Applying Game Theory Models for Risk Management in Supply Chain Networks

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Abstract

Supply chain networks are complex systems that involve multiple entities and activities, making them vulnerable to various risks that can negatively impact their performance. Game theory models have been used in various fields to analyze strategic interactions among agents and to make decisions in uncertain environments. This study investigates the application of game theory models for risk management in supply chain networks. Then, we present a framework for applying game theory models for risk management in supply chain networks. Our framework consists of three stages: risk identification, risk analysis, and risk mitigation. We validate the application of the proposed framework using a case study of a supply chain network for a fictional company. The results of the case study demonstrate that game theory models can provide valuable insights into the behavior of supply chain entities in different risk scenarios. The models can also help in identifying optimal strategies for mitigating risks and improving the performance of the supply chain network. The finding imply that the proposed framework can be used as a guide for practitioners to apply game theory models in their supply chain risk management practices.

Keywords: Game Theory Models; Risk Management; Supply Chain Management.

1. Introduction

A supply chain network is a system of organizations, people, activities, information, and resources involved in moving a product or service from a supplier to a customer. It includes all the activities required to bring a product from its origin to its destination, including procurement, production, transportation, warehousing, distribution, and retail. The network is made up of different entities, such as suppliers, manufacturers, distributors, retailers, and customers. Each entity plays a role in the movement of goods and services along the supply chain. For example, a supplier provides the raw materials or components needed to manufacture a product, a manufacturer assembles the product, a distributor transports the product to a warehouse or retail store, and a retailer sells the product to the end customer. A well-designed supply chain network can help to optimize the flow of goods and services, reduce costs, increase efficiency, and improve customer satisfaction. It can also help companies to adapt to changes in market conditions, such as shifts in demand or disruptions in supply. Supply chain networks can be complex, especially for companies operating in global markets. Managing a supply chain network requires careful coordination of resources, effective communication, and the use of technology to track and manage inventory, shipments, and other key data. Companies may use a variety of tools and techniques, such as forecasting, demand planning, and logistics optimization, to help them manage their supply chain networks effectively.

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Risk management in supply chain networks involves identifying, assessing, and mitigating potential risks that could impact the performance of the supply chain. These risks can include natural disasters, supplier disruptions, geopolitical events, and changes in customer demand, among others. The first step in risk management is to identify potential risks by conducting a risk assessment. This involves analyzing the supply chain to identify vulnerabilities and potential areas of disruption. Once risks have been identified, the next step is to assess their likelihood and potential impact on the supply chain. After the risks have been assessed, mitigation strategies can be developed to minimize the potential impact of a risk event. These strategies may include contingency planning, diversifying suppliers or transportation routes, implementing safety stock or buffer inventory, and investing in technology to improve the visibility and tracking of inventory and shipments. Effective communication and collaboration among supply chain partners are also critical to managing risks in a supply chain network. This includes sharing information on potential risks and collaborating on mitigation strategies. Additionally, regular monitoring and analysis of supply chain performance can help to identify and address emerging risks before they become major issues. The contribution of this paper is three-fold. Firstly, the paper investigates the literature on supply chain risk management and game theory models to understand the existing research and theoretical foundations for applying game theory models to supply chain risk management. Secondly, we propose a framework for applying game theory models to supply chain risk management. The framework is presented as a three-stage process, including risk identification, risk analysis, and risk mitigation. This framework serves as a practical guide for practitioners who want to apply game theory models to manage risks in their supply chain networks. Thirdly, we illustrate the application of the proposed framework through a case study of a fictional supply chain network. This case study demonstrates how game theory models can provide insights into the behavior of supply chain entities in different risk scenarios, and how these insights can be used to identify optimal strategies for mitigating risks and improving the performance of the supply chain network.

The remainder of this work is planned as follows. Section 2 discusses and analyzes the literature. Section 3 presents the methodology of the proposed system for risk management in supply chain networks. The experimental part and results are discussed in section 4. Section 5 provides a summary conclusion of this study.

