People's Democratic Republic of Algeria
Ministry of Higher Education and Scientific Research

Larbi Ben M'hidi University of Oum El Bouaghi
Faculty of Exact Sciences and Natural and Life Sciences
Department of Mathematics and Computer Science
Research Laboratory on Computer Science's Complex Systems ReLa$(CS)^2$

PhD Thesis

Submitted in partial fulfillment of the requirements
for the degree of Doctorat in Computer Science

Option: Artificial Intelligence and Imaging

Multi-Agent Simulation for Decision Support in Supply Chains Risk Management

By:

Ahlem MEZIANI

Presented for defense in a public examination on: January 11th, 2024

Supervised by:
Pr.Abdelhabib BOUROUIS
Professor
University of Oum El Bouaghi.

Co-supervised by:
Dr. Mohamed Sedik CHEBOUT
MCA
University of Oum El Bouaghi.

Jury members:

Dr. Marir Toufik	MCA	University of Oum El Bouaghi	Chairman
Pr. Bourouis Abdelhabib	Professor	University of Oum El Bouaghi	Supervisor
Dr. Chebout Mohamed Seddik	MCA	University of Oum El Bouaghi	Co-Supervisor
Pr. Kahloul Laid	Professor	University of Biskra	Examiner
Dr. Kerkouche Elhillali	MCA	University of Jijel	Examiner
Dr. Khalfaoui Khaled	MCA	University of Jijel	Examiner

Acknowledgements

Firstly, I express my deepest gratitude to my supervisor, Pr. Abdelhabib Bourouis, Professor at the University of Oum El Bouaghi, for his unwavering support, guidance, and mentorship throughout my Ph.D. journey. His expertise and encouragement have profoundly shaped my research.

Special appreciation goes to my co-supervisor, Dr. Mohamed Seddik Chebout, MCA at the University of Oum El Bouaghi, for his dedicated assistance and scholarly insights during the course of this thesis.

I extend warm thanks to Dr. Toufik Marir, MCA at the University of Oum El Bouaghi, for granting me the honor of serving as the president of my jury. I am also grateful to Pr. Laid Kahloul, Dr. Elhillali Kerkouche, and Dr. Khaled Khalfaoui from the University of Biskra and the University of Jijel for their contributions as examiners, enriching the academic discourse surrounding my thesis. Their collective guidance and support have been instrumental in the successful completion of my research.

Lastly, I wish to express my deepest gratitude to my husband and my family, who have been my unwavering pillars throughout this academic journey. Their love, steadfast support, and constant encouragement have been an invaluable source of inspiration. Their caring presence has illuminated the dark moments and made successes even sweeter. Their sacrifices and understanding have enabled me to pursue my academic aspirations with determination and confidence. I am infinitely thankful for their unconditional love and invaluable support, which have enriched not only my academic life but also every aspect of my life.

In loving memory of my beloved father, whose inspiration and support have been invaluable throughout my life and studies, I dedicate this doctoral thesis. May God grant him His mercy and paradise. His memory will continue to inspire me and guide my steps in this work and beyond.

Abstract

Supply chain risk management (SCRM) is a vital component of contemporary supply chain management. This is because supply chain disruptions (SC) can have significant and detrimental effects, such as financial losses, reputational damage, and even the failure of a business. Nonetheless, implementing SCRM can be difficult due to the intricate and unpredictable nature of SC operations. These operations involve a variety of entities, geographies, and processes, thereby introducing complexity and uncertainty to the task of SCRM. In order to implement effective SCRM, it is necessary to identify, evaluate, and mitigate various sources of risk in real-time, including control, process, demand, and supply risks. However, currently there is no comprehensive decision support system (DSS) that can assist decision-makers in all the stages of the SCRM process. Although several risk assessment mechanisms exist, they are not capable of handling the complexity of SCRM-related issues in real-time. Furthermore, existing DSSs tend to focus on specific aspects of SCRM and do not take into account the entire process. Therefore, there is a need for a more holistic approach that can deal with the intricacies and uncertainties of SCRM-related issues, and provide decision-makers with up-to-date information to make well-informed decisions. The proposed framework, NeutroMAS4SCRM, combines Neutrosophic Data AHP with a multi-agent system (MAS) to manage supply chain risks (SCRs) more effectively. It leverages the MAS for prompt coordination and response, and the NDAHP technique for event extraction from current datasets and risk evaluation. The framework can identify potential risks that require comprehensive risk management and classify them based on predefined criteria using the NDAHP approach, which surpasses the limitations of vagueness, uncertainty, and complexity. Moreover, it immediately notifies relevant individuals of unexpected changes and utilizes simulation methods to establish a quantitative risk assessment and control system. The proposed MAS for the supply chain is implemented on the JADE agent platform, where message content based on FIPA-ACL is specified using a dedicated AgentSCRM ontology. The simulation-based DSS evaluates the framework by assessing cost risks and harmful effects, determining its efficacy in assisting companies to manage risks efficiently. The simulation results demonstrated that the NeutroMAS4SCRM framework can effectively decrease risk costs. In conclusion, NeutroMAS4SCRM is a promising tool for decision-makers seeking to enhance their SCRM strategies and improve their capabilities to address unforeseen risks.

Keywords: Supply Chain Risk Management; Ontology; Neutrosophic Data AHP; Multi Agent System; Simulation.

Résumé

La gestion des risques de la chaîne d'approvisionnement (SCRM) est un élément essentiel de la gestion contemporaine de la chaîne d'approvisionnement. Cela s'explique par les perturbations de la chaîne d'approvisionnement (SC) qui peuvent avoir des effets significatifs et néfastes. Néanmoins, la mise en œuvre de la SCRM peut être difficile en raison de la nature complexe et imprévisible des opérations de sc. Ces opérations impliquent une variété d'entités, de géographies et de processus, introduisant ainsi complexité et incertitude dans la tâche de la SCRM. Afin de mettre en œuvre une SCRM efficace, il est nécessaire d'identifier, d'évaluer et de atténuer diverses sources de risque en temps réel, notamment les risques de contrôle, de processus, de demande et d'approvisionnement. Cependant, il n'existe actuellement aucun système complet de soutien à la décision (DSS) capable d'assister les décideurs à toutes les étapes du processus de la SCRM. Bien que plusieurs mécanismes d'évaluation des risques existent, ils ne sont pas capables de gérer la complexité des problèmes liés à la SCRM en temps réel. De plus, les DSS existants ont tendance à se concentrer sur des aspects spécifiques de la SCRM et ne tiennent pas compte de l'ensemble du processus. Il est donc nécessaire d'adopter une approche plus holistique qui puisse traiter les complexités et les incertitudes des problèmes liés à la SCRM et fournir aux décideurs des informations à jour pour prendre des décisions éclairées. Le cadre proposé, NeutroMAS4SCRM, combine Neutrosophic Data AHP avec un système multi-agent (MAS) pour gérer plus efficacement les risques de la chaîne d'approvisionnement. Il tire parti du MAS pour une coordination et une réponse rapides, ainsi que de la technique NDAHP pour l'extraction d'événements à partir de jeux de données actuels et l'évaluation des risques. Le cadre peut identifier les risques potentiels nécessitant une gestion complète des risques et les classer en fonction de critères prédéfinis en utilisant l'approche NDAHP, qui surpasse les limitations du flou, de l'incertitude et de la complexité. De plus, il informe immédiatement les personnes concernées des changements inattendus et utilise des méthodes de simulation pour établir un système d'évaluation quantitative des risques et de contrôle. Le MAS proposé pour la chaîne d'approvisionnement est implémenté sur la plate-forme d'agent JADE, où le contenu des messages basé sur FIPA-ACL est spécifié à l'aide d'une ontologie dédiée, AgentSCRM. Les résultats de la simulation ont démontré que le cadre NeutroMAS4SCRM peut réduire efficacement les coûts liés aux risques alors c'est un outil prometteur pour les décideurs cherchant à améliorer leurs stratégies de gestion des risques de SC et à renforcer leurs capacités à faire face aux risques imprévus.

Mots-clés: Gestion des risques de la chaîne d'approvisionnement; Ontologie; Neutrosophic Data AHP; Système multi-agent; Simulation.

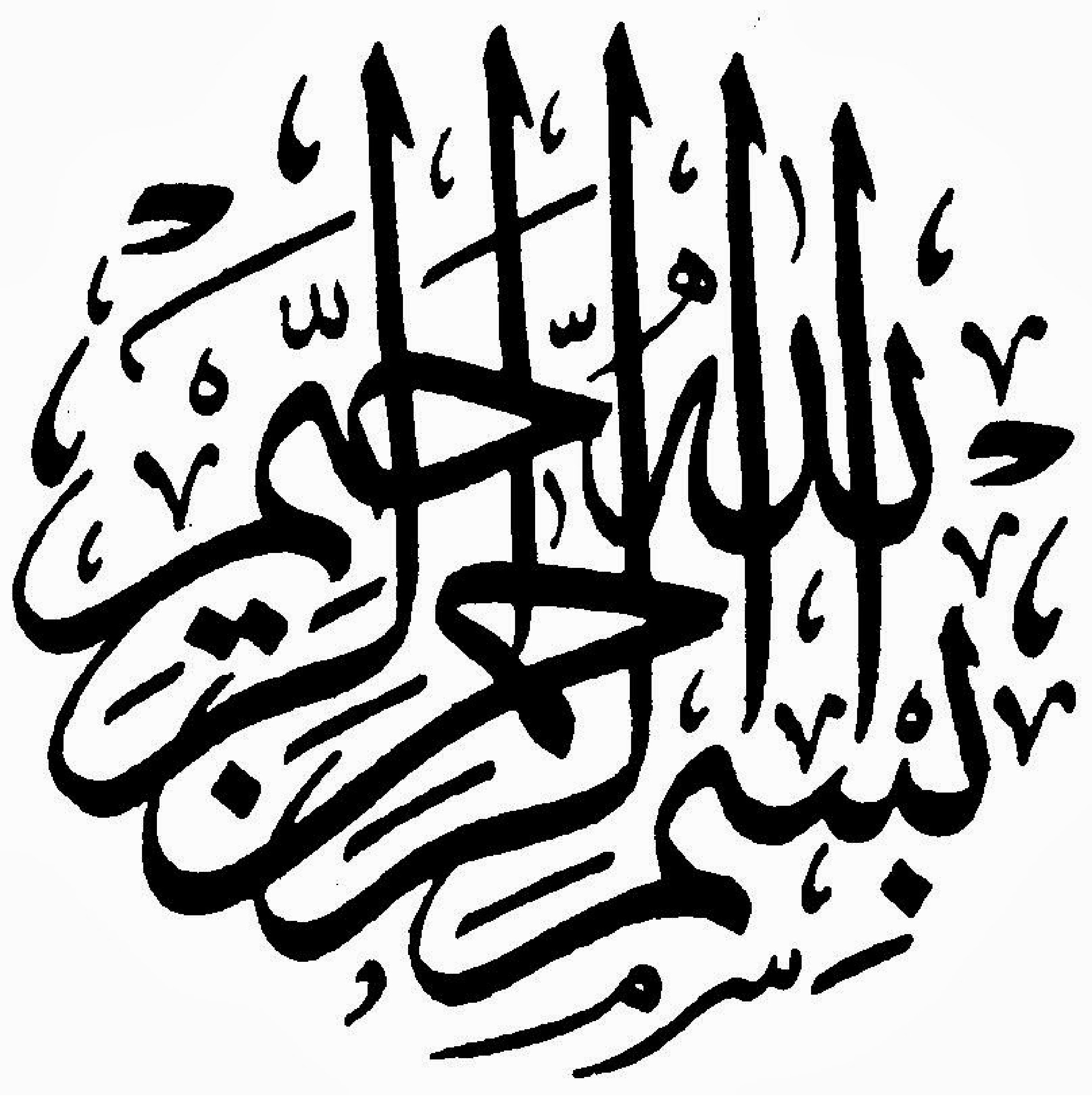
ملخص

تعد إدارة أخطار سلسلة التوريد (SCRM) عنصراً حيوياً من عناصر إدارة سلسلة التوريد المعاصرة. وذلك لان اضطرابات سلسلة الإمداد يمكن أن تكون له آثار كبيرة وضارة، مثل الخسائر المالية، والضرر الذي يلحق بالسمعة، بل وحتى فشل الأعمال التجارية. ومع ذلك، يمكن أن يكون تنفيذ آلية إدارة المواد SCRM أمراً صعباً بسبب الطبيعة المعقدة التي لا يمكن التنبؤ بها لعمليات سلسلة التوريد. وتشمل هذه العمليات مجموعة متنوعة من الكيانات، والمناطق الجغرافية، والعمليات، مما يُحدث تعقيداً وعدم يقيناً لمهمة الآلية.

من أجل تنفيذ آلية إدارة المخاطر على نحو فعال، من الضروري تحديد مختلف مصادر الاخطار وتقييمها والتخفيف من حدتها في الوقت الحقيقي، بما في ذلك أخطار المراقبة، والعمليات، والطلب، والعرض. ومع ذلك لا يوجد حالياً نظام شامل لدعم القرار (DSSs) يمكن أن يساعد صناع القرار في جميع مراحل عملية إدارة أخطار سلسلة التوريد على الرغم من وجود العديد من آليات تقييم المخاطر، فإنها غير قادرة على التعامل مع التعقيد وعدم اليقين والغموض في القضايا المتعلقة بسلسلة التوريد في الوقت الحقيقي. وعلاوة على ذلك، تميل نظم دعم القرار الحالية إلى التركيز على جوانب محددة من إدارة أخطار سلسلة التوريد ولا تأخذ في الاعتبار العملية برمتها. ولذلك، هناك حاجة إلى نهج أكثر شمولاً يمكن أن يعالج التعقيدات والشكوك وعدم اليقين في المسائل المتعلقة بإدارة أخطار سلسلة التوريد، وأن يزود صناع القرار بمعلومات محدثة لاتخاذ قرارات مستنيرة.

