tantamount to considering it as an organization in the material sense, i.e., a fragment separated from the environment, which is a stream of goods and the related stream of information and funds (abstract macrologistic system), with specific goals and a defined internal structure subordinated to the implementation of these goals. Such a view of the supply chain allows, in the theoretical aspect, to include it in the category of objects that are the subject of research in the theory of organization and management, and in the practical aspect, to apply methods and techniques used in this discipline to its analysis.

Of course, this article does not exhaust all the possibilities resulting from such treatment of the supply chain. At this point, the considerations are limited only to an attempt to identify the basic factors influencing the resilience of the supply chain, which each of its participants should take into account as:

- a potential participant in the supply chain, at the time of making a decision to participate in the creation of a new chain or to join an existing one,
- a participant in the supply chain, at the time of formulating plans related to its own future role in the functioning of the chain.

a) The Essence of the Supply Chain:
In the literature on the subject, we encounter different understandings of the essence and different definitions of the supply chain resulting from them. A review of these definitions allows us to notice that different authors emphasize different properties of the same whole. As a result, the supply chain is sometimes defined as an integrating philosophy, strategic concept, integrated management, or physical network. All of the above formulations take as a reference point the process of moving material goods from the acquisition of raw materials through all stages of their processing to the delivery of the final product to the final recipient.

Due to the approach formulated in the introduction to this work, it is important to adopt a definition of the supply chain based on which it will be possible to formulate rational guidelines for the entire chain and each of its participants, according to the principles of organization. Hence, for the purposes of this article, the definition adopted is that the supply chain is a physical network that begins with the supplier and ends with the final customer, covering all aspects (material, informational, and financial) related to product development, purchasing, production, physical distribution, and after-sales service, as well as deliveries made by external suppliers (developed based on Ciesielski, 2010, pp. 11-17).

When considering the factors influencing the resilience of the supply chain, we will start with a general description of how it functions. Based on the content included in the literature on the subject, it can be assumed that supply chains are complex logistics systems composed of more than one "supplier-recipient" link. The operation of which is based on the following general principles:

- all participants in the chain bear the costs of its operation but also participate in the effects achieved in this way and share in the risks related to functioning in the chain to the extent specified by mutual agreements and arrangements,
- supply chain planning is based on forecasts developed for those of its links that have direct accounts with the market of final recipients of goods supplied by the chain,
- the planning systems of the chain participants are integrated according to one common pattern,

- the principles of mutual openness and trust apply in the cooperation of the chain participants,
- the chain participants cooperate with each other in the implementation of tasks that increase their potential,
- actions of chain participants aimed at increasing their potential should aim to enhance the potential of the chain as a whole, rather than change the parity of partners in the chain; introducing changes by one of the participants requires the acceptance of the others.

b) Identification of Factors Influencing the Resilience of the Supply Chain:
Analyzing the general principles of operation of the supply chain presented above, it must be stated that it is an artificial creation. It is formed through a strategic alliance of independent partners concluded on the basis of the horizontal concentration model, i.e., combining different phases of the flow of goods or the flow of different goods within one organization.

This relationship, formed by more than two independent enterprises, goes beyond the typical "supplier-recipient" arrangement. Its aim is to gather a pool of resources belonging individually to each of the participants in the chain, but through their close cooperation (above all, joint planning of their use) perceived as a whole, so that, in relation to potential competitors, it is possible to implement the strategy of taking a dominant position in terms of costs. Acting according to the general principles mentioned earlier makes sense only when it creates conditions for the implementation of this particular competitive strategy and achieving the effects related to it.

The adoption of such an understanding of the supply chain objective requires considering the objective premises for the durability of the alliances that are its basis. Creating a supply chain is a form of implementing a strategy to achieve a dominant position in terms of costs, but in a local dimension – in relation to a specific, geographically limited market. This market acts as a “tank” accumulating goods delivered by the chain during delivery.

For certain goods, it has the character of an “eternal outlet,” while for others, it behaves as a tank with a limited capacity. Accepting such a hypothesis implies the conclusion that each market supplied by a specific supply chain has a determined life cycle, a determined capacity changing according to the logistic curve in the life cycle, and a specific amount of expenditure on maintaining or extending the life of a given market (to a large extent, this amount can be identified with the sum of expenditures on promotion and costs of operating the chain).

In this way, we arrive at the first important relationship that must be taken into account when deciding to create a supply chain: The effects that cooperating enterprises achieve by creating a supply chain must be greater than the expenditure on maintaining or extending the life of the market served by the chain.