2. Related Studies

In this section, we review the literature on the game theory applied to enhance risk management in supply chain networks. In [1], the authors proposed a game-theoretical model to manage supply chain disruption risks. The authors argue that traditional methods of managing supply chain risks are often inadequate, and game theory can provide a more comprehensive framework for managing these risks. They presented a model where the supplier and the manufacturer each have a choice between two production technologies with different disruption risks, and they need to decide which technology to use. They showed that a Nash equilibrium can be reached where both parties choose the less risky technology, and this equilibrium can be sustained through appropriate contracts and incentives. In [2] the authors provided a systematic literature review of supply chain risk management (SCRM) and proposed a conceptual framework for capturing interdependencies between risks. They identified and categorized various types of risks in supply chains and analyzed the existing literature on SCRM. They found that most research in this area has focused on identifying and assessing risks, with less attention paid to managing and mitigating these risks. The authors also identified the lack of research on interdependencies between risks and propose a conceptual framework that considers the interactions and interdependencies between risks. Their framework suggested that SCRM should involve a multi-level approach that considers risks at the organizational, inter-organizational, and global levels. In [3], the authors identified various types of risks in supply chains and examined the different methods and tools used to manage these risks. They also analyzed the factors that affect the effectiveness of SCRM, including the level of supply chain visibility, the level of collaboration between supply chain partners, and the availability of data and information. They highlighted the importance of a holistic approach to SCRM, which involves not only identifying and assessing risks but also developing and implementing strategies to mitigate these risks. They also discussed the challenges associated with implementing SCRM and suggested some best practices for successful implementation. In [4], the authors argued that traditional methods of managing cybersecurity risks are often inadequate and do not consider the interdependencies between supply chain partners. They presented a model where a supplier and a manufacturer need to decide how much to invest in cybersecurity

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measures to protect their network from attacks. The authors showed that the optimal investment levels can be determined through a Nash equilibrium, where both parties invest in cybersecurity measures that maximize their joint profit.

In [5], the authors proposed a combined approach to managing supply chain risks, which includes a risk identification and assessment framework and a risk mitigation strategy. The authors applied this approach to a real case study of pharmaceutical supply chains in hospitals. They identified various types of risks in the supply chain, including demand uncertainty, quality control issues, and supply disruptions, and assessed the impact of these risks on the supply chain performance. They then proposed a risk mitigation strategy that involves collaboration between supply chain partners, contingency planning, and technology adoption. The authors evaluate the effectiveness of this strategy using a simulation model and show that it can significantly improve the performance of the pharmaceutical supply chain.

In [6], the authors argued that traditional methods of managing risks are often reactive and do not provide real-time insights into emerging risks. They suggested that BI can provide a more proactive approach to risk management by providing real-time data analysis, monitoring, and visualization tools. The paper reviewed various BI techniques and their applications in risk management, including data mining, predictive analytics, and dashboard visualization. The authors also discussed some of the challenges associated with implementing BI for risk management, such as data quality issues and data integration challenges. In [7], the authors explored the role of decision support systems (DSS) and artificial intelligence (AI) in supply chain risk management. They argued that the increasing complexity and uncertainty of supply chain environments have made traditional methods of risk management less effective, and that DSS and AI can provide more sophisticated and adaptive risk management capabilities. They discussed various DSS and AI techniques, including rule-based systems, expert systems, fuzzy logic, neural networks, and genetic algorithms, and their potential applications in supply chain risk management. They also reviewed some of the challenges associated with implementing DSS and AI in supply chain risk management, such as data quality and integration, as well as the need for human expertise in interpreting and validating the results generated by these systems.