يجمع الإطار المقترح **NeutroMAS4SCRM** ، بين تقنية Neutrosophic Data AHP ونظام وساطة متعدد االوكلاء (MAS) لإدارة أخطار سلسلة التوريد بشكل أكثر فعالية. يستعين النظام ب (MAS) من أجل التنسيق والاستجابة الفوريين، وبتقنية NDAHP لاستخراج الأحداث من مجموعات البيانات الحالية وتقييم المخاطر. ويمكن للإطار أن يحدد المخاطر المحتملة التي تتطلب إدارة شاملة للأخطار وأن يصنفها استناداً إلى معايير محددة مسبقاً باستخدام نهج NDAHAP الذي يتجاوز حدود الغموض وعدم اليقين والتعقيد. وعلاوة على ذلك، فإنه يبلّغ فوراً الأفراد ذوي الصلة بالتغييرات غير المتوقعة ويستخدم أساليب محاكاة لإنشاء نظام للتقييم الكمي للأخطار ومراقبتها. نظام (MAS) المقترح لسلسلة الإمداد مُنفَّذ على منصة (JADE) للوكلاء، حيث يُحدَّد محتوى الرسائل المتبادلة استناداً إلى (FIPA-ACL) باستخدام أونتولوجيا AgentSCRM المقترحة. يقوم نظام دعم اتخاذ القرار المعتمد على المحاكاة بتقييم الإطار من خلال تقيم تكاليف الاخطار والآثار الضارة، وتحديد فعاليته في مساعدة ودعم الشركات على إدارة الاخطار بكفاءة. وأثبتت نتائج المحاكاة أن إطار **NeutroMAS4SCRM** يمكن أن يقلل بفعالية من تكاليف المخاطر. وخلاصة القول إن آلية **NeutroMAS4SCRM** هي أداة واعدة لصناع القرار الذين يسعون إلى تعزيز استراتيجياتهم لإدارة أخطار سلسلة التوريد وتحسين قدراتهم على التصدي للمخاطر غير المتوقعة.

الكلمات المفتاحية: إدارة المخاطر في سلسلة التوريد، علمية التسلسل الهرمي لتحليل البيانات النيتروسوفية، الأنتولوجيا، نظام متعدد العوامل، المحاكاة.


بسم الله الرحمن الرحيم

Contents

List of Figures

List of Tables

List of publications

Internationnal Journals

- Ahlem Meziani, Abdelhabib Bourouis, and Mohamed Sedik Chebout. **Neutromas4scrm: a combined multi-agent system with neutrosophic data analytic hierarchy process framework for supply chain risk management**. *Journal of Intelligent & Fuzzy Systems*, 44:3695–3716, 2023.

Internationnal Conferences

- Ahlem Meziani, Abdelhabib Bourouis, and Mohamed Sedik Chebout. **Neutrosophic data analytic hierarchy process for multi criteria decision making: Applied to supply chain risk managment.** *In 2022 International Conference on Advanced Aspects of Software Engineering (ICAASE)*, pages 1–6. IEEE, 2022. 3

List of Abbreviations

ABM	Agent-Based Modeling
AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANP	Analytic Network Process
AUML	Agent Unified Modeling Language
AOSE	Agent-Oriented Software Engineering
BBN	Bayesian Belief Networks
CPFR	Collaborative Planning Forecasting and Replenishment
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DSS	Decision Support System
ELECTRE	Elimination and Choice Expressing the REality
FAHP	Fuzzy Analytic Hierarchy Process
FIPA	Foundation for Intelligent Physical Agents
FTA	Fault Tree Analysis
FMEA	Failure Mode and Effect Analysis
GSC	Green Supply Chain
JADE	Java Agent Development Framework
KQML	Knowledge Query and Manipulation Language
KRI	Key Risk Indicator
MADM	Multi-Attribute Decision Making
MAS	Multi-Agent System
MCDM	Multiple Criteria Decision Making
MODM	Multiple Objective Decision Making
NAHP	Neutrosophic Analytic Hierarchy Process
NDAHP	Neutrosophic Data Analytic Hierarchy Process
OWL	Web Ontology Language
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
RDF	Resource Description Framework
SVNN	Single-Valued Neutrosophic Number
SVNS	Single Valued Neutrosophic Set
SC	Supply Chain
SCM	Supply Chain Management
SCRM	Supply Chain Risk Management
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VMI	Vendor Managed Inventory

Chapter 1

General Introduction

Chapter 1

General Introduction

Contents

1.1 Introduction

Supply chain disruptions can lead to significant losses for companies, as seen with Boeing's experience over the past ten years, during which it recorded losses of $2 billion [6]. In 2010, typhoons, floods, and earthquakes claimed the lives of 297,000 people, resulting in more than $ 123.9 billion in direct economic losses worldwide [7]. Moreover, [8] provides additional examples of financial losses caused by supply chain disruptions. While the globalization of the supply chain can bring significant benefits to businesses, it also exposes them to increased risks, some of which could lead to interruptions.

Globally, the vulnerability of supply chains has never been more apparent than now, due to the recent emergence of the COVID-19 virus [9]. Each significant disruption inspires the scientific community to refocus its efforts on prevention and recovery, considering the dynamism and complexity of the modern business environment.

A wide range of events can disrupt a supply chain, including operational problems, disruptive events [10], supply-side difficulties, demand-side uncertainty, growing global competition, rising cost pressures, increasing customer expectations, and ever-increasing complexity [11]. Demand and lead-time uncertainty risks are linked to operational risks and are often examined in the context of the bullwhip effect [12]. Supply chain disruptions and risks can result in various consequences, including reduced product quality, lower service levels, delayed deliveries, increased recovery costs, damage to corporate image and reputation, compromised security and health, and financial deficits, as discussed in [13].

The recent pandemic has disrupted trade flows among countries, particularly between border-sharing nations, resulting in lower export earnings [14]. A study presented in [15] revealed that among a sample of 209 companies, 113 had their financial performance negatively affected by supply chain disruptions, while the rest experienced a decline in their level of service. Moreover, risks can disrupt not only a company's direct operations but also those of its trading partners, thus affecting the company itself. The Business Continuity Institute found that most supply chain disruptions experienced by a company originate outside its borders: 48.9 % of disruptions occurred at a first-tier supplier, 24.9 % at a second-tier supplier, and 12.2% at a level beyond second-tier suppliers [16]. Addressing and mitigating the negative effects generated by such risks requires a considerable amount of work to achieve in the area of supply chain risk management (SCRM) in both practitioner and academic circles [17].

Supply chain managers aim to create plans for detecting, evaluating, managing, and overseeing potential hazards within their supply chains [17]. However, despite these efforts, several knowledge gaps still exist [18]. Decision makers have achieved significant improvements in managing supply chains and mitigating their recurrent risks through enhanced coordinated planning and execution using techniques such as Vendor Managed Inventory (VMI) or Collaborative Planning Forecasting and Replenishment (CPFR) [19, 20]. However, support for decision-making requires prior knowledge and understanding of the problems and processes leading to a decision. Therefore, there is a significant interest in tools and strategies that encourage making well-informed decisions, assist in evaluating and analyzing their direct and indirect implications, and provide a robust basis for subsequent choices and decisions. The complexity of SCRM issues requires that all available technologies be used in an integrative and collaborative manner. Indeed, as informed by the study conducted by [15], 59 % of the companies studied have not implemented proactive or flexible processes to deal with adverse events.

Although the availability of real-time information in combination with corresponding data processing and intelligent tools allows a faster reaction to changing conditions along the supply chain, according to [21]. This provides a new opportunity for managers to react and manage SC risk in a shorter time frame, in addition to shifting from decision support only to predicting what decisions need to be made. But little literature work goes into this context.

In conclusion, the management of supply chain risks is critical for businesses in today's dynamic and complex business environment. However, despite significant efforts by practitioners and academia to develop frameworks and strategies for supply chain risk management, there are still several gaps in knowledge and understanding of how to effectively manage these risks. Decision-makers have made significant progress in managing supply chain risks through coordinated planning and execution, but support for decision-making requires prior knowledge and understanding of the problems and processes leading to a decision. Additionally, while the availability of real-time information and intelligent tools provides an opportunity for faster reaction to changing conditions along the supply chain, there is little literature on this subject. Therefore, further research and development of new tools and strategies are needed to effectively manage supply chain risks and minimize their negative impacts on businesses. Additionally, it is imperative to shift focus from solely providing decision support to accurately predicting which decisions need to be made. Furthermore, given that decisions often rely on contradictory, incomplete, and uncertain data, and must be made in real-time, a proactive approach is crucial for successful supply chain risk management.

1.2 Motivation

Despite the research revolution in the field of SCRM, several research gaps have been revealed. One of these gaps is the lack of attention given to collaboration between companies. Only with the right risk assessment can companies find the appropriate solution to manage the risk in a limited time. A process of know-how is needed to choose the right risk assessment method and guide decision-makers in implementing these risk management methods in the presence of incomplete, conflicting, and uncertain information.

The necessary values can be found in the database or by consulting subject-matter experts and their knowledge and experience. In addition, specialists prefer to offer their knowledge of linguistic characteristics, since it is extremely difficult to accurately quantify such data.

Generally, expert assessments are subjective estimates, and numerous theories, like the fuzzy theory, have been utilized to address this subjectivity. Nonetheless, the fuzzy theory falls short in accounting for the occurrence of indeterminacy in practical scenarios, resulting in inadequate management of vague, conflicting, and uncertain information.

There is a need for a model that can capture the details of real systems by retrieving data from company databases and assessing risks in real time. This information must then be disseminated across company networks without relying on the expertise of domain specialists for decision-making. However, there is currently no literature that addresses these needs simultaneously.

This integration is essential for developing a comprehensive risk assessment model that can handle complex and unpredictable situations in real-time decision-making. Furthermore, such a model can be implemented in the supply chain management process to provide decision-makers with accurate and timely information to support risk mitigation efforts. Therefore, more research is needed to address this research gap and develop an integrated risk assessment model that combines both the assessment of risk in complex settings and real-time decision-making.

Our proposed model aims to make significant contributions to the field of industrial risk management by developing a comprehensive system that models risk assessment and facilitates real-time collaboration among companies in the supply chain. However, it is crucial to acknowledge that the information used in risk assessment is often uncertain, incomplete, and conflicting. Therefore, our model must account for these factors to provide an accurate evaluation of potential risks.

1.3 Context and Problematic

What makes risk management challenging is that the current business climate is rapidly changing, and decision-making time frames are becoming shorter. The field of SCRM has received significant attention from researchers in recent years [18, 22, 23]. Various measures of SC performance have been considered, such as [24], which determined how incorporating a backup supply location in a network can increase performance in the event of disruptions. Similarly, the authors in [25] evaluated the performance of single and dual-sourcing strategies in a supply network subject to disruptions, while the authors in [26] used redundancy and flexibility strategies in an automotive supply network to assess their performance against disruptions. It has been shown that SC complexity has a positive relationship with disruption frequency [27, 28].

Even if a number of remarkable studies have been published on disruption-related performance measures such as resilience, robustness, stability, and flexibility, there is still a gap between practical needs and research results. New markets, lower costs, internet opportunities, commercial treaties, and developing communication are some of the benefits of globalization. However, political instabilities, cultural diversities, extended distances, and standardization difficulties make SC more vulnerable to risks [29].

Most SCRM literature focuses on a central company and its closest business partners instead of the larger supply network. Even so, there are some cases where studies on multi-tiered supply networks have been conducted.

Unfortunately, the understanding of what exactly is meant by SCR, which information should be monitored, and how risk management and mitigation can be designed in light of these risks is heterogeneous [23]. So far, despite the efforts of researchers, the SC still suffers from more shortcomings and a lack of understanding, as well as the difficulty of identifying the elements directly leading to problems and dangers. As illustrated by [30], this research area is evolving and growing strongly and, thus, merits further scientific awareness. Quantitative and qualitative analyses, as well as empirical studies and theoretical contributions, are in balance.

Many researchers have suggested supporting SC managers in decision-making [31, 32]. The development of models and decision support (DS) tools in the field of supply chain risk management can significantly improve decision-making regarding resilient and sustainable supply chains [33, 34]. The effective utilization of decision support systems in SCRM can lead to significant benefits. However, currently, there is a lack of a comprehensive framework and holistic approach to the use of DSS that covers all four stages of SCRM. Furthermore, the application of DSS in SCRM is often limited to risk mitigation, neglecting other risk treatment options such as risk avoidance or risk sharing. A comprehensive approach to managing supply chain risks is essential for understanding the adoption of certain DSS that benefit from a holistic approach to SCRM [35].

As far as we know, there is no complete and quantitative decision support system (DSS) for supply chain management (SCM) that can handle the challenges of intense competition. A model that offers a solution to address the current gap is needed. Currently, there is a lack of a method for modeling multiple risks related to purchasing, manufacturing, and sales, which can assist managers in making optimal decisions to balance cost, profit, and risk management processes. Such a model would provide managers with the necessary tools to make informed decisions in the face of complex supply chain risks.

The aim of this research project is to propose a versatile simulation model that addresses specific identified gaps discussed in the current literature. This model is designed to provide answers to the following questions:

- Which method should be chosen for risk assessment in the presence of uncertain, incomplete, and imprecise information?
- How can decision-makers be supported in responding to risks with the most appropriate and optimal decision?
- How can decision support be provided throughout all stages of the risk management process?
- How can real-time collaboration between supply chain organizations be ensured to respond to risks?

1.4 Theoretical background

1.4.1 Supply chain and its management

The supply chain is a relatively new concept. It is quite often defined as "the following stages of production and distribution of a product from the suppliers of the suppliers of the producers to the customers of its customers".

To better understand the supply chain concept (see figure 1.1), we propose to review the definitions of this term used in the literature. Christopher in [36] defines the supply chain as "the network of companies that participate, upstream and downstream, in the various processes and activities that create value in the form of products and services delivered to the end consumer. In other words, a supply chain is made up of several companies: upstream (supply of materials and components), downstream (distribution), and the end customer".