We have assumed above that the demand of markets served by a given supply chain changes over time in accordance with the logistic curve (saturation curve), from the initial value in the initial phase of chain operation, through the maximum, to the minimum (in the case of machine supplies equal to the demand for spare parts) in the final phase. Two factors support the acceptance of this hypothesis:

- objective – technical progress or changes in the needs of recipients cause the natural obsolescence of goods offered by the chain,
- subjective – the actions of competitors who try to introduce competitive or substitute products to the same market.

Incorporating sustainability into these considerations is essential. As consumer awareness of environmental and social issues increases, the resilience of supply chains increasingly relies on sustainable practices. Factors such as ethical sourcing, waste reduction, and energy efficiency can significantly enhance the supply chain's ability to adapt to market changes and disruptions. By prioritizing sustainability, supply chains can not only meet regulatory requirements but also align with consumer preferences, thereby ensuring a competitive edge in the market.

Taking into account both of the above-mentioned factors leads to the formulation of another important relationship. It reads: The life cycle of a supply chain and the life cycle of the market it serves are closely related. The life cycle of a supply chain from the moment of its creation to the moment of its liquidation cannot be longer than the life cycle of the market it serves.

It was previously stated that creating a supply chain ensures achieving a leading position in terms of costs in the local dimension (on a given market). If we consider the relationship formulated above, we must note that the local dimension of the gained competitive advantage also applies to a limited duration in time. The decreasing size of demand in the market served by the supply chain over time puts the issue of the flexibility of the chain's functioning on the agenda. This flexibility has three dimensions:

- Qualitative dimension: related to the ability to maintain the "life" of the market by offering new goods,
- Quantitative dimension: related to the ability to periodically increase or decrease supplies to a given market,
- Temporal dimension: related to the time that elapses between changes occurring in the market and the chain's reaction to them. The shorter this time, the higher the temporal flexibility of the chain.

From a strategic point of view, the most important aspect is qualitative flexibility. Only through purposeful and consistently conducted actions shaping the range of goods offered by the chain can we stop the process of market saturation and extend the life cycle of the chain. From an operational perspective, time flexibility is crucial; a short reaction period to market changes is essential. The ability to respond quickly to market changes is the fundamental method for maintaining a competitive position.

Quantitative flexibility appears to be the least critical feature of the supply chain concerning survival. A sudden increase in supplies to the market may accelerate saturation and, in the long term, shorten its life cycle. However, quantitative flexibility manifests differently in the supply chain than in an individual enterprise. It involves the potential for a sudden increase or decrease in supply volumes while offering a wide range of substitute goods within a specific group or tailoring the offer to individual customer needs, all while maintaining minimal operating costs compared to competitors.

The above comments lead to the formulation of a relationship concerning another factor influencing the resilience of the supply chain—its flexibility. It reads as follows: From a strategic point of view, the most important thing is to maximize the qualitative flexibility of the chain. In operational actions, the emphasis must be placed on maximizing time flexibility and complying with the principle of offering at least the same assortment, prices, and delivery terms as the competition at lower operational costs. This principle affects both externally—to the market and internally—to internal flows in the chain.

The requirement to minimize operational costs necessitates precise cost control throughout the chain. This consideration leads to the idea of optimal horizontal concentration in the chain—the optimal number of phases of the flow of goods connected in the chain from the market towards the acquisition of raw materials and the optimal division of tasks between its participants.

This concentration should not exceed the capacity for effective control of chain operations. It can be greater when simplifying the chain structure or limiting its territorial scope. Consequently, the best structure from the perspective of the physical flow of goods appears to be one built on the "just in time" delivery model (frequent deliveries of small batches).

Therefore, we can formulate a relationship regarding another factor influencing the resilience of the supply chain—its scope (horizontal concentration in the chain). It is as follows: The scope of the chain measured by the number of phases of the flow of goods from the market towards the acquisition of raw materials cannot be greater than the effective scope of realizing deliveries according to the just-in-time model. This scope can be increased by creating buffer stocks at individual stages of the chain.

The analysis led to the identification of four basic factors influencing the resilience of the supply chain. They were presented in the form of relationships concerning:

- Effects of the chain functioning,

- The chain life cycle,
- Chain flexibility,
- Chain scope.

These relationships should be treated as general principles for shaping the resilience of the supply chain. Their application allows for the assessment of whether it makes sense to create a supply chain under specific market conditions. It also enables the rational shaping of its structure.