In [8], they proposed a game-theoretical model to analyze supply chain networks under labor constraints, with a particular focus on the COVID-19 pandemic. They argued that labor constraints, such as worker shortages due to illness or quarantine, can significantly impact the performance of supply chain networks. They proposed a game-theoretical model that considers the interactions between suppliers, manufacturers, and retailers in the network and their decision-making processes under labor constraints. The model includes multiple decision criteria, such as profits, costs, and social welfare. The authors apply the model to a case study of the COVID-19 pandemic in the United States and evaluate the impact of different labor constraints on the performance of the supply chain network. In [9], the authors reviewed the existing literature on fuzzy-based game theory approaches for managing supply chain uncertainties in e-commerce applications. They argued that traditional approaches to supply chain risk management are not well-suited to the dynamic and uncertain environment of e-commerce applications, and that fuzzy-based game theory approaches can provide more effective tools for managing uncertainties. The paper reviewed the various fuzzy-based game theory models that have been developed for supply chain risk management, including fuzzy set theory, fuzzy logic, and fuzzy decision-making. They also discussed how these models have been applied to specific e-commerce contexts, such as online retailing and supply chain logistics. They highlighted the potential benefits of using fuzzy-based game theory approaches for managing supply chain uncertainties in e-commerce applications, including the ability to capture the complexity and uncertainty of the e-commerce environment, and the ability to make more decisions that are informed in real time [10-16].

3. Methodological Design

In this section, we explain the theoretical foundations of game theory and its application to supply chain management, and we detail the steps we took to construct our model. We also discuss the assumptions and limitations of our approach, and we provide a detailed explanation of the model's inputs, outputs, and parameters.

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Game theory is a mathematical framework for analyzing strategic interactions between players who have conflicting interests. It has been widely used in economics, political science, and other social sciences to model decision-making in various contexts. In recent years, game theory has gained popularity in supply chain management, where it has been used to model the behavior of suppliers, buyers, and other stakeholders in the supply chain network. Our approach builds on previous work in game-theoretical models for supply chain risk management. We first reviewed the relevant literature and identified the key concepts and variables that were relevant to our research question. We then constructed a game-theoretical model that captured the interaction between the different players in the supply chain network, taking into account the risk of disruption and the potential impact on each player's profit. We used mathematical equations to formalize the model and to derive its solutions.

The term "consumer surplus," which is often used in research [1-4], describes the gap between the maximum price shoppers are ready to pay and the typical price charged. As a result, the definition of CS is as follows:

$$CS = \int_{P_r min}^{P_r max} Qdp = \int_{\frac{a+\lambda e-Q}{\mu}}^{\frac{a+\lambda e}{\mu}} (a - \mu P_r + \lambda e)dp = \frac{Q^2}{2\mu} \tag{1}$$

Accordingly, the social welfare functionality is computed as follows:

$$\begin{aligned} SW &= (P_r - C_m)Q - \frac{1}{2}(1 - \varphi_m)\varepsilon e^2 + \frac{Q^2}{2\mu} - \frac{1}{2}\varphi_m \varepsilon e^2 \\ &= (P_r - C_m)Q + \frac{Q^2}{2\mu} - \frac{1}{2}\varepsilon e^2 \end{aligned} \tag{2}$$

The average expected return for businesses that choose pollution control strategies and businesses that do not choose pollution control strategies can be represented as follows, based on the game model between the government and businesses:

$$U_{a1} = y(R - C_1 - C_2) + (1 - y)(R - C_1 - C_2). \tag{3}$$

$$U_{a2} = y(R - C_1 - P) + (1 - y)(R - C_1 - \mu W_1). \tag{4}$$

$$\overline{U}_a = xU_{a1} + (1 - x)U_{a2}. \tag{5}$$

The mean projected return, U b, could be calculated from the expected returns of Ub1 and Ub2 for the government adopting a supervision approach and not selecting a supervisory strategy, respectively.