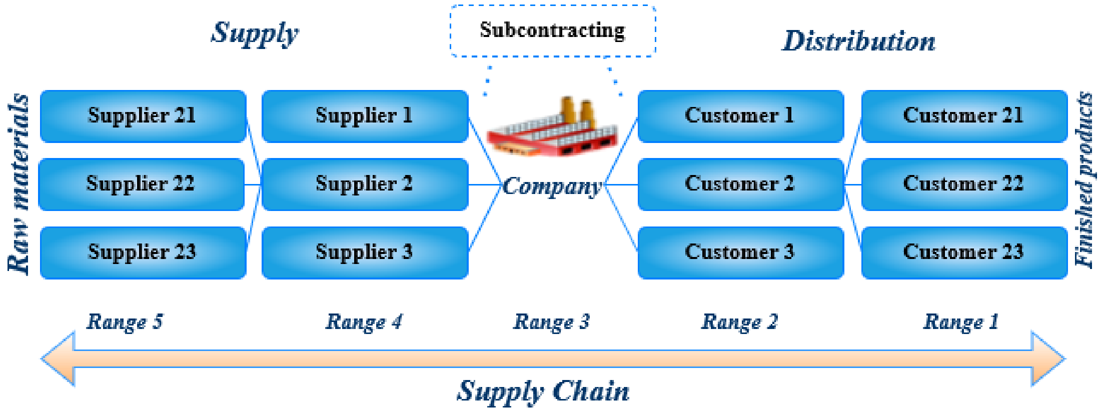


Figure 1.1: Example of supply chain.

To further explore the definitions of the supply chain in literature, Lummus [37] defined the supply chain as " the network of entities through which the material flow passes. These entities include suppliers, carriers, assembly sites, distribution centers, retailers, and customers ". A more general definition is that proposed by Poirier [38] "A supply chain is the system through which companies bring their products and services to their customers". For our work, we retain the definition from [39] which defines the supply chain as follows: "a supply chain consists of all the steps involved directly or indirectly in the satisfaction of a customer's request. The supply chain includes not only the manufacturer and its suppliers but also carriers, storage centers, retailers, and the customers themselves".

In this manuscript, the supply chain is defined as the network of partners involved in the production of a given product or family of products. Partnerships in the supply chain are based on a client-supplier relationship, where each partner is free to make their own decisions and accept or refuse requests from other partners.

It is important to distinguish between the terms "supply chain" and "supply chain management". While the supply chain refers to the network of partners involved in the production and distribution of a product or family of products, supply chain management encompasses the approaches, processes, and functions necessary for reducing costs, increasing flexibility, and optimizing performance within the supply chain.

There are several definitions of supply chain management in the literature, and many authors highlight the difficulty of defining SCM. Vakharia [40] defines SCM as "the art and science of creating and enhancing synergistic relationships between partners in the same supply chain with the common goal of delivering, just in time, the right products and right services to the right customer with the best quantity".

Simchi-Levi presents an alternative definition of SCM in his work [41]. He defines SCM as "The SCM is a strategy which aims at the same time at the reduction of the global costs, allowing a more competitive position to all the various parts of the supply chain, and the optimization of the end customer satisfaction through greater adaptability of production and distribution systems".

1.4.2 Supply chain management in a high-disruption environment

In recent years, as noted by Harland [42] and Hillman [43], working relationships between companies have become more complex and turbulent. This growing complexity has a significant impact on supply chain management, which involves the management and control of the flow of goods and information between members of a supply chain.

This complexity is further exacerbated by newer pressures and issues, such as cost pressures, "short-termism," the technicality of goods and services, the shortening of lead times (time to market, time to business, time to benefit, and lead time), and the search for flexibility and productivity. These pressures often lead to lean management practices at all levels, according to Fabbe [44].

The issue of information uncertainty in the supply chain (SC) is mainly related to dealing with uncertain and imprecise orders. The development of uncertainty in the supply, production, and distribution functions contributes significantly to the complexity of decision-making in the SC. Various uncertainties specific to each function are therefore present in the chain. According to research addressing this problem, the most challenging source of uncertainty relates to demand uncertainty [45]. This uncertainty is expressed in terms of quantity, distribution among suppliers, dates of need, and so on. If we consider producers' roles in the SC, uncertainty at the production level is related to breakdown rates, scrap, delivery times, and so on. Uncertainty at the distribution level leads to delivery delays, additional quantities delivered in case of incorrect transport, and so on [46].

The performance of many distributed systems is affected by the instability caused by their decision-making and informational structures. Each entity in such systems acts autonomously without a clear view of how its decisions affect the rest of the system. One significant effect of the fluctuation of demands from one partner to another in the supply chain is the bullwhip effect [47]. The bullwhip effect can lead to various problems, including scheduling difficulties, labor management issues, challenges in controlling inventory and warehousing requirements, poor customer service (such as delivery delays, discrepancies between the quantities ordered and delivered, and billing errors), as well as excessive administrative efforts.

In a high-pressure environment such as a pandemic, natural disaster or economic crisis, the supply chain becomes more vulnerable to disruptive events. The challenges faced by companies in managing the supply chain become even more pronounced due to the lack of coordination, uncertainties, and bullwhip effect. These factors can result in disruptions, delays in deliveries, excess inventory, and loss of customers. To manage the supply chain in such an environment, it is crucial to establish strong relationships between partners, improve coordination and communication, develop contingency plans, and leverage digital technologies to enhance visibility and agility. Addressing these issues is essential to building a resilient and efficient supply chain that can withstand disruptions and emerge stronger from the challenges.

1.4.3 Risk and risk management in the supply chain

According to the standard ISO 31000 [1] and as presented in Figure 1.2, risk is perceived as the consequence of events of internal or external origin that may affect the achievement of the initially set objective. For a risk to exist, these events must occur in an uncertain manner, whether due to their nature (unknown, unimaginable, etc.), occurrence (unplanned, etc.), or intensity. To comply with the previously cited standard, risk refers to the impact of these events on the target (or objectives).

A first definition of risk in the field of supply chain management was given by [48]. They define risk as *"a variation in the distribution of possible supply chain outcomes, their likelihood, and their subjective values"*. Therefore, a risk is a disruption in the flow between the supply chain's components. This potential variability can thus affect the flow of information, materials, and products and can modify the use of resources (human and equipment). Through an empirical study, [49] examined the connection between business performance and risk level for a sample of 1004 publicly listed Indian companies between the years 2000 and 2015.

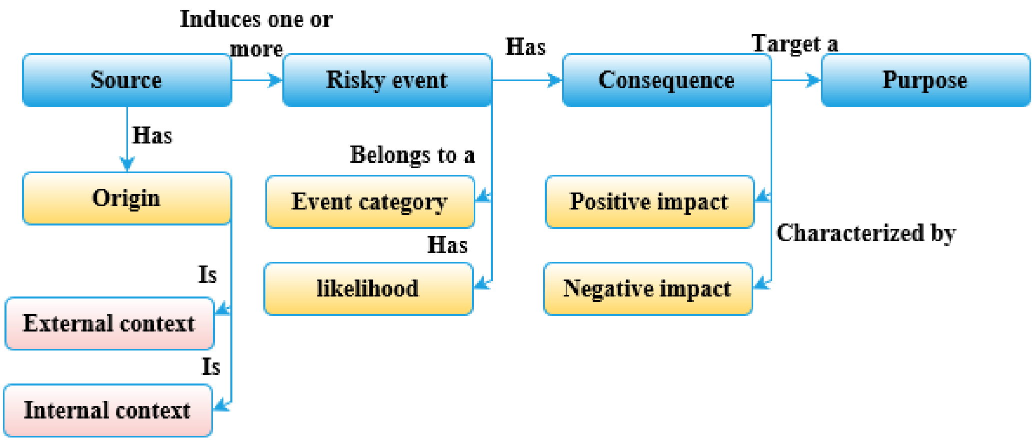


Figure 1.2: Risk and vocabulary around risk, according to [1].

At the end of this study, they proved that the worst performing companies, or those that fall below the industry median in the performance rankings, have a negative or paradoxical risk-return association.

The concept of risk has two sides: a threat and an opportunity. While risk is often associated with negative outcomes, it can also present opportunities for growth and success. Decision-makers who take calculated risks and embrace a positive view of risk can assess potential strategies and determine which risks are worth taking. Taking on a certain level of risk can lead to potential benefits or rewards, such as investing in a new market or technology. Although there is always uncertainty involved, those who are willing to take risks based on their own understanding of the future and decision-making processes can reap the rewards of their efforts.

In risk management, the idea of risk having two sides is also common. On the one hand, risk can represent a potential threat to an organization or individual, such as the risk of financial loss, reputational damage, or physical harm. These risks must be identified, assessed, and managed to minimize their negative impact on the organization.

However, finding the right balance between these two sides of risk is crucial. Too much risk can lead to excessive exposure to threats, while too little risk can lead to missed opportunities for growth and innovation. Effective risk management involves identifying and assessing both the threats and opportunities associated with different types of risk, and then developing strategies to manage these risks in a way that maximizes the benefits while minimizing the negative impacts.

According to [50], risk management can be defined as the systematic process of analyzing, identifying, and responding to risks. It aims to maximize the chances and impact of positive events while minimizing the probability and impact of negative events in order to achieve objectives. In the context of supply chain management, risk management is an emerging discipline that seeks to understand and avoid the effects of adverse disruptions that may occur in a supply chain.

In a complex environment, complete awareness of what will happen is impossible. There is always a risk that certain events will occur and disrupt the smooth running of activities. When this risk is questioned before its realization, it becomes clear that different people may perceive the situation in different ways. Risk management can help improve decision-making related to the evaluation and selection of alternative strategies. In other words, a key objective of risk management is to enhance the organization's decision-making process.

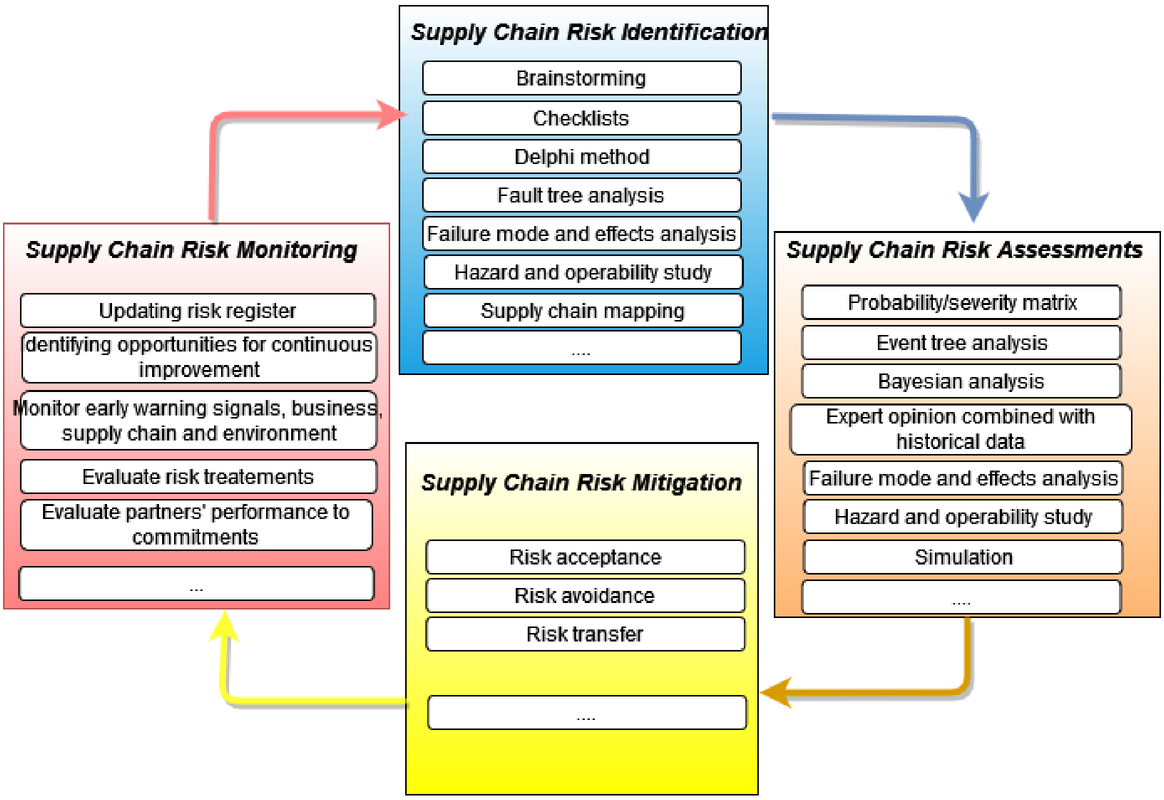


Figure 1.3: SCRM process with the most used methods.

In this regard, it should be recalled that SCRM is "the identification and management of risks originating from inside or outside the supply chain, through a coordinated approach involving the members of the chain and seeking to reduce the vulnerability of the latter, that is to say of the supply chain as a whole" [18].

The collaborative approach to risk management is achieved through the implementation of tools and methods (as presented in Figure 1.3) that the various actors in a supply chain define together. The objective is to optimize decision-making against the risks that threaten the supply chain. Therefore, the management of risk is the best choice for the supply chain to achieve its objectives efficiently and effectively.

1.4.4 Collaborative risk mitigation in Supply Chains

From now on, supply chain managers must integrate into their problems and decisions the fact that their organizations are interconnected with many industrial partners, such as suppliers, subcontractors, co-contractors, and distributors. This growing number of partners is particularly linked to the phenomenon of outsourcing, which has resulted in many activities that were previously managed internally. In addition, the globalization of the economy, with the internationalization of production processes and the relocation of activities, has led to a geographical (and cultural) distance between industrial partners. This distance often makes coordination and collaboration between actors more difficult.