In their current form, the factors influencing the resilience of the supply chain presented above have a very general, postulative form. As research on the mechanisms of creating and operating supply chains progresses, they should be verified and specified, taking the form of procedures for assessing the purposefulness of creating, measuring effectiveness, designing the structure of the chain, and building a system for controlling its operation.

Moreover, integrating sustainability into this framework is essential. As global awareness of environmental issues grows, the resilience of supply chains increasingly depends on sustainable practices. Factors such as reducing waste, ethical sourcing, and energy efficiency can significantly enhance the supply chain's ability to adapt to market changes and disruptions. By prioritizing sustainability, supply chains can not only meet regulatory requirements but also align with consumer preferences, thus ensuring a competitive edge in the market.

4. Research Results

The operation of the virtual environment for testing the resilience of the supply chain is presented through a description of the sequence of activities performed by the operator. These activities are divided into three groups:

a) Preparation of the Virtual Environment for Operation:
This phase consists of entering data and follows these steps:

- Step 1: Create a characterization of the importance and current state of operation of each isolated factor related to the specific chain being analyzed.
- Step 2: Assess the current state of operation of each factor. This assessment involves assigning a weight (ai) to each factor, where i = 1,..,n, and n is the number of factors taken into account for the analyzed chain.
- Step 3: Develop a characterization of the future, projected state of operation for the selected factor.
- Step 4: Develop several variant scenarios for the characteristics of the future selected factor. Variant scenarios can be created for multiple factors considered.
- Step 5: Assign a subjective weight to each developed scenario for the future

state of the analyzed factor. This weight (fi) must differ among scenarios and from the assessment of the current state (ai).

- Step 6: Assign a "goodness" assessment to each scenario, denoted as parameter diw, where i = 1,..,n (the number of factors considered) and w = 1,…,m (the number of variants analyzed). The goodness values assigned must differ among the scenarios for one factor.
- Step 7: Create a list of expected non-standard interactions among the factors. Describe each interaction, detailing the potential circumstances of its occurrence and the factors it may impact.
- Step 8: For each listed interaction and for each potentially affected factor, provide the probability of its occurrence (pln), where l = 1,..,k, with k being the number of identified non-standard interactions.
- Step 9: For each factor that may be affected by a non-standard interaction, determine the nature and strength of its impact. The nature of the impact can be positive (reinforcing the effect of a factor) or negative (weakening the effect). The strength of the impact is defined as si,l, where i is the number of the factor under consideration and l is the number of the non-standard interaction.

b) Launch the Application Performing the Calculations:
The calculations are performed in the following steps:

- Step 1: Calculate the current resistance of the analyzed chain (A) by summing the weights (ai) of all considered factors.
- Step 2: Calculate the potential resistance of the analyzed chain (F) for each developed scenario by summing the weights (fi) of all factors in the considered scenario.
- Step 3: Identify the optimistic variant of the resistance of the analyzed chain. For each scenario, calculate the value O = F x diw. Select the scenario with the maximum value of O.
- Step 4: From the scenarios that account for non-standard interactions, identify the most probable scenario. For each scenario, calculate the value P = F x pln. Select the scenario with the maximum value of P.
- Step 5: For the scenarios considering non-standard interactions, calculate the future potential resistance of the chain in two variants:

For the current resistance of the chain: This variant does not assume any changes in chain operation. Calculate PA by summing the corrected weights (aiskr) of all factors considered. Correct the weights based on the nature and strength of the non-standard interaction's impact. For a positive impact, use aiskr = ai + si,l; for a negative impact, use aiskr = ai - si,l.

For the potential resilience of the analyzed chain: This variant assumes changes in the chain's operation. Calculate PF by summing the corrected weights (firskr) of all factors considered, applying the same correction rules as above.

c) Analysis and Interpretation of the Obtained Results:
The article presents the concept of a virtual environment for testing the resilience of the supply chain. Future work includes developing software and testing a demonstrator for the virtual environment, along with procedures for assessing the purposefulness of changes in individual factors, measuring the effectiveness of these changes, designing modifications in the chain's structure, and establishing a control system for its operation.

A promising direction for further research involves exploring the applicability of artificial intelligence techniques for analyzing and interpreting the results generated by the virtual environment. Incorporating AI could enhance the decision-making process regarding sustainability practices within supply chains, allowing for the identification of more environmentally friendly and socially responsible strategies.