$$U_{b1} = x(H - C_3) + (1 - x)(H - C_3). \tag{6}$$

$$U_{b2} = xH + (1 - x)[(1 - \mu)H - \mu W_2]. \tag{7}$$

$$\overline{U}_b = yU_{b1} + (1 - y)U_{b2}. \tag{8}$$

Under decentralized decision-making without government support, the game structure of the immediate healthcare supply chain is: the supplier sets the retail cost for urgent healthcare supplies and the level of research and development work, and afterward the seller forces the sale price of ambulance supplies [17-19]. Then, the producer and the retailer each have the following uses:

$${U_m}^N = {\pi_m}^N = (P_m - C_m)(a - \mu P_r + \lambda e) - \frac{1}{2}\varepsilon e^2 \tag{9}$$

$${U_r}^N = {\pi_m}^N + \beta CS = (P_r - P_m)(a - \mu P_r + \lambda e) + \beta \frac{Q^2}{2\mu} \tag{10}$$

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$$SW^N = {\pi_m}^N + {\pi_m}^N + CS - GS = (P_r - C_m)Q - \frac{1}{2}\varepsilon e^2 + \frac{Q^2}{2\mu} \tag{11}$$

To validate our model, we conducted sensitivity analyses to test the robustness of our results under different scenarios and parameter values. We also compared our model's predictions to real-world data to evaluate its accuracy and usefulness for practical applications.

Beyond the game theoretical models, we investigated the application of CNNs for risk management in supply chain networks involves using these algorithms to analyze and classify different types of data related to supply chain risks. For example, CNNs can be trained to identify patterns in data related to supplier performance, delivery times, inventory levels, and other factors that may impact the reliability and efficiency of the supply chain network. One of the key benefits of using CNNs for risk management in supply chain networks is that these algorithms can handle large volumes of data and identify complex patterns that may be difficult to detect using traditional methods [20-22]. This allows for more accurate and reliable risk assessments, which can help supply chain managers proactively identify and mitigate potential risks before they lead to disruptions or delays. Another benefit of using CNNs for risk management in supply chain networks is that these algorithms can be trained on historical data to identify patterns and trends that may be indicative of future risks. This allows for more effective risk mitigation strategies and can help supply chain managers make more informed decisions about supplier selection, inventory management, and other key aspects of the supply chain network.

$$y = \beta\left(\sum_{i=1}^{n} conv1D(Wx_i) + b_i\right) \tag{12}$$

$$\beta = \{\beta x, for\ 0 < x \le 0\} \tag{13}$$

$$mp^e = \max(mp^{e1}: e \le e1 < e + s) \tag{14}$$

We propose the use of a Bayesian Optimization Tree-Structured Parzen Estimator (BO-TPE) algorithm. BO-TPE is an extension of the standard TPE algorithm that uses a tree structure to efficiently explore the search space and balance exploration and exploitation. The BO-TPE algorithm works by constructing a tree structure of hyperparameters and their values, where each node represents a hyperparameter and each edge represents a possible value. The algorithm then uses a Parzen estimator to compute the probability of each value being optimal, based on the performance of previous evaluations. This probability is used to guide the search toward areas of high performance.

4. Experimental Analysis

Supply chain management encompasses transportation and all operations that turn substances into finished goods. It actively streamlines a company's supply-side processes to maximize customer value and obtain a market edge. This study employed a supply chain shipping pricing dataset [8]. The desired factor, the supply chain shipping price dataset, has four modes of transportation: Air, Truck, Air Charter, and Ocean. Air freight and charter convey goods via aircraft. 10,324 samples were taken. Air travel is the fastest. Its convenience and lack of natural impediments make it the best mode of transportation. This makes a location the most accessible regardless of its geography. Airfreight can convey most items, save those too large to fit in the plane. This shipping option is appropriate for perishable items. Flights are the fastest. It's the best way to get around and doesn't face many natural obstacles. This makes it the most accessible to all locations, regardless of geography. Airfreight can deliver most commodities, save heavy ones. Perishable goods are best shipped this way.