Managing the distributed supply chain requires adopting a cooperative approach. Indeed, when the decision-making power is equitably distributed, cooperation is an effective way to satisfactorily manage the distributed decision-making process underlying supply chain management.

Cooperation is the way to go beyond the limits of individual action. In this sense, companies opting for a cooperative mode of operation expect in return a minimization of risks and a reduction of uncertainty, as well as an increase in industrial performance [51]. So, as we have previously pointed out, the implementation of a successful approach to risk management in the supply chain requires the deployment of cooperation policies along the chain. The interest of such policies lies in:

- ***Additional visibility:*** By implementing cooperation policies, different levels of the supply chain can interact with each other more effectively. This allows companies to gain additional visibility into the operations of their partners and suppliers, enabling them to better identify and mitigate potential risks.
- ***Anticipation of risks:*** Cooperation policies can also help companies anticipate potential risks by facilitating the exchange of information and allowing for joint risk management strategies. This can help companies be more proactive in their approach to risk management, reducing the likelihood of costly disruptions.
- ***Enrichment of work methods and tools:*** Collaboration between partners can also lead to the development of new work methods and tools. By sharing knowledge and best practices, companies can learn from each other and improve their operations. For

example, a manufacturer might learn about a more efficient production technique from a supplier, leading to increased efficiency across the supply chain.

- ***Increased flexibility:*** Cooperation policies can also enable companies to be more flexible and responsive to changes in the market. By working closely with partners, companies can more easily adjust their operations to changes in demand or disruptions in the supply chain.

- ***Improved customer satisfaction:*** A well-managed and cooperative supply chain can also lead to improved customer satisfaction. Companies can build stronger relationships with their customers and improve their reputation on the market by making sure that their products are delivered on time and are of the quality that their customers want.

- ***Reduced costs:*** Finally, cooperation policies can lead to cost savings for companies. By working closely with partners, companies can identify areas where costs can be reduced, such as through joint procurement or the consolidation of shipments. This can help improve the overall profitability of the supply chain.

Indeed, addressing one risk alone while ignoring their relationships can exacerbate other disruptive events. The actions taken by a factory to address a risk may also increase the level of risk for its partners.

Finally, it is important for supply chain managers to recognize that risks in the supply chain are interconnected, and addressing them in isolation can lead to unintended consequences. Instead, a collaborative approach that takes into account the relationships between risks and involves all partners in the chain can be more effective in mitigating risks and ensuring the success of the supply chain. By working together and sharing information, companies can minimize risks and uncertainty, enhance their performance, and achieve better outcomes for all parties involved.

1.4.5 The decision-making procedure in SCRM

Basic problems in decision-making are optimality, multiple objectives, risk, uncertainty, and complexity. To increase credibility and thereby reduce complexity, decisions must be made even in the face of complete uncertainty. In the last few decades, the direction of decision support systems (DSS) has changed drastically towards emphasizing risk. Both practitioners and academicians are advocating for the development of DSS to assist companies in assessing their supply chain risks and choosing suitable mitigation strategies [52].

To our knowledge, there is no complete and quantitative DSS for supply chain management that is capable of addressing the constraints of the current gap. A model is needed that offers a solution to address the restrictions of the current gap, including the absence of a method for modeling multiple risks related to purchasing, manufacturing, and sales. This model should assist the manager in making optimal decisions in real-time to balance cost, profit, and risk management processes, especially in the presence of contradictory and uncertain information flows.

1.5 Objectives and Contributions

The impact of SCRs on organizational performance can be attributed to the rising prevalence of high complexity and instability in the global supply chain. The ability to withstand external threats and potential risks within the supply chain is of primary concern. Unfortunately, understanding what SCRM means and which information should be controlled can be difficult. By considering these risks, we can design risk reduction and management strategies. Addressing these essential knowledge gaps, this review shows that achieving a sustainable supply chain is not a destination but a journey [53]. Actions in one area frequently influence actions in another area. For these reasons, it makes sense to address sustainability and SCR cooperatively.

The proposed thesis work aims to develop a decision-support system that can effectively take risks into account for supply chain managers. The system will simulate the supply chain in real-time and ensure cooperation and risk response. It will also provide methods for evaluating risks in a contradictory, uncertain, and incomplete environment. With this system, supply chain managers can make informed decisions that balance cost, profit, and risk management processes. This will lead to a more sustainable and resilient supply chain that can withstand external threats and potential countermeasures.

Our research goals and contributions are:

- The present work gives a global overview of SCRM and displays different works that combine the latest scientific summaries showing the contribution of decision-making systems and multi agent systems in the development and resolution of SC problems. For multi-agent systems and their contribution to SCRMs, if we are talking about the rating of their current use, we can say that it is modest, but if we are talking about their capacity as an intelligent decision-making support system, they are really countable and can be said to be such that their methods can get the SCs out of their problem through their ability and characteristic.

- The proposition of NeutroMAS4SCRM, a new framework for supply chain risk management based on a multi-agent system (MAS) for coordination and real-time response. This system enables the provision of support during the various phases of risk analysis, from the identification of threats to the quantification of the scenarios selected. Our distributed system has the capacity to communicate all risk information among network partners; in contrast to traditional corporate systems where risk-generating event data is held in an isolated and centralized way, this elimination of information asymmetries provides a transition to real-time risk management.

- In order to attain this objective, the research also makes a contribution to the proposal of a communication mechanism among agents for Supply Chain Risk Management (SCRM) that is based on ontology.

- The neutrosophic logic has been employed in this thesis to address the challenge of evaluating risks based on contradictory, uncertain, and incomplete data. By leveraging the capability of neutrosophic logic to handle indeterminate and inconsistent information, a comprehensive risk assessment framework has been developed. This framework allows decision-makers to make informed and effective decisions in the face of incomplete and uncertain data, leading to more robust risk management strategies.

- The suggestion of a strategy that prioritizes risk management during the decision-making process is made, which involves utilizing the Neutrosophic Data Analytical Hierarchy Process method that aims to extract events from existing datasets and evaluate the associated risks.
- The proposal of detailed validation scenarios for our agent-based system for risk management in a distributed supply chain.

1.6 Structure of the thesis

The thesis unfolds through a series of intricately well-crafted chapters, each dedicated to exploring various facets of supply chain risk management, ontology-based approaches, simulation methodologies, and the development of the NeutroMAS4SCRM system.

- Chapter 1 of the thesis begins with an introduction, followed by a discussion of the motivation behind the research. The chapter then discusses the context and problematic of managing supply chains in a high disruption environment, providing a theoretical background on supply chain management, risk management, and the decision-making procedure for supply chain risk management (SCRM). The chapter also explores the importance of cooperation and collaboration as a risk mitigation strategy. Finally, the objectives and contributions of the thesis are outlined, and the chapter ends with a summary of the thesis structure.
- Chapter 2 provides an introduction to supply chain risk management (SCRM), covering the basic concepts, the SCRM process (risk identification, assessment, mitigation, and monitoring), and the scope of risk management in the supply chain. The chapter also presents an overview of independent techniques such as qualitative, quantitative, simulation, artificial intelligence, and hybrid approaches, and their application in SCRM. Additionally, the chapter compares decision support systems (DSS) and SCRM, and presents a literature mapping through bibliometric network and a literature review. The chapter concludes with a summary of the main points discussed in the chapter.
- Chapter 3 of the thesis is focused on introducing the concept of Neutrosophic Logic, which is a generalization of fuzzy logic and intuitionistic fuzzy logic. The chapter starts by discussing the basics of fuzzy sets and intuitionistic fuzzy sets, followed by the introduction of Neutrosophic sets and their various operations. The concept of Single Valued Neutrosophic Sets (SVNS) is then introduced, along with its operations, including complement, containment, union, intersection, and difference.

  The classic Analytic Hierarchy Process (AHP) method is then introduced and explained in detail, including its strengths, steps, and limitations. Finally, the chapter concludes by introducing the Neutrosophic Data AHP, which is an extension of the classic AHP method that can handle uncertain, incomplete, and inconsistent data. Overall, Chapter 3 provides a comprehensive overview of Neutrosophic Logic and its application in decision-making processes.

- Chapter 4 deals with simulation through multi-agent systems. It first defines the general framework of simulation and a general view of multi-agent systems. Then, a presentation of design methods and simulation platforms of an existing multi-agent system is given. This is followed by a comparison between implementation platforms to choose the appropriate platform for our problem. Finally, the proposal of a multi-agent architecture of the model that aims to evaluate risks based on the use of data from a current and real-time database. already proposed in the third chapter is realized.

- Chapter 5 of the thesis focuses on the development of an ontology-based approach for SCRM using smart multi-agent systems. The chapter starts with an introduction, followed by a discussion on the AgentSCRM ontology, highlighting its advantages for MAS and its use in SCRM. The formal specification of the problem is then presented, including definitions, statements, and implications. The potential benefits of the approach are discussed, including cost reduction related to risk, automation of event management, and propagation of risk effects throughout the supply chain network. The implementation of the approach is then described, and the chapter concludes with a summary of the key findings. The chapter highlights the importance of using an ontology-based approach in SCRM to achieve more effective risk management and improved supply chain performance.

- Chapter 6 of the thesis ends with a general conclusion which summarizes the main strengths of this work. We also present perspectives and recommendations for the evolution of this work.

Chapter 2

Supply Chain Risk Management SCRM

Chapter 2

Supply Chain Risk Management

Contents

2.1 Introduction

MAnaging risk has become a crucial challenge for supply chain managers owing to several factors. The literature in the domain of SCRM is chaotic and disorganized, as indicated by [54], but recently significant advancements have been observed, and the basic reasons for the disruptions and their influence on SC execution and performance are revealed in [17, 55, 56].

As researchers further engage in this emergent research topic, a natural first step is to define and classify SCRs [57], SCRM is aimed at developing strategies for the identification, assessment, treatment, and monitoring of risks in SCs [17].

Several contemporary studies have provided thorough reviews to synthesize numerous SCRM research articles. Some studies have focused on the risk management process, such as Sodhi and Son's review of approaches to mitigate risks in SCRM, including both proactive and reactive strategies [8]. Other researchers have conducted in-depth systematic literature reviews of SCRM strategies, such as Kilubi et al.'s review of peer-reviewed academic journal articles from 2000 to 2015 [58]. Mitigation strategies can be decided based on the expected level of management, which could be operational, tactical, or strategic, depending on the nature of the problem and requirements [59].

Other extensive research has investigated the different kinds and origins of risks in SCRM. For instance, Manuj and Mentzer conducted a literature review aiming to identify the categories and sources of global supply chain risks [52]. Rangel and Machado [60] proposed a classification system for supply chain risks, which comprises 14 types of vulnerabilities that may affect a supply chain. In a study conducted by Ho et al. [17], a comprehensive analysis was performed on 224 international journals published from 2003 to 2013. The researchers focused on categorizing these journals according to various aspects such as the definition of supply chain risk, the different types of risks identified, the factors that contribute to these risks, as well as the strategies recommended for managing or mitigating these risks.

Some literature reviews are general and broad, while others are more focused on specific areas within SCRM. For instance, studies such as [61] have focused on the risk of supplier non-conformance, while others like [34, 62] have examined reputational risk. Other research, such as [63] has studied the challenges arising from changing market conditions due to new competitors or rivalry among current ones. Additionally, [64] examined publications from 2014–2016 and categorized them from different perspectives, concluding that stochastic modeling approaches are now more common in SCM, contradicting previous research that favored deterministic approaches. Quality risk, specifically product risk, has been analyzed in [65]. While SCRM mainly focuses on risk mitigation, some researchers have also discussed SC resilience and its significance in SCRM research [55].

This section aims to give an overview of risk management in logistics chains by looking at the most important points that are directly or indirectly related to risks in SC. The management of risks in logistics chains is essential to ensuring the continuity of activities and customer satisfaction.

2.2 Supply chain risk management

Supply chain management encompasses a multifaceted collection of operations and functions that are inherently accompanied by an extensive array of interconnected risks. The concept of risk is subject to various definitions. In decision theory, risk is a measure of the set of feasible negative outcomes from a single rational decision and their probabilistic values. In the field of supply chain management, the term "risk" is also replaced with "vulnerability", which means "at risk" as presented by [66].

Table 2.1: Main SCRM definitions.

Reference	SCRM Definition
[67]	"SCRM is defined as the identification and management of risks for the supply chain, through a coordinated approach among supply chain members, to reduce supply chain vulnerability as a whole."
[52]	"Global SCRM is the identification and evaluation of risks and consequent losses in the global supply chain, and implementation of appropriate strategies through a coordinated approach among supply chain members with the objective of reducing one or more of the following - losses, probability, speed of event, speed of losses, the time for detection of the events, frequency, or exposure - for supply chain outcomes that in turn lead to close matching of actual cost savings and profitability with those desired. "
[68]	"To evaluate, control and monitor risk in order to safeguard supply continuity and maximize profitability, The process of planning, organizing, leading and controlling the activities of an organization in order to minimize the effects of risk on an organization's capital and earnings (includes financial, strategic, operational, accidental losses and other risks)."
[69]	"Supply chain solutions that ensure supply continues to meet demand in case of a disruption or soon after the occurrence of such a disruption."
[18]	"The identification, assessment, treatment, and monitoring of supply chain risks, with the aid of the internal implementation of tools, techniques and strategies and of external coordination and collaboration with supply chain members so as to reduce vulnerability and ensure continuity coupled with profitability, leading to competitive advantage."

SCRM is a relative and multifaceted concept. In the literature, it has no unique, universal, or common definition, and each author discusses SCRM according to his own point of view. In [70], authors focused on the concepts of vulnerability and resilience. Some definitions focused on the risk management process, including identification, evaluation, treatment, and monitoring [17, 71]. Other definitions highlighted the importance of selecting and implementing appropriate SCRM strategies [72]. Table 2.1 summarizes the most common definitions used in the literature.