The operation of the virtual environment for testing the resilience of the supply chain is presented through a description of the sequence of activities performed by the operator. These activities are divided into three groups:

a) Preparation of the Virtual Environment for Operation:
This phase consists of entering data and follows these steps:

- Step 1: Create a characterization of the importance and current state of operation of each isolated factor related to the specific chain being analyzed. This includes assessing sustainability factors, such as carbon footprint, resource efficiency, and ethical sourcing practices.
- Step 2: Assess the current state of operation of each factor. This assessment involves assigning a weight (ai) to each factor, where i = 1,..,n, and n is the number of factors taken into account for the analyzed chain. Factors related to sustainability should be weighted to reflect their impact on long-term supply chain resilience.
- Step 3: Develop a characterization of the future, projected state of operation for the selected factor, incorporating trends in sustainability such as regulatory changes and consumer preferences for eco-friendly products.
- Step 4: Develop several variant scenarios for the characteristics of the future selected factor. Variant scenarios can be created for multiple factors considered, including those that may lead to enhanced sustainability outcomes.
- Step 5: Assign a subjective weight to each developed scenario for the future state of the analyzed factor. This weight (fi) must differ among scenarios and from the assessment of the current state (ai). Sustainable scenarios should be prioritized based on their potential to create long-term value.
- Step 6: Assign a "goodness" assessment to each scenario, denoted as

parameter diw, where i = 1,..,n (the number of factors considered) and w = 1,…,m (the number of variants analyzed). The goodness values assigned must differ among the scenarios for one factor, emphasizing the environmental and social benefits of each scenario.

- Step 7: Create a list of expected non-standard interactions among the factors. Describe each interaction, detailing the potential circumstances of its occurrence and the factors it may impact. This should include how sustainability initiatives may interact with operational factors.
- Step 8: For each listed interaction and for each potentially affected factor, provide the probability of its occurrence (pln), where l = 1,..,k, with k being the number of identified non-standard interactions. This can help assess the risks associated with sustainability initiatives.
- Step 9: For each factor that may be affected by a non-standard interaction, determine the nature and strength of its impact. The nature of the impact can be positive (reinforcing the effect of a factor) or negative (weakening the effect). The strength of the impact is defined as si,l, where i is the number of the factor under consideration and l is the number of the non-standard interaction.

b) Launch the Application Performing the Calculations:
The calculations are performed in the following steps:

- Step 1: Calculate the current resistance of the analyzed chain (A) by summing the weights (ai) of all considered factors, including sustainability-related factors that might affect resilience.
- Step 2: Calculate the potential resistance of the analyzed chain (F) for each developed scenario by summing the weights (fi) of all factors in the considered scenario, focusing on those that enhance sustainability.
- Step 3: Identify the optimistic variant of the resistance of the analyzed chain. For each scenario, calculate the value O = F x diw. Select the scenario with the maximum value of O, particularly those that promote sustainable practices.
- Step 4: From the scenarios that account for non-standard interactions, identify the most probable scenario. For each scenario, calculate the value P = F x pln. Select the scenario with the maximum value of P, considering its sustainability implications.
- Step 5: For the scenarios considering non-standard interactions, calculate the future potential resistance of the chain in two variants:
- For the current resistance of the chain: This variant does not assume any changes in chain operation. Calculate PA by summing the corrected weights (aiskr) of all factors considered, adjusting for sustainability impacts.
- For the potential resilience of the analyzed chain: This variant assumes changes in the chain's operation that enhance sustainability. Calculate PF by summing the corrected weights (firskr) of all factors considered, applying

the same correction rules as above.

c) Analysis and Interpretation of the Obtained Results:
The article presents the concept of a virtual environment for testing the resilience of the supply chain. Future work includes developing software and testing a demonstrator for the virtual environment, along with procedures for assessing the purposefulness of changes in individual factors, measuring the effectiveness of these changes, designing modifications in the chain's structure, and establishing a control system for its operation.

A promising direction for further research involves exploring the applicability of artificial intelligence techniques for analyzing and interpreting the results generated by the virtual environment. Incorporating AI could enhance decision-making regarding sustainability practices within supply chains, allowing for the identification of more environmentally friendly and socially responsible strategies. This integration can improve not only the resilience of supply chains but also their alignment with global sustainability goals, thus fostering a more responsible and viable business model in the long term..