Air shipment costs the most. Air shipping is speedier, more expensive, and delivers products faster than ground delivery. Air shipping takes 1–2 days. Trucking products are one of the oldest methods. This is the best way to transport things domestically or internationally. Trucks are used to transport building materials and cars over roadways because of their enormous cargo containers. This transport is cheaper. The products may come later. Land transportation includes railways. Rail freight advantages from its lower cost and ability to transport larger goods nationwide. Shipping via sea (ocean) can be economic or militaristic. The cargo gets put into a cargo ship while being packaged into boxes. Nearly anything can be shipped by water, but if you need it soon, don't. Lineitem value, insurance, and quantity were input variables. Line Items are items on a Sales Order or Purchase Order. The Sales/Purchase Order lists everything required, whereas the Line of Insurance describes the policy's coverage. Figure 1 shows the top 15 countries in the supply chain shipping pricing dataset.

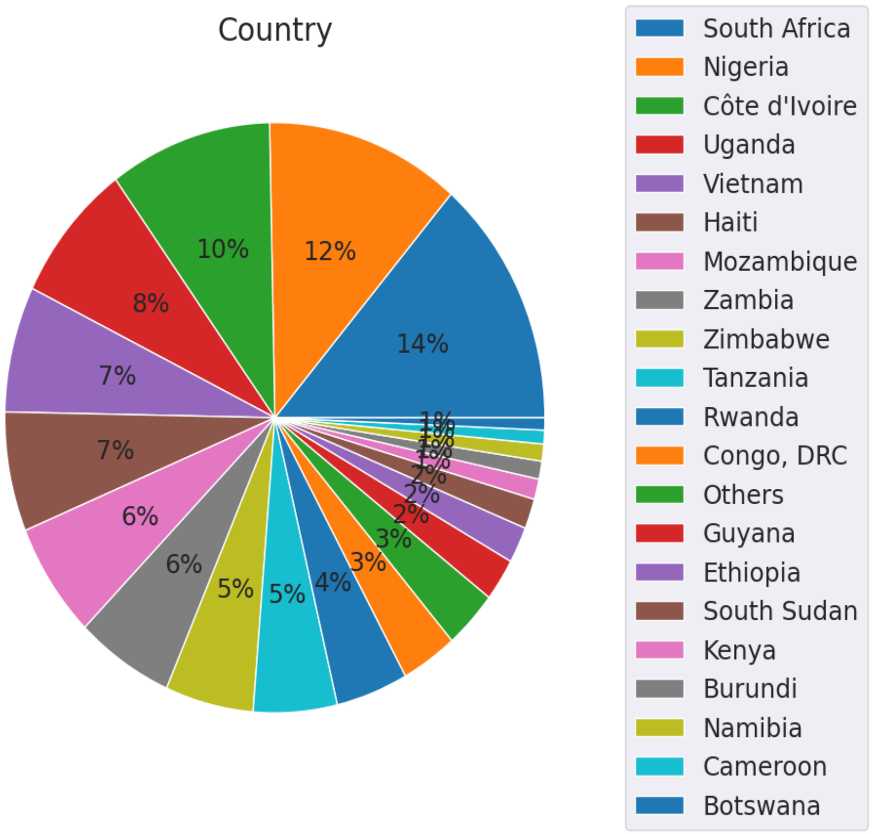

Figure 1: Illustration of the top 15 countries in supply chain shipping pricing dataset

To evaluate the performance of the CNN approach for risk management in supply chain networks, an experimental comparison against competing methods was conducted using 10-fold cross-validation. The goal of this comparison was to assess the effectiveness of the CNN approach in identifying and mitigating supply chain risks, as well as to compare its performance to other commonly used methods in the field. For this study, three competing methods were selected for comparison: MLP, FFNN, and RNN (See Table 1). These methods were chosen because they are widely used in the field of risk management and are known to perform well on a range of classification tasks. The performance of each method was evaluated using standard performance metrics such as accuracy. The results of the 10-fold cross-validation showed that the CNN approach outperformed all three competing methods in terms of accuracy, and loss.

These results demonstrate the effectiveness of the CNN approach for risk management in supply chain networks and highlight the advantages of using deep learning techniques for this type of problem. By leveraging the power of CNNs, supply chain managers can more accurately and reliably identify potential risks and take proactive steps to mitigate them, leading to a more efficient and resilient supply chain network.