After reviewing the most commonly cited definitions in the literature, it has been determined that the definition of SCR is often imprecise, unclear, and lacking in a comprehensive definition. Some researchers have suggested that SCR is solely focused on events. This traditional view of risk has been developed over the past few centuries, defining risk in terms of the likelihood of disruptive events occurring and their subsequent consequences. As a result, SCR is still challenging to evaluate, track, manage, and incorporate into mathematical decision-making models. This viewpoint was expressed in [23].

2.3 Supply chain risk management process

SCRM is essentially a decision-making process whereby managers evaluate the sources of SCR and make decisions on whether to accept an assessed risk or implement strategies to diminish the probability and potential consequences of its occurrence [52]. The primary objective of supply chain risk management is to decrease the susceptibility of the supply chain and enhance its ability to recover from disruptive events.

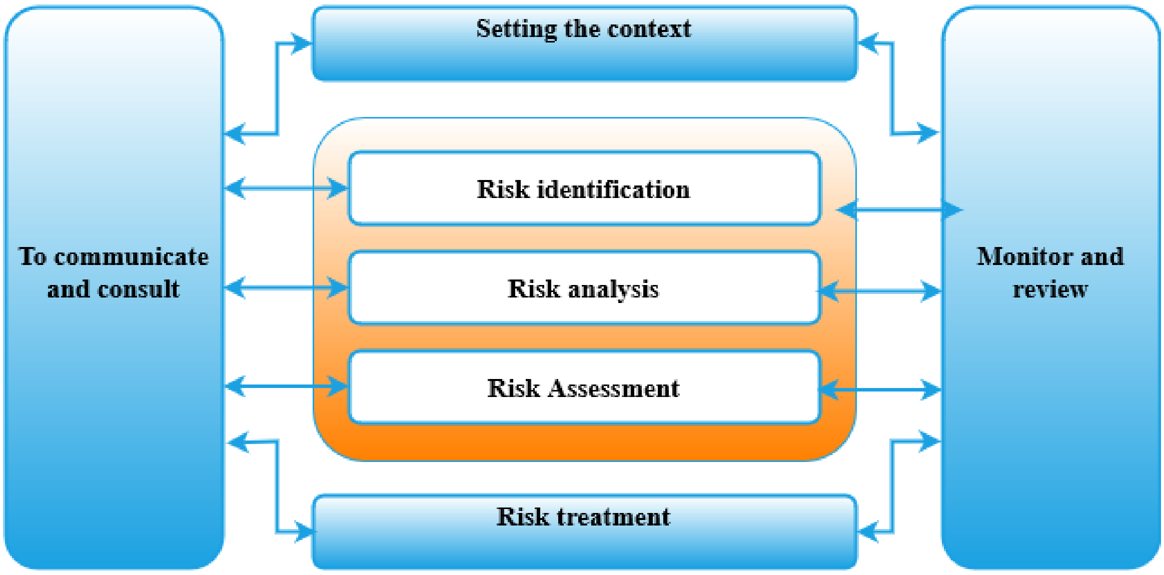


Figure 2.1: The risk management process [1].

Risk management is a method to find a compromise between performance on the one hand and risk on the other [73]. The goal is by no means to avoid all possible risks. Not only is this theoretically impossible, but it would inevitably be at the expense of performance. Rather, risk management seeks to trace the source of each risk and determine whether there is a suitable measure to manage it.

SCRM is a risk management approach applied to the supply chain. According to the standard ISO [1], risk management consists of a set of "coordinated activities aimed at guiding and controlling an organization (in this case, the supply chain) with respect to risks". The approach is based on a process consisting of a series of steps integrated into a continuous process, as shown in the figure 2.1.

The model in Figure 2.1 represents a dynamic structure for the overall risk management process, which has a hierarchical structure comprising different levels, with higher levels further divided into stages and sub-stages. The processes are interactive and adaptable to changes, reassessment, and improvement.

Although the model presents a sequential and transparent order of steps, such as risk analysis, risk assessment, and risk management, some of these processes can be performed simultaneously. Skipping processes and returning to previous steps is also possible, depending on various factors such as the availability and accessibility of additional risk-related data and information, the depth and scope of analysis, study outcomes, and the needs and redefinitions of decision makers. In many situations, this flexibility is essential to providing a timely and effective response to emerging risks.

One of the key aspects of the SCRM process is that it is interactive and responsive to change. This means that the process is not a static one and may involve skipping processes, reverting to previous processes, or performing processes simultaneously. This is due to the fact that new risk-related data and information may become available, leading to a reassessment and redefinition of decision-makers' needs and priorities.

Another important aspect of the SCRM process is that it involves stakeholders from across the supply chain. This includes suppliers, customers, and other partners involved in the supply chain. Collaboration and communication between stakeholders are essential to the success of the SCRM process.

Overall, the SCRM process is a complex and multifaceted approach that requires careful planning, implementation, and monitoring to be effective. It involves a range of different tools and techniques, including risk assessment, risk mitigation strategies, and continuous monitoring and evaluation. By successfully implementing the SCRM process, organizations can reduce the impact of supply chain disruptions and enhance their resilience in the face of uncertainty.

In the following section, we will provide a detailed explanation of each step of the SCRM process, accompanied by a description of the appropriate and most commonly used methods for each step.

2.3.1 Risk Identification

Risk identification is the first and most important step in the SCRM process. For efficient risk management, SC must be separated into elements such as manufacturers, warehouses, suppliers, and distribution channels, and the risks associated with each component should be examined specifically [29]. This step involves the identification of risk types, factors, or both [17].

Risk identification is a crucial step in the SCR process, as it involves identifying potential risks that could impact the organization's supply chain operations. This process allows companies to anticipate potential disruptions, develop mitigation strategies, and enhance their resilience to supply chain disruptions.

Several classifications of risks faced by organizations in SC have been presented. For example, [74] had presented a review of some risk characteristics and their definitions through a literature review. However, their review was not exhaustive in identifying all different types of potential risks. Also [75] had contributed to identify and assess SCR across multiple product categories using cognitive maps and Analytic Hierarchy Process (AHP) methodology. Another study by Samvedi [76] proposed an approach that integrates fuzzy TOPSIS and fuzzy AHP to quantify supply chain risk. Some studies have focused on identifying both types and factors of supply chain risks, such as the qualitative value-focused process engineering methodology proposed by [77]. Some researchers had focused on the development of qualitative or quantitative methods for identifying SCRs, such as [54, 78, 79].

By reviewing current SCRM research. An exceedingly developed literature was found regarding the mitigation of SCRs. Finally, and as a conclusion, the step of risk identification, and specifically their categorization, is incomplete. The future research should move from typologies to taxonomies, as presented in [80]. The idea behind this is that future research in SCRM should focus on developing a more systematic and structured way of classifying and categorizing risks.

Typologies are a simple way of grouping risks based on common characteristics or features, but they can be limited in their ability to provide a comprehensive understanding of risk. Taxonomies, on the other hand, involve a more detailed and structured classification system that can help identify the underlying causes of risk and how they are interconnected.

By moving from typologies to taxonomies in SCRM research, scholars can gain a deeper understanding of the complex interrelationships among different types of risks and develop more effective strategies for managing them. This shift can help organizations better anticipate and respond to risks, ultimately improving their resilience and competitiveness in the marketplace.

It is also important to note that risk identification should not only focus on internal risks but also on external risks that may arise from suppliers, customers, and other stakeholders in the supply chain. This could include risks such as natural disasters, geopolitical instability, economic downturns, supplier bankruptcy, product quality issues, and cyber-attacks.

Overall, effective risk identification is a critical aspect of SCRM, as it enables organizations to proactively manage supply chain risks, reduce the impact of disruptions, and enhance their overall supply chain resilience.

2.3.1.1 Supply chain risk identification methods

The success of SCRM depends on the identification and assessment of potential risks that could disrupt the supply chain. To achieve this, various methods have been proposed to identify SCRs. However, the choice of the appropriate method depends on the scope of the application and the case under study. Before starting to identify risks, it is necessary to map the system accurately to understand its components and processes. Additionally, it is essential to consider multiple perspectives to ensure comprehensive risk identification.

In this section, we discuss some of the methods proposed in the literature to identify SCRs. These methods range from qualitative to quantitative approaches, with some combining both approaches as presented in Table 2.2. Each of these methods has its advantages and limitations, and choosing the most appropriate method requires careful consideration of the objectives and scope of the study.

2.3.2 Risk assessment

Risk assessment is a crucial step in the SCRM process that involves identifying and analyzing potential risks and their potential impacts on the supply chain. It is the process of evaluating the likelihood and potential consequences of a risk event and its impact on the supply chain. Risk assessment is typically conducted by collecting data on potential risks, analyzing the data, and developing a risk profile that outlines the probability and potential impact of each risk event. The purpose of risk assessment is to provide decision-makers with the information they need to make informed decisions about risk mitigation strategies and to develop a risk management plan that prioritizes risks based on their probability and potential impact on the supply chain.

Qualitative risk assessment involves assessing the likelihood and impact of each risk based on expert judgment and subjective analysis. This method relies on subjective data, such as the opinions and experiences of individuals involved in the supply chain, to evaluate risks.

Quantitative risk assessment, on the other hand, involves the use of statistical and mathematical models to quantify the probability and impact of each identified risk. This method uses objective data, such as historical data and scientific evidence, to evaluate risks.

Both qualitative and quantitative methods can be used alone or in combination, depending on the nature and complexity of the SCRs being assessed. The chosen risk assessment method should be appropriate for the specific context of the supply chain being evaluated.

A framework for the identification, measurement, and prioritization of SCRs has been planned by [81] and it combines both quantitative and qualitative techniques to effectively assess SCR. Another study proposed the fault tree approach to analyze and assess the operational risk at the drilling, primary transport, and refining stages of an oil supply chain [82].

A large variety of quantitative methods have been used to address this problem, including mathematical programming and data envelopment analysis approaches [83, 84, 85]. Additionally, multi-criteria decision-making and analytic hierarchy process approaches [17], the decision tree approach [86], and fuzzy-based failure mode and effect analysis with ordered weighted averaging approach [87] have been utilized. Furthermore, [81] presented a framework for risk evaluation that employed probability theory and fuzzy logic. Similarly, a fuzzy inference system for SCRM has been proposed [88].

2.3.2.1 Supply chain risk assessment methods

Most assessment methods (as presented in Table 2.3) classify risks based on two key factors, namely the impact and the occurrence of the risk. These factors can be measured quantitatively in terms of probabilities and effective measures of impact (such as costs measured in currencies

Table 2.2: SCR identification methods.

Method	Description
Brainstorming	The brainstorming method consists of bringing together a group of chosen people who are asked to freely express their ideas, thoughts, and intuitions on one or more themes. The goal is to generate a maximum of ideas, suggestions, and proposals on a topic, knowing that it is easier to make an overly creative idea applicable than to generate a creative solution from a banal idea. A moderator leads the discussion and records the ideas put forward, which will then be analyzed, classified, and possibly deepened. The method is based on the establishment of a good group dynamic that helps remove inhibitions and encourages everyone to reciprocate the ideas put forward by the other participants. The brainstorming technique is quite easy to implement and requires a minimum of resources.
Checklists	This method is considered simple to use. It consists of building a list, as complete as possible, of adverse events likely to constitute threats.
Delphi method	The purpose of the Delphi method is to identify convergences of opinion and reach a certain consensus on certain topics by interviewing experts using successive questionnaires. The most common objective of Delphi studies is to provide experts with insight into areas of uncertainty to support decision-making.
Fault tree analysis	It is used to identify the causes relating to the feared events. Starting from a single event, it is a question of looking for the combinations of events leading to its realization. Fault tree analysis can also be continued in the context of reconstructing the causes of an accident. The method consists of a graphical representation of the multiple causes of a feared event. It visualizes the relationships between equipment failures, human errors, and environmental factors that can lead to accidents.
HAZOP	Systematic review of design and operating principles based on: • The search for all the causes of drift of the various operating parameters, • Analysis of the consequences linked to these deviations, • The means of correction or protection to be applied, if necessary. This review allows the systematic identification of operating and maintenance problems, and facilitates studies to make corrections or protections to the system under study.
Ishikawa cause and effects diagram	The Ishikawa diagram is a tool that makes it possible to identify the possible causes of an observed effect and, therefore, to determine the means to remedy it. It is presented in the form of fishbones, classifying the categories of causes inventoried according to (material, labor, equipment, method, and environment).
Surveys and interviews	Using questionnaires and structured or semi-structured interviews to ask experts to identify supply chain vulnerabilities.
Expert Panels	Expert panels are groups of individuals who have expertise in different areas of the supply chain. They can provide insights into potential risks and suggest ways to mitigate them.
Supply Chain Mapping	This method involves mapping out the entire supply chain to identify potential risks and their impact on the supply chain. By mapping the supply chain, it is possible to identify the risks that are associated with each component of the supply chain.
Root Cause Analysis	This method involves identifying the underlying cause of a problem rather than just addressing the symptoms. By identifying the root cause of a risk, it is possible to develop effective mitigation strategies that address the underlying problem.
Risk Scenarios	This method involves creating hypothetical situations that could cause disruption in the supply chain. By examining these scenarios, risks that might not have been considered previously can be identified.

or ruptures measured in coins) or qualitatively, typically expressed in terms of an ordinal scale like very high, high,low, and very low.

The assessment methods commonly used in the risk assessment phase, such as brainstorming and scenario analysis, are similar to those used in the identification phase. However, another popular method for assessing SCRs is the risk matrix. This involves plotting the likelihood of a risk occurring against its potential impact, typically on a two-dimensional grid. The resulting matrix is then divided into categories that indicate the level of risk associated with each scenario. The risk matrix approach enables organizations to prioritize risks based on their severity and develop appropriate response strategies.

In contrast, the Failure mode and effects analysis (FMEA) approach associates each risk with a measure of criticality, which is determined by multiplying the probability of occurrence, impact, and detectability. This method is particularly useful for identifying potential failure modes and determining the likelihood and impact of each failure.