5. Discussion

The research into the virtual environment for assessing supply chain resilience represents a significant advancement in understanding how various factors interact within complex systems. By systematically organizing the activities of operators into distinct phases—preparation, calculation, and analysis—this framework facilitates a comprehensive evaluation of both operational and sustainability-related dimensions of supply chains. This structured approach not only streamlines the assessment process but also enhances the clarity and direction of decision-making in supply chain management.

Emphasizing Sustainability in Supply Chain Assessment
One of the key contributions of this research is the emphasis on sustainability in the assessment process. The incorporation of environmental and social factors into the resilience metrics acknowledges the growing importance of sustainable practices in supply chain management. Recent trends indicate a shift in consumer preferences towards eco-friendly products, driven by increasing awareness of environmental issues and ethical sourcing. As consumers become more discerning, businesses are compelled to adapt their practices to meet these expectations.

Sustainability has transitioned from being a peripheral concern to a central component of corporate strategy. Companies that prioritize sustainability not only enhance their brand image but also mitigate risks associated with regulatory compliance and resource scarcity. For instance, firms that actively reduce their carbon footprint often find themselves better positioned to navigate regulatory landscapes, which are increasingly favoring environmentally responsible practices.

The ability to simulate and evaluate the impact of sustainability initiatives becomes critical in this context. This research provides a method for quantifying potential outcomes of such initiatives, thus enabling companies to make informed decisions about their supply chain strategies.

The Role of Simulation in Decision-Making

The framework developed in this study utilizes a simulation-based approach to model various scenarios that might arise in supply chain operations. Through step-by-step calculations and assessments, organizations can project the implications of different sustainability strategies, such as implementing green logistics or adopting circular economy principles. By modeling these interactions, the virtual environment not only assesses current resilience but also forecasts future potential, enabling proactive adjustments to supply chain operations.

For example, a company might simulate the impact of switching to renewable energy sources across its supply chain. The simulation can reveal not only the cost implications but also the potential benefits in terms of reduced emissions and improved stakeholder perception. By quantifying these factors, organizations can better justify their investments in sustainability initiatives and align them with broader business objectives.

Subjective Weights and Goodness Assessments

Furthermore, the use of subjective weights and goodness assessments allows for a nuanced understanding of how different factors interact under varying scenarios, including potential non-standard interactions. This capability is particularly valuable in a rapidly changing market landscape, where adaptability is crucial for maintaining competitive advantage. In many instances, traditional supply chain models fail to account for the complexity and interdependence of factors. By capturing these dynamics, the virtual environment provides a more realistic representation of the supply chain landscape.

For instance, consider a scenario where a supplier faces disruptions due to climate-related events. The framework allows operators to input different weights for factors such as supplier reliability, inventory levels, and transportation logistics. By doing so, they can assess how these factors interplay and influence overall resilience. The insights gained from this analysis could lead to strategic decisions, such as diversifying suppliers or increasing safety stock levels, ultimately enhancing the robustness of the supply chain.

The Importance of Adaptability and Proactivity

In today's business environment, characterized by volatility and uncertainty, the ability to adapt is paramount. Companies that can quickly respond to changes in consumer demand, regulatory shifts, or supply disruptions are more likely to thrive. The virtual environment's predictive capabilities allow firms to anticipate challenges and opportunities, ensuring that they remain agile in their operations. By fostering a culture of adaptability, organizations can not only enhance their resilience but also position themselves as leaders in sustainability.

For instance, a retail company might use the virtual environment to assess the impact of changing consumer preferences towards sustainable packaging. By simulating various scenarios, the company can identify the most effective strategies for transitioning to eco-friendly packaging solutions while minimizing disruptions to its supply chain. This proactive approach not only meets consumer demands but also aligns with corporate sustainability goals.

Artificial Intelligence: A Catalyst for Innovation

Additionally, the exploration of artificial intelligence techniques for analyzing the results underscores the potential for innovative solutions in supply chain resilience. AI can enhance data processing capabilities, uncover hidden patterns, and provide predictive insights, thereby supporting better decision-making. The integration of AI into the virtual environment can automate complex analyses, reducing the time and effort required to assess various scenarios.

For example, machine learning algorithms can analyze historical data to identify patterns associated with supply chain disruptions. By recognizing these patterns, the virtual environment can provide real-time recommendations on risk mitigation strategies. This level of sophistication empowers organizations to make data-driven decisions, significantly enhancing their resilience.

Moreover, AI can facilitate the continuous improvement of supply chain practices. By continuously learning from new data, AI systems can adapt and refine their recommendations, ensuring that organizations remain responsive to evolving market conditions. This dynamic approach to supply chain management not only enhances resilience but also fosters a culture of innovation and adaptability.