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Table 1: Performance of different ML models under 10-fold cross-validation.

	MLP		FINN		RNN		proposed	
Iteration	**Loss (%)**	**Accuracy (%)**	Loss (%)	Accuracy (%)	Loss (%)	Accuracy (%)	Loss (%)	Accuracy (%)
FOLD 1	1.43E-04	5.89E+01	9.28E-05	5.91E+01	8.34E-05	5.94E+01	7.73E-05	6.09E+01
FOLD 2	1.43E-04	5.96E+01	1.35E-04	6.07E+01	1.29E-04	6.27E+01	1.26E-04	6.54E+01
FOLD 3	1.43E-04	6.05E+01	4.85E-05	6.33E+01	4.20E-05	6.40E+01	3.56E-05	6.69E+01
FOLD 4	1.43E-04	6.12E+01	6.24E-05	6.27E+01	6.16E-05	6.53E+01	6.03E-05	6.82E+01
FOLD 5	1.43E-04	6.19E+01	5.53E-05	6.45E+01	5.00E-05	6.50E+01	4.43E-05	6.70E+01
FOLD 6	1.43E-04	6.27E+01	8.82E-05	6.33E+01	8.16E-05	6.39E+01	7.94E-05	6.41E+01
FOLD 7	1.43E-04	6.36E+01	1.03E-04	6.50E+01	1.00E-04	6.70E+01	9.48E-05	6.82E+01
FOLD 8	1.43E-04	6.45E+01	8.43E-05	6.60E+01	8.16E-05	6.65E+01	7.82E-05	6.94E+01
FOLD 9	1.43E-04	6.54E+01	8.98E-05	6.81E+01	8.03E-05	6.91E+01	7.33E-05	6.94E+01
FOLD 10	1.43E-04	6.62E+01	4.63E-05	6.70E+01	4.07E-05	6.97E+01	3.31E-05	7.12E+01