Both the risk matrix and FMEA approaches provide a structured framework for assessing and prioritizing risks, which helps organizations make informed decisions about risk mitigation and management. By using these methods, organizations can gain a better understanding of potential risks and their impact, enabling them to take proactive measures to manage those risks.

2.3.3 Risk mitigation

Countermeasures must be established at this SCRM phase in order to address the risks that have been examined. The elements required for the design of countermeasures are provided by the risk assessment phase, and the manager can decide whether to transfer, reduce, or accept the risk. Further study is required in order to identify the best countermeasure.

Also, this phase consists of choosing a solution to deal with the risk and implementing it. It is also defined as a "process intended to modify a risk". The standard ISO [1] cites several examples of possible options:

- ***Risk avoidance:*** refraining from engaging in activities that entail risk. While this is the least risky and least expensive strategy, it may hinder the development of the company. Typically, the risk is transferred to other companies or deferred. Possible strategies for risk avoidance include discontinuing the sale of a product that poses a risk to consumer health or safety, changing suppliers to avoid delivery delays or defective products, or withdrawing from a geographic market where political or economic conditions are unstable [52]. Refusing to do business with a customer who represents too great a financial risk, implementing strict security procedures to prevent cyber attacks or fraud, and avoiding risky commercial activities in countries with unreliable or complex laws and regulations are also examples of risk avoidance strategies for businesses. Typically, this involves making a decision not to go to the beach in hazardous weather conditions (to go or not to go?).
- ***Accept the risk:*** "maintenance of the risk based on a reasoned choice." Acceptance consists of not intervening on the event itself or even on the vulnerability. Generally,

Table 2.3: SCR assessments methods.

Method	Description
Bowtie analysis	This method makes it possible to consider a probabilistic approach to risk management. It is a connection between a fault tree and an event tree, generally used in the study of highly critical events.
Bayesian analysis	Bayesian analysis is a statistical method that uses Bayes' theorem to update the probabilities of hypotheses based on new information. It provides a framework for modeling uncertainty and updating beliefs based on observed evidence. The probabilities in a Bayesian analysis are expressed as probabilities, not point estimates, and they can be updated as new data becomes available. The approach is particularly useful in situations where prior knowledge is available and where it is important to take that knowledge into account when making predictions.
Event tree analysis	It is a technique for identifying and analyzing the frequency of hazards using inductive reasoning to convert various initiating events into possible consequences relating to the operation or failure of technical, human, or organizational safety devices. Unlike fault tree analysis, event tree analysis assumes the failure of a component or part of the system and attempts to determine the resulting events. The event tree analysis takes place in several preliminary steps: • Consideration of an initiating event. • Identification of security functions to control its evolution. • Building the tree. • Description and exploitation of the sequences of events identified.
Monte Carlo Simulation	Monte Carlo simulations are used to simulate deterministic systems with stochastic input parameters. Their essence is the use of repeated experiments to evaluate the system. MCS make it possible to generate by random drawing a large number N of values respecting the probability distributions associated with the various random variables. Indeed, at each simulation, the values of the uncertain input variables are randomly sampled from the probability distributions that will have been described as input. At each random draw, the response of the system is evaluated. The sample and the results obtained for an iteration are saved. This operation is repeated hundreds or even thousands of times. In our case, 1000 iterations are performed. The result of all the iterations is a distribution of the probabilities of the different possible outcomes. The Monte Carlo simulation therefore makes it possible to consider all the possible consequences of a decision and assess its impact for a better approach in the face of uncertainty.
Failure mode and effects analysis (***FMEA***)	Is a fundamental hazard frequency identification and analysis technique that analyzes all the failure modes of a given piece of equipment and their effects on both other components and the system itself. This analysis aims first to identify the impact of each mode of failure of the components of a system on its various functions and then to prioritize these modes of failure according to their ease of detection and treatment. This method deals with detailed aspects to demonstrate the reliability and security of a system, and it contains 3 primary parts; • Identification of failure modes. • Identification of potential causes of each mode. • Estimation of the effects generated.
SWIFT (***Structured What-if Technique***)	SWIFT is a qualitative method that involves brainstorming potential scenarios and evaluating the consequences of each scenario. The method is designed to identify the most significant and likely scenarios and their potential impacts.

acceptance is established when the probability of occurrence is so low that the organization bets that it will not happen and decides not to invest in another strategy. The other scenario is when the cost of prevention exceeds the cost of the risk occurrence itself. Note that in the latter case, a crisis management plan may be relevant. Here are some examples to illustrate risk acceptance:

- ◇ A company that decides not to install a fire suppression system in a small office because it considers the probability of fire to be very low and the cost of installing such a system to be disproportionate to the risk involved.
- ◇ An investor who decides to purchase shares in a company with highly volatile results because he believes that the long-term growth prospects justify the risk taken.
- ◇ A municipality that decides to build a bridge in a known seismic zone, despite the risks of earthquakes, because it believes that the benefits to the local community far outweigh the costs and risks involved.

These examples show that risk acceptance can be justified in certain circumstances, depending on the risk assessment, probability of occurrence, and costs and benefits involved. However, it is important to remember that risk acceptance does not mean that the organization or individual involved should completely ignore the risk, but rather that they should be aware of it and be prepared to take measures to manage it in the event of its occurrence.

- ***Risk Transfer:*** Organizations may choose to transfer the risk to an individual or entity that is capable and willing to assume it. The cost of risk transfer is generally higher than the cost of internal risk management, which is the main justification for pursuing this strategy. It is important to note, however, that transferring the risk does not necessarily diminish or eliminate it. In fact, if the risk is transferred to an entity that is unable to effectively manage it, the transferred risk may actually increase. The most common method of risk transfer is through insurance. Here are some detailed examples of risk transfer:

  - ◇ An individual may purchase health insurance to transfer the risk of large medical expenses to an insurance company.
  - ◇ A company that operates in a high-risk industry may purchase liability insurance to transfer the risk of potential lawsuits to an insurance company.
  - ◇ A construction company may transfer the risk of damages caused by accidents on a building site to a third-party contractor through a contract that assigns liability.
  - ◇ A small business may outsource its IT operations to an external company that specializes in cybersecurity to transfer the risk of data breaches and cyber attacks to the external company.
  - ◇ An investor may transfer the risk of a potential loss in the stock market by purchasing put options, which give them the right to sell a stock at a predetermined price.

- ***Risk Mitigation:*** Since the significance of a risk depends on the likelihood of occurrence and the impact of the risk, an organization can choose to mitigate the risk by either reducing the likelihood that the risk will occur or by reducing the impact of the risk. In an ideal situation, managers would aim to reduce both the likelihood and impact of the risk.

When an organization decides to reduce risk, it should make changes to the design that remove the risks without introducing new risks. This can be achieved by implementing protective measures or controls. One of the key aspects of mitigation strategies is creating flexibility to adapt to sudden or unexpected events and changes at minimal cost and without disrupting the rest of the system.

- ◇ A company that operates in an area prone to earthquakes may decide to build its headquarters in a building designed to withstand seismic activity, or it may implement an earthquake early warning system to alert employees to evacuate in time.
- ◇ A financial institution that wants to reduce the risk of fraud may implement a two-factor authentication process for its online banking system, which requires customers to provide two forms of identification to access their accounts.
- ◇ An airline company that wants to reduce the risk of a terrorist attack may implement additional security measures such as passenger and baggage screening, and random searches to identify potential threats.
- ◇ A software development company that wants to reduce the risk of data breaches may implement data encryption and regularly backup its systems to protect against cyber attacks.
- ◇ A manufacturing company that wants to reduce the risk of workplace injuries may implement safety training for its employees, provide protective gear, and install safety equipment such as alarms and sensors to alert employees of potential hazards.

According to research conducted by the Business Continuity Institute in 2013, 75% of companies experiment with at least one significant SC disruption a year [89]. Considering potential losses from disruptions, mitigation strategies could be critical for the survival of a company [90].

Safety stocks, collaboration, multiple sourcing, and the sharing of information have been identified in [91] as some of the most significant ways to deliver countermeasures to risks. Similarly, the authors in [92], had added flexible transportation as an appropriate measure to mitigate SCRs. Increasing collaboration with partners, including supply and process flexibilities, increasing demand, risk sharing, and building buffers or redundancies across SCs, has been suggested by [8] as general strategies to be adopted for mitigating risks. However, the present advancement exhibits a lack of consistency among different strategies, which may hinder the implementation of SCRM effectively. Hence, a better agreement on particular terms and notions concerning SCRM strategies is required.

Models for sourcing and inventory mitigation have been reviewed simultaneously by [93, 94]. Furthermore, a two-stage DSS that assists managers to select not only mitigation strategies for SCR but also mitigation tactics when risks happen has been proposed in [35]. A non-linear mixed-integer programming model has been developed and used to simulate resilience strategies to mitigate the risk of correlated disruptions [95]. Adding to all this work, a quantitative DSS to select appropriate mitigation measures for SCR has been proposed in [96].

The leading limitation of current studies is their restrained focus on capturing interdependencies between SCRs and mitigation strategies. Keeping in view the significance of modeling systemic risks and capturing non-linear complex interactions [97]. Researchers have started modeling SCRs interdependency [98, 99]. In this context as well, a model has been introduced for prioritizing strategies within a probabilistic network of interacting risks and strategies [100]. To capture the risk appetite of a decision-maker, another study has proposed an expected utility-based method to select optimal strategies [101]. Furthermore, the authors in [99], claimed that, among the most remarkable drawbacks, the major limitation of existing models is their inability to capture the holistic nature of SCRs. Many techniques are incapable of considering risk propagation. In the same direction, the authors in [89], had observed the existence of gaps in considering supplier selection and risk mitigation simultaneously.

It is possible to classify risk mitigation strategies into two groups: proactive and reactive. In a reactive approach, no action is taken earlier than the incidence of a risky event, but it's applied to mitigate its probability and impact after it occurs. Yet it doesn't achieve its maximum capacity on the grounds that it concentrates on minimizing the consequence of a risk instead of the likelihood of its event [102]. In a proactive approach, schemes are implemented to mitigate the risks before they happen. Proactive SCRM means arranging ahead to diminish hazards before they arise [58].

An investigation conducted by the authors of [59] has shown that SCRM using both strategies when appropriate positively affects organizational performance. Because agility achieved through flexibility is necessary to adapt to customer-related risks, and robustness obtained through redundancy is a necessary premise to handle supplier-related risks.

Eight top SCRM strategies have been identified by [58]. Recently, Ivanov has mentioned that reactive approaches can be based either on purely recovery policies without any SC proactive protection or integrated with proactive approaches [66].

2.3.3.1 Supply chain risk mitigation methods

The table 2.4 outlines various methods for mitigating supply chain risks, which involve taking steps to minimize the negative impact of unforeseen events on the flow of goods and services from suppliers to customers. Some of these methods include:

2.3.4 Risk monitoring

The final stage involves continuously monitoring the effects of the response strategy for a particular risk [34]. In this stage, which comprises both observations about changing situations and environments and supervision about previous assessments, new risks can be identified, and new judgments about previously specified risks may be revised by means of this phase [29], after which new solutions may be proposed.

Table 2.4: SCR mitigation methods.

Method	Description
Diversification of suppliers	Using multiple suppliers for the same goods or services to reduce the risk of disruption to the supply chain if one supplier experiences difficulties.
Risk assessment and planning	Identifying potential risks and vulnerabilities in the supply chain, and developing contingency plans to address these risks before they occur.
Supply chain visibility	Using technology and other tools to gain better visibility into the supply chain, so that potential disruptions can be identified and addressed more quickly.
Collaborative relationships with suppliers	Building strong relationships with suppliers based on trust and collaboration, so that they are more likely to work with you to mitigate risks and respond to unexpected events.
Inventory management	Maintaining appropriate levels of inventory to ensure that there are enough goods or services available to meet demand, even if there are disruptions in the supply chain.
Continuous improvement	Regularly reviewing and improving the supply chain processes to reduce the risk of disruptions and increase the efficiency of the overall supply chain.

Monitoring supply risk is essential, as it can provide an early alert when risk levels are rising, granting firms time to react and behave to these changing situations by altering their alleviation strategies, as highlighted in [103].

Comparatively, risk monitoring has received less awareness in the literature [17, 18, 103, 104]. Only ten papers out of 354 had paid explicit attention to monitoring, according to the work led by [18].

In contrast, there are recent works that incarnate risk monitoring through performance measurement systems [104]. Also, a SC visualization scheme with real-time monitoring and risk management has been proposed in [105].

Until now, the question of what method to use for risk monitoring as a truly independent stage in the SCRM process isnt yet addressed. In addition, the decision-making tools for helping the decision-maker in the process of risk monitoring remains unclear and are not addressed in the literature.

2.3.4.1 Supply chain risk monitoring methods

The modern global economy relies heavily on complex supply chain networks that can span multiple countries, continents, and industries. While these networks can provide significant benefits in terms of efficiency and cost savings, they can also pose significant risks. Disruptions to the supply chain can arise from a range of factors, including natural disasters, geopolitical events, labor disputes, and technology failures. These disruptions can lead to delayed deliveries, increased costs, and reputational damage. To mitigate these risks, companies need to implement effective methods for monitoring their supply chains.

The table 2.5 presents a selection of methods that can be used to monitor and manage risks in the SC, enabling companies to maintain a reliable and resilient supply chain network.

Table 2.5: SCR monitoring methods.

Method	Description
Regular Communication with Suppliers	Maintain regular communication with suppliers to stay informed about potential risks in the supply chain.
Continuous Risk Assessment	Conduct continuous risk assessments to identify potential risks in the supply chain.
Performance Monitoring	Monitor the performance of suppliers to identify any potential risks.
Diversification of Suppliers	Consider diversifying suppliers to reduce the risk of disruption in the event that one supplier experiences a disruption.
Scenario Planning	Develop and test different scenarios to assess the impact of potential risks on the supply chain.
Technology Integration	Utilize technology, such as data analytics and machine learning, to monitor the supply chain and identify potential risks in real-time.
Collaboration and Transparency	Foster collaboration and transparency with suppliers to promote a shared understanding of risks and a willingness to work together to mitigate them.
Early Warning Systems	Use data analytics to identify early warning signals of potential disruptions in the supply chain.
Supplier Audits	Conduct audits to assess supplier compliance with quality, safety, and environmental standards.
Supply Chain Mapping	Map the entire supply chain to identify potential vulnerabilities and risks.
Contingency Planning	Develop contingency plans for potential supply chain disruptions, such as alternative sourcing or inventory management.
Continuous Improvement	Implement a continuous improvement program to identify and address supply chain risks on an ongoing basis.

2.4 The scope of risk management in the supply chain

It is important to remember that supply chains are complex networks, not simple linear chains. Physical flows and information flows move within and between nodes in the networks that connect organizations. The source of risk can therefore be located within the scope of the organization as well as with its partners, upstream or downstream in the chain, and on any type of flow.

Thus, from a practical point of view, we observe that cooperation in risk management is particularly difficult at the supply chain level and that this difficulty increases with the number of partners involved. Moreover, managing risks is a long-term process that involves investments. However, evaluating the real benefit of this management is complex since its objective is precisely to prevent loss. The distribution of costs and benefits between actors is therefore problematic, especially when the chain might need to reconfigure and exclude an unreliable partner, as may be the case in a logic of resilience.

To properly assess risks along the supply chain, information must be shared throughout the chain. However, a company that is vulnerable to an element will be reluctant to report it to its partners. These partners will then be able to set up efficient information systems to increase visibility into the functioning of the different organizations. However, these systems rarely allow an outside eye to identify risks that are often difficult to assess even internally.

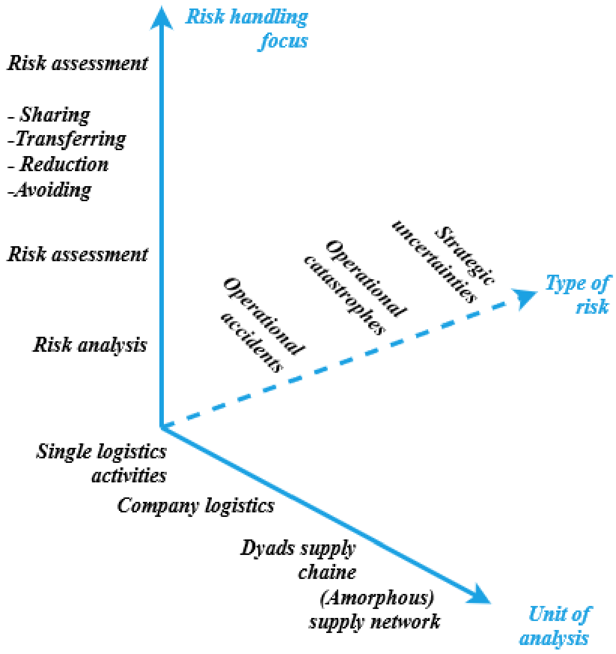


Figure 2.2: Supply Chain Risk Analysis Framework [2].

As a result, when considering supply chain risk and logistics risk, different units of analysis can be considered. In this point, we rely on the analysis framework proposed by [2], illustrated by Figure 2.2. It should be noted that the logistics of an organization (company logistics) and operational events (operational accidents) are present as relevant levels of analysis.

To determine the most appropriate unit of analysis for logistics risk management, a distinction must be made between atomistic logistics risk and holistic logistics risk. If the risk is atomistic, only a part of the logistics chain needs to be assessed and managed. However, if the risk is holistic, then the entire logistics chain must be included in the assessment and management. Atomistic logistics risk management can be performed by a single organization alone, while holistic logistics risk management requires the involvement of multiple organizations. For instance, if the logistics risk relates to an organization's internal information system, it can be managed by the organization alone.

For each risk, risk management therefore leads to a choice between four strategies: avoidance, reduction, acceptance, or transfer. The choice of one or the other of these strategies may be influenced by the scope of risk management. Depending on the nature of the latter, either atomistic or holistic, it will be possible to favor an organizational framework or an inter-organizational framework for this management.

2.5 Overview of independent techniques

Supply Chain Risk research employs a diverse range of methodologies and tools, encompassing both empirical studies such as case-based research [106] and mathematical and simulation models [107]. Research can range from general investigations, such as the development of a SCRM framework [108], to more specialized inquiries, such as the examination of procurement risk management [109]. Classification of modeling approaches and methodologies is employed to gain a better understanding of the various tools and techniques utilized in SCRM research.

According to our literature overview, the following classification can be proposed, which represents an extension of the works of [110]. They had proposed a classification of solution methods into four categories that determine different solution techniques.

The first category, ***"General Solver Exact Solution"*** is a method of solving supply chain risk management problems using mathematical programming software. This method aims to provide the best possible solution for a given problem or reach a solution within a specified acceptable range of quality. It is an approach that involves using algorithms and mathematical models to find optimal or near-optimal solutions for complex problems [110]. This type of solution method is often used in supply chain optimization problems that involve multiple constraints, such as limited resources, delivery deadlines, and inventory levels. The General Solver Exact Solution method is particularly useful in identifying the most efficient and cost-effective solutions for supply chain risk management problems.

The principal benefit of the optimization approach is the pursuit of the best solution and achieving optimality. However, employing optimization-based decision-making poses challenges due to uncertainty, complexity, and multiple objectives. Moreover, decision-making is a dynamic process that requires adaptation and fine-tuning. Hence, it is difficult to develop a general selection function for Multiple Criteria Decision Making (MCDM). While finding optimal solutions is feasible, it can be time-consuming, as pointed out by [66].

Optimization is the process of finding the best solution to a given problem, and it is often used in a variety of fields such as engineering, economics, and operations research. The resolution obtained is either optimal or adequate enough based on a predetermined acceptable gap specified by the decision-maker. By imposing computational time constraints, an off-the-shelf solver provides solutions of the second category, namely, heuristic solutions. Specific solution algorithms offer exact or heuristic solutions. The former is obtained by using special-purpose techniques such as decomposition methods, column generation, branch-and-cut, and branch-and-bound.

Decomposition methods involve breaking down a complex optimization problem into smaller, more manageable sub-problems that can then be solved separately. Column generation is a technique used for solving linear and mixed-integer programming problems where the problem is divided into a master problem and a subproblem. The master problem is solved iteratively by adding new variables to the solution until the optimal solution is found. Branch-and-cut and branch-and-bound are methods used for solving combinatorial optimization problems where the search space is too large to explore exhaustively. Branch-and-cut involves systematically eliminating infeasible solutions, while branch-and-bound involves dividing the search space into smaller sub-spaces and exploring each sub-space until the optimal solution is found.

When the number of discrete variables is considerable, which often occurs, then the resulting models are comparatively more complicated, and realistically sized problems can only be solved with a heuristic method. Heuristics are algorithms that provide good solutions in a reasonable amount of time but do not guarantee optimal solutions. They are often used when the problem is too complex to be solved exactly within a reasonable time frame or when an approximate solution is acceptable. Heuristics are smart rules that often lead to beneficial, but not necessarily the best solutions. Examples of heuristic methods include nature-based heuristics such as ant colony optimization and genetic algorithms, as well as linear programming-based heuristics and meta-heuristics like Lagrangian relaxation.

Heuristic approaches are usually easier to implement and require much less data than exact optimization methods. However, the quality of the solution is commonly unknown, and heuristics may fail to find the optimal solution, particularly for very large and complex problems. In situations where problem sizes are large, heuristic-based approaches are often used, as exact methods may be too computationally intensive. While heuristics can be a powerful tool for solving optimization problems, it is important to carefully consider the trade-offs between the quality of the solution and the computational resources required to obtain it.

Simulation involves imitating the behavior of one system with another. By making changes to the simulated system, it is expected to gain a better understanding of the dynamics of the physical system. The tools and principles of discrete-event simulation are used to implement discrete models.

Simulation provides a set of features that compensate for the limitations of optimization. In particular, simulation models allow for the analysis of systems and the discovery of solutions where methods such as mathematical programming and analytic calculations fail. Simulation models also enable the measurement of values and the tracking of entities within the level of abstraction, as well as the addition of measurements and statistical analysis at any time. Additionally, simulation models can manipulate and animate the system behavior in real-time.

Therefore, simulation is an ideal tool for further analyzing the performance of a proposed design derived from an optimization model [56].

One promising aspect of model-based decision-making is the combination of simulation methods with optimization methods in an iterative way, which is referred to as optimization-based simulation [111, 112]. For example, Meisel et al. [113] utilized simulation and optimization methods to analyze the performance of a make-to-order strategy in the presence of uncertainties, while Ivanov et al. [114] applied a hybrid optimization-based simulation approach to analyze supply chain disruptions and recovery strategies.

Incorporating simulation and optimization methods in an iterative way provides several advantages over using them individually. Optimization-based simulation allows for the evaluation of a wide range of system configurations and decision alternatives while considering the inherent uncertainties and dynamic behavior of the system. It can also identify optimal solutions that may not be found through traditional optimization methods alone. Additionally, optimization-based simulation can provide insights into the system's behavior under different scenarios, enabling decision-makers to evaluate and compare the performance of different strategies before implementation. Overall, the integration of simulation and optimization methods in an iterative approach can help decision-makers make more informed and effective decisions.

In the following sections, we will discuss these five methods in detail and review recent literature.

2.5.1 Qualitative approaches

Managing one type of risk may additionally exacerbate other risks. The qualitative approach simplifies the recognition and examination of the level of risk. The calculation methods are simple to understand and implement.

A more intensive qualitative method, the Structured What-If Technique, uses a lead question "What if?" systematically to identify deviations from normal conditions using a predefined checklist [115]. With Hazard and Operational studies, another qualitative approach, hazards and weaknesses are identified by evaluating deviations from original designs [98]. However, both methods are time and resource consuming and only identify risks that need further analysis using a different method. Moreover, they do not allow direct comparisons of different scenarios.

Failure mode and effect analysis (FMEA) is a technique used to identify possible failures and predict their effects on the system as a whole [116]. FMEA provides the basis for more in-depth analyses, such as Fault Tree Analysis (FTA), which can be conducted using either a qualitative or quantitative approach [117, 118]. Although FTA has been used for multiple applications, it is not suitable for systems with dynamic properties, such as SC.

Cause and effect analysis is another risk analysis technique used in several fields. Its application to SC can provide interesting insights into risks [119]. However, the tool's usefulness in proactively managing SCR is limited to cases with historical data.

The application of a decision support system in supply chains by employing Multiple Criteria Decision Making is a constant challenge. MCDM methods can consider the outcomes of uncertainties at every phase of the decision-making process and examine the sensitivity of results to the inputs. Therefore, MCDM has become increasingly widespread in decision making.

Several MCDM tools are implemented, such as Analytical Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and VIKOR. [120] has also proposed a built-in approach using a combined AHP and Quality Function Deployment.

AHP-based approaches are usually applied to the prioritization of risk factors in SCM [121]. In addition, the TOPSIS approach can evaluate a large number of choices and criteria.

Risk checklist and risk taxonomy are two qualitative tools applied in risk factor identification [122]. The risk taxonomy provides a structure to arrange the checklist of risk factors into general classes. However, the two methods consider less about the interconnections of risk factors. Several MCDM approaches are exposed in Figure 2.3.

MCDM analysis methods are more appropriate when the various alternative choices are known, and the decision maker needs a structured way of making choices among them. In addition, qualitative methods do not allow for the determination of probabilities and results using numerical measures. The evaluation of risk and its results are subjective, making cost-benefit analysis more difficult, and the results depend on the quality of the risk management team.

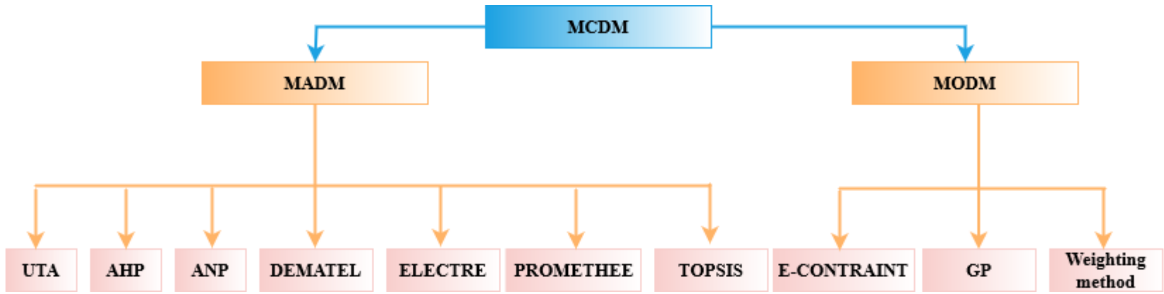


Figure 2.3: The MCDM analysis methods.

Here are some additional disadvantages of qualitative methods in risk analysis:

- ***Lack of precision:*** Qualitative methods are often imprecise and subjective, which can lead to inconsistencies and inaccuracies in the analysis.
- ***Limited scope:*** Qualitative methods are typically limited in scope and may not cover all possible risks, leading to incomplete risk assessments.
- ***Difficulty in comparing risks:*** Qualitative methods do not provide a clear basis for comparing the relative importance or severity of different risks, making it difficult to prioritize risks.
- ***Reliance on expert judgment:*** Qualitative methods rely heavily on the judgment and expertise of the risk management team, which may introduce biases and errors into the analysis.
- ***Time-consuming:*** Qualitative methods can be time-consuming and resource-intensive, especially when using more intensive methods such as the Structured What-If Technique or Hazard and Operational studies.
- ***Lack of standardization:*** Qualitative methods are often not standardized, which can make it difficult to compare results across different studies or organizations.

2.5.2 Quantitative approaches

The principal purpose of the quantitative strategy is to make an most efficient decision by employing mathematical and statistical models in a situation when the chance of all outcomes is uncertain.

Researchers have investigated a range of methods to reflect on-consideration on uncertainty within the framework of mathematical programming, two main approaches are stochastic and deterministic. In the deterministic approach, the out-turn of the model is fully determined by the parameter values and the initial conditions. However, the stochastic approach has inherent randomness and is a general method for finding optimal decisions prior to learning some of the random variables [123].

Quantitative approach to decision-making brings better results when the problem is precisely defined, several alternatives exist and decision outcomes are effortlessly assessable. However, in the situation where countless external factors are outside of the decision-maker's control and their probability is obscure, the quantitative methods can become untrustworthy.

Quantitative approach techniques, particularly the ones relying on statistical software, have the feature of proposing the best resolution of the problem without even identifying all potential alternatives. This feature is quite useful in problems where the number of possible alternatives is large though only a few are worth considering for selection so once the problem and conditions are determined the decision making process becomes quick.

In their explanation, [23] emphasized the importance of quantifying risk in stochastic optimization problems to make decisions that mitigate its extent. To assess and compare various solutions for limiting risk, decision-makers must quantify imprecise parameters using risk measures such as mean-variance approaches, standard deviation, value-at-risk, conditional-value-at-risk, and premiums. Risk measures are statistical tools used to describe the relationship between uncertainty and the extent of its associated harm or benefit. For instance, the value-at-risk measure is the maximum potential loss that can occur over a specified period with a given confidence level. Similarly, the conditional value-at-risk measure combines the potential loss beyond the value-at-risk with the probability of that loss occurring. Using these measures, decision-makers can quantify the potential risk involved in various decisions and identify the best course of action to mitigate risk [64].

In recent literature, mathematical modeling in supply chain management has mostly utilized the stochastic approach, as noted by [64]. In a similar vein, Aqlan et al. [124] undertook a study that involved quantifying risks within the supply chain domain and effectively achieving risk reduction with minimal cost implications. Notably, they also took into consideration the correlations between different risks. However, it is important to note that they did not establish a direct connection between the impact of risks and operational metrics like inventory levels. Similarly, [125] addressed uncertainty in location and capacity decisions for manufacturers and assemblers, but did not consider the potential risks that may arise from disruptions in connections between different facilities. On the other hand, [126] developed a multi-scale superstructure for the biofuel supply chain, enabling systematic decision-making across three production strategies. In the stochastic approach, uncertainty is represented by a set of scenarios, as the modeling process takes into account the inherent uncertainty and risk in the system.

Mathematical programming has been extensively used to support risk management in the SC field. For instance, mixed integer programming has been used to model a dynamic SC portfolio problem of order allocation and supplier selection in [127], and for SC contingency planning in [128]. [96] proposed a quantitative DSS to select appropriate mitigation measures for SCRs using a stochastic integer linear programming framework. Similarly, [129] prioritized new product development plans based on SCR factors using mathematical programming, but the results are specific to Snowa company and require analysis over a longer period to be generalized.

From the Table 2.7, it can be noted that the problem of supply-side has taken a lion's share in previous studies. A mathematical and heuristic approach that can be implemented to solve real-world supply disruption problems has been recommended by [130]. However, environmental aspects weren't incorporated, and only a single type of item was considered.

Bayesian Belief Networks (BBNs) are a well-known quantitative technique that can be utilized to describe the cause and effect relationship between various events and could be adapted for SCR analysis. Another powerful capability of BBNs is the back-propagation capability, where a certain risk can be declared as if it occurred to investigate probable root causes that may have led to that risk event. These capabilities are especially useful in SCRM because they can be used by supply chain managers to investigate what events are likely to influence key performance measures [98]. A hierarchical assessment method used a Bayesian network for material risk detection in green supply chains has been proposed in [131].

Quantitative research in SCRM typically models the trade-off between purchasing from alternate suppliers and holding inventory, or models the interplay between suppliers and customers [132].

The results obtained with quantitative methods can be expressed in specific management terminology. The evaluations are based on objective methods, and administrative performance can be carefully monitored. Cost analysis can be implemented to select the most suitable applicable measures. However, the calculation methods are complicated, and without an automatic tool, the process can be difficult to implement. The values of risk impacts are based on subjective opinions of people involved, and the process is very complex and time-consuming.

Here are some disadvantages of quantitative methods:

- Quantitative methods often rely on numerical data, which may not capture the full complexity of real-world phenomena. They can be less effective in capturing nuances and context than qualitative methods.
- The process of collecting and analyzing quantitative data can be time-consuming and resource-intensive.
- Quantitative methods are susceptible to biases and errors, such as selection bias, sampling bias, and measurement error. These issues can undermine the accuracy and reliability of the results.
- The assumptions and models used in quantitative analysis may not always be applicable to real-world situations, which can limit the generalizability of the findings.
- Quantitative methods often rely on statistical techniques that may be difficult to understand for non-experts, making it challenging to communicate the results to decision-makers who are not familiar with the methods.

- Quantitative methods may not fully capture the subjective experiences and perceptions of stakeholders, which can limit their ability to inform policy and decision-making in certain contexts.

2.5.3 Simulation approaches

The benefit of the simulation method is that it studies the behavior of a system without building it, and it can also help to find a solution to an unexpected phenomenon. However, it presents some drawbacks, such as the difficulty in interpreting the simulation results and the high cost of building a simulation model.

According to Tako et al.[133], three primary simulation methods have been recognized, namely system dynamics simulation, discrete-event, and agent-based simulation. Table 2.6 provides a comparison of the three major simulation approaches based on several criteria:

- ***Decision-making levels***: This criterion refers to the level at which the simulation models decision-making.
- ***Data requirements***: This criterion refers to the amount of data required to build a simulation model.
- ***Construct behavior change while execution***: This criterion refers to whether the simulation can change the behavior of the system during execution.
- ***Models complexity***: This criterion refers to the complexity of the simulation models.
- ***Maturity of the simulation technology***: This criterion refers to the level of development of the simulation technology.
- ***Time advance mechanisms***: This criterion refers to how the simulation model advances in time.
- ***Levels of aggregation***: This criterion refers to the level of detail of the simulation models.
- ***Types of modeling procedure:*** This criterion refers to the modeling approach used to build simulation models.

Overall, the selection of a simulation approach depends on the nature, goal, and aggregation level of the phenomena being modeled.

While system dynamics is used for modeling the behavior of complex systems over time, discrete-event simulation is process-centric and facilitates the simulation of interdependent systems through the occurrence of time-dependent discrete events that approximate real-world processes. The latter is widely used in industrial and research circles, and there are now several commercially available discrete-event simulation software packages, such as Arena [134], SimEvents [135], Anylogic [136], and ProModel [137]. The agent-based approach has acquired ample reputation to be an active sub-area of the computational economics

Table 2.6: Comparison of the three major simulation formalisms.

Criteria	System dynamics	Discrete event	Agents based
Decision-making levels	Strategic	Tactical and operational	Strategic, tactical and operational
Data requirements	Low	High	Medium
Construct behavior change while execution	Yes	No	Yes
Models complexity	Low	High	Medium
Maturity of the simulation Technology	Mature	Mature	Needs development
Time Advance mechanisms	Time step	Next event	Time step or next event
Levels of aggregation	High	Low	Medium
Types of Modeling procedure	Top-down	Bottom-Up	Bottom-Up

community. It uses agent-based modeling as both a descriptive and normative approach to optimizing complicated, non-differentiable status.

Agent based modeling approach allows for emulating emerging behavior's resulting from the interaction of autonomous agents. There have been a number of agent based simulation models within SC domains enabling a means of addressing complexity. Simulation to model the interactions among SC entities where each entity can take different actions have been used by [109, 138]. Also, multi-agent simulation models are increasingly being used in SCRM, as examples [139, 140].

In the realm of SCRM research, mathematical and stochastic optimization techniques tend to dominate, whereas the potential of simulation modeling remains largely unexplored. Simulation modeling involves the replication of real-world processes or systems. In their study, Trucco et al. [141] employed a research methodology that involved a synergistic utilization of discrete event simulation and system dynamics. On a similar note, Burgholzer et al. [142] developed models aimed at analyzing intermodal transport networks, employing a traffic microsimulation approach. Schlüter et al. [143], in their research, introduced a versatile simulation-based approach designed to assess digitalization scenarios prior to their actual implementation. Additionally, in an independent study, Park et al. [144] proposed an innovative framework for evaluating vendors.

Simulation modeling techniques enable the examination of specific characteristics and details of supply chain components. This facilitates not only the visualization of network operations but also the tracing of each individual process. Additionally, simulation modeling permits the observation of the effects of various disruptions and recovery policies over time, while also considering gradual capacity degradation and recovery, as pointed out by [56].

While simulation can be a useful tool for risk management, there are some potential disadvantages to consider. Here are some possible disadvantages of simulation in risk management:

- ***Complexity***: Simulations can be complex and time-consuming to set up and run. This can make it difficult to understand and communicate the results, especially for those who are not familiar with simulation modeling.

- ***Uncertainty***: Simulations involve making assumptions about how a system or process works. These assumptions may not always be accurate, which can lead to inaccurate or misleading results.
- ***Cost:*** Building and running simulations can be expensive, especially for large or complex systems. This cost may not always be justified by the potential benefits of using simulation.
- ***Limited scope***: Simulations are only as good as the data and assumptions used to create them. If important factors are left out or assumptions are incorrect, the simulation may not accurately represent the real-world system or process.
- ***Overreliance***: Simulation can be a powerful tool, but it should not be relied on exclusively. Risk management should involve a combination of approaches, including simulation, expert judgment, and other analytical tools, to ensure a comprehensive and accurate assessment of risk.

Table 2.7: Quantitative approaches applied in SCRM.

Reference	SCRM Process				Problem area	Approches (Empirical/analytical)	Decision Making	Methodology, Techniques and Modeling
	I	A	M	M				
[124]	•	•	•	-	Quantify and mitigate supply chain risks	High-end server manufacturing SC	-	Bow-Tie analysis and optimization techniques
[125]	•	-	-	-	Supply chain network designing and assembly line balancing under uncertainty	Real case	Yes	mixed integer nonlinear programming formulation based on two stage stochastic programming method
[145]	•	•	•	-	Supply chain risk	Indian e-commerce firm	Yes	mixed integer programming formulation
[146]	•	-	-	-	Demand risk	Illustrative Example	-	Quantitative model
[147]	-	•	-	-	Multi-stage and Multi-period supply chain network design problem	An Iranian glass company (AFGC).	Yes	Generic mathematical formulation, Simulation approach
[126]	•	•	•	-	Supply chain network uncertainty	biofuel production in the United Kingdom	Yes	A mixed integer (piece-wise) linear program (MILP)
[96]	•	•	•	-	Supply chain risk management	Chicco–Artsana, a large manufacturer and distributor of baby care products	Yes	Stochastic integer linear programming approach, Fuzzy-extended pairwise comparisons
[29]	•	•	•	•	Supply risks	An international automotive company.	-	Linear programming model
[148]	-	-	•	-	Supply disruptions	Realistic supply chains	Yes	Approximate dynamic programming algorithms
[149]	-	•	-	-	Uncertainty,outsourcing	Numerical experiments		Mixed integer linear programming model
[98]	•	•	•	-	Risk management	Case study aerospace manufacturers	Yes	Bayesian belief networks
[132]	-	-	•	-	Risk sharing, Demand uncertainty	-	Yes	mathematical model
[150]	•	•	•	-	Supplier selection	Real world case	Yes	Analytic network process, Multi-objective programming
[151]	•	•	•	•	Risk mitigation strategies	Simulation study	Yes	BBN, Failure Modes and Effects Analysis
[130]	-	-	•	-	Supply disruption,	Simulation, Numerical results	-	Mathematical model, Simulation
[129]	•	•	-	-	Supply chain risk	Entekhab Industrial Group in Iran	-	Risk-assessment matrix and Shannon fuzzy entropy
[152]	-	•	•	-	Demand uncertainty	Numerical examples	-	Game theory
[153]	-	•	-	-	Cooperative advertising	Numerical experiments	Yes	Conditional value-at-risk (CVaR)

I: identification A: assessment M: mitigation M: monitoring

2.5.4 Artificial intelligence

Intelligent systems are a broad term that covers approaches to the design, optimization, and control of various complex systems without requiring mathematical models, similar to how humans work [154]. Artificial intelligence (AI) is an extensive scientific discipline that allows computer science to solve problems by emulating complicated biological processes such as self-correction, reasoning, and learning. Compared to traditional programming techniques, expert system approaches provide added flexibility with the capacity to model rules as data rather than as code. By facilitating turnaround, artificial intelligence provides a means that can allow organizations to adapt more easily to changing needs.

Methodologies and techniques that fall under the umbrella of AI are numerous, and they encompass a range of approaches that simulate and optimize complex systems. Some of these methodologies include agent-based modeling (ABM) and MAS, which involve the simulation of individual agents' behavior and the interactions and coordination of multiple agents, respectively.

ABM is designed to model individual agents with homogeneous or heterogeneous characteristics, while MAS typically involves agents with heterogeneous characteristics. ABM agents do not necessarily coordinate with each other, while coordination and cooperation between agents are essential in MAS. Moreover, ABM is typically used to model relatively simple systems, while MAS is used to model more complex systems that involve multiple agents with different abilities and objectives. ABM is usually applied in a bottom-up approach, where the behavior of individual agents is modeled first, and the emergent properties of the system are observed. In contrast, MAS is applied in a top-down approach, where the objectives of the system are defined first, and the agents' behaviors are modeled to achieve those objectives.

Other approaches that are part of AI include automated reasoning based on existing knowledge, machine learning, and big data analytics techniques. Table 2.8 provides a comprehensive overview of the application of these AI techniques in the fields of SCRM and Decision Support Systems.

Fuzzy logic can be a useful tool in creating transparent and intuitive decision-support models for any application [155]. Fuzzy sets are the elementary concepts that sustain fuzzy set theory and have the capacity to