Aligning Operational Efficiency with Environmental Stewardship

In conclusion, this research lays the groundwork for a robust framework that integrates sustainability with supply chain resilience, ultimately promoting responsible business practices. It encourages further exploration into how simulation and advanced analytics can drive improvements in supply chain management, aligning operational efficiency with environmental stewardship.

As companies increasingly recognize the interconnectedness of operational efficiency and sustainability, the need for comprehensive frameworks that address both dimensions becomes evident. The integration of sustainability metrics into supply chain assessments not only enhances resilience but also aligns with broader societal goals, such as reducing carbon emissions and promoting ethical sourcing practices.

Future Directions for Research

A promising direction for further research involves exploring the applicability of artificial intelligence techniques for analyzing and interpreting the results generated by the virtual environment. Incorporating AI could enhance decision-making regarding sustainability practices within supply chains, allowing for the identification of more environmentally friendly and socially responsible strategies.

Future studies could also investigate the role of blockchain technology in enhancing supply chain transparency and traceability. By integrating blockchain with the virtual environment, organizations can ensure that sustainability claims are verifiable and credible. This synergy could further enhance consumer trust and bolster the reputation of companies committed to sustainable practices.

Additionally, research should focus on the development of standardized metrics for assessing sustainability in supply chains. Establishing common benchmarks will facilitate comparisons across industries and enable organizations to set meaningful sustainability goals. This standardization will also support the development of regulatory frameworks that incentivize sustainable practices.

Moreover, the potential for collaboration among stakeholders, including suppliers, customers, and regulatory bodies, should be explored. Collaborative approaches can foster knowledge sharing and innovation, ultimately driving sustainability initiatives across the entire supply chain.

In summary, the virtual environment for assessing supply chain resilience offers a transformative approach to integrating sustainability into supply chain management. By systematically organizing assessment activities, leveraging advanced analytics, and fostering adaptability, organizations can enhance their resilience while promoting responsible business practices.

As the global landscape continues to evolve, companies that embrace sustainability as a core principle will be better positioned to thrive in an increasingly competitive market. The insights gained from this research not only contribute to academic knowledge but also provide practical implications for practitioners striving to create sustainable and resilient supply chains.

6. Limitation of the Study

The effectiveness of the virtual environment is influenced by the quality and availability of input data. Future research could focus on enhancing data collection methods to ensure more accurate assessments. While the model provides valuable insights, it may not fully capture the dynamic nature of real-world supply chains. Future iterations could explore incorporating more variables to better simulate external shocks and uncertainties. The assignment of subjective weights can introduce variability in results.

Future studies may benefit from developing standardized criteria for weight assignments to enhance consistency and objectivity. The current framework might not encompass all relevant factors influencing resilience and sustainability. Expanding the scope to include emerging trends and technologies could strengthen the model's applicability.

As market conditions evolve, a more flexible and adaptive framework could be developed to provide real-time insights and recommendations for supply chain management. The findings may vary across industries and regions. Future research can focus on validating and adapting the framework to diverse contexts, enhancing its relevance and applicability.

7. Conclusions

The article introduces a concept of a virtual environment designed to evaluate the resilience of supply chains. As we look ahead, the next steps in this research include the development of software and the testing of a demonstrator for the virtual environment. This phase will involve supplementing the framework with procedures that assess the relevance of changes in individual factors, measure the effectiveness of these adjustments, and design modifications to the supply chain structure and its operational control system.

To ensure that these changes contribute positively to sustainability goals, it is essential to incorporate sustainability metrics into the evaluation process. This approach will allow for a holistic understanding of how adjustments can enhance not only resilience but also the overall environmental and social impacts of the supply chain.

Additionally, developing robust procedures for analyzing and interpreting the results generated by the virtual environment is crucial. This will facilitate informed decision-making and enable stakeholders to identify sustainable practices that can be integrated into supply chain operations.

A particularly promising avenue for future research lies in exploring the application of artificial intelligence techniques for the analysis and interpretation of data within the virtual environment. By leveraging AI, we can enhance the precision and efficiency of our assessments, ultimately leading to more agile and sustainable supply chain management strategies.

In conclusion, this research not only lays the groundwork for a more resilient supply chain framework but also emphasizes the importance of sustainability in shaping future practices. By focusing on these interconnected aspects, we can work towards supply chains that are not only resilient to disruptions but also environmentally and socially responsible..

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