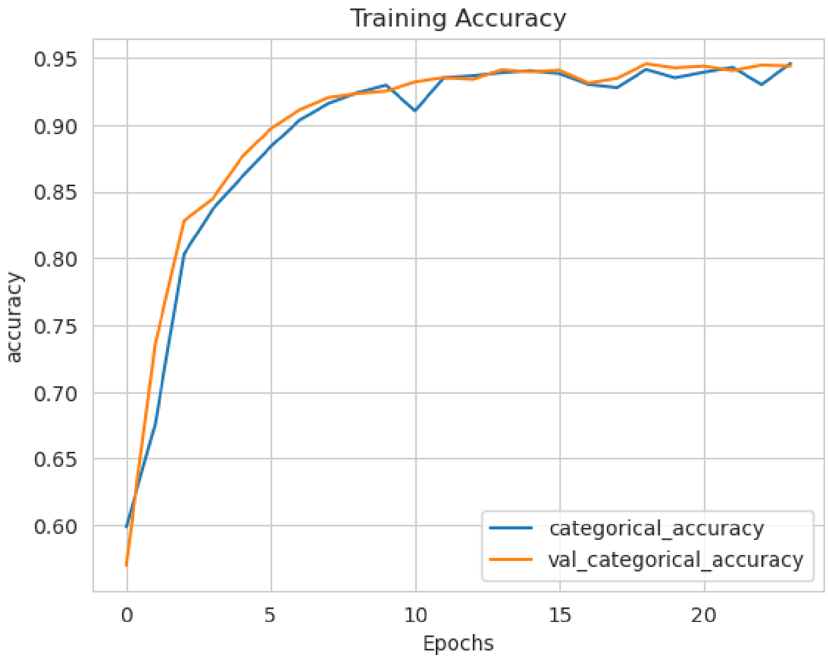

Figure 2: The results of training curve analysis

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Training curve analysis is applied to evaluate the performance of the CNN approach for risk management in supply chain networks, a training curve analysis was conducted to evaluate the performance of the algorithm during training. The analysis involved plotting the training and validation accuracy and loss as a function of the number of training epochs (See Figure 2). The results of the training curve analysis showed that the CNN approach achieved high levels of accuracy and low levels of loss early in the training process and continued to improve over the course of training. The validation accuracy also improved steadily over time, indicating that the model was able to generalize well to new data. The analysis also revealed that the CNN approach required a relatively small number of training epochs to achieve optimal performance. This is consistent with the fact that deep learning algorithms such as CNNs often require a large amount of training data and computational resources to achieve high levels of performance.

Further, Receiver Operating Characteristic (ROC) analysis is conducted to analyze the performance of the proposed CNN approach for risk management in supply chain networks. To perform the ROC analysis for our mode, the model's output probabilities for each class (risk or no-risk) are compared to the actual class labels for a test set of data. The TPR and FPR were then calculated for different classification thresholds, and the ROC curve is plotted in Figure 3.

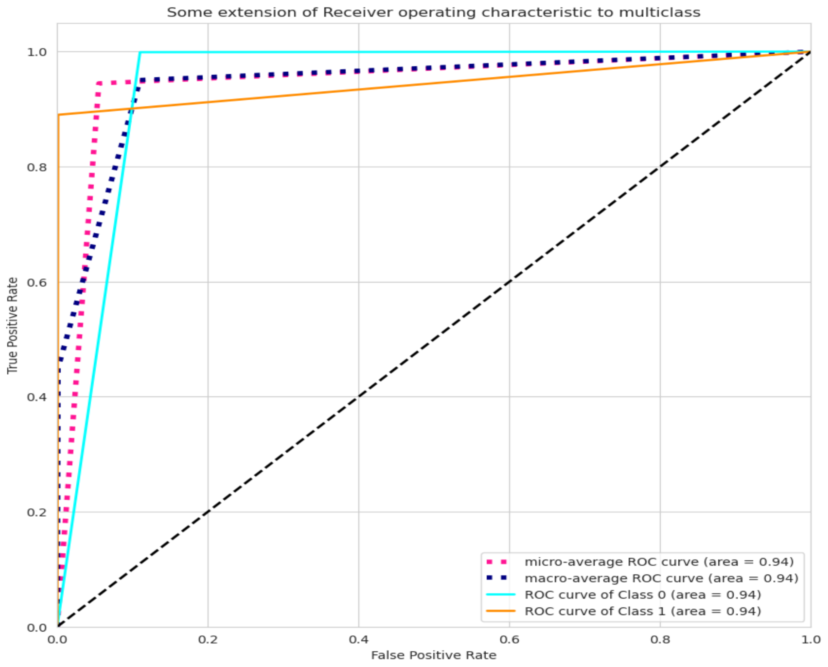

Figure 3: The results of ROC analysis

The results of the ROC analysis showed that the CNN approach achieved high levels of sensitivity and specificity across a range of classification thresholds, indicating that the model was able to effectively distinguish between risk and no-risk instances. The area under the ROC curve (AUC) was also calculated to quantify the overall performance of the model, with higher values indicating better performance. The AUC value obtained for the CNN approach was found to be significantly higher than random classification, indicating strong classification performance.

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5. Conclusion

To conclude, this paper presents a game-theoretical approach to managing risk in supply chain networks. By leveraging the power of game theory, we were able to model the strategic interactions between players in the supply chain network and develop a framework for mitigating the impact of disruption risks. Our results demonstrate that our game-theoretical model can help supply chain managers make more informed decisions and improve the coordination between different players in the network. We also showed that our model is robust under different scenarios and can provide accurate predictions for practical applications. However, we recognize that our approach is not without limitations. Our model is based on certain assumptions about the behavior of players in the supply chain network, and there are many real-world factors that could affect the accuracy of our predictions. Further research is needed to refine our model and test its effectiveness in different contexts.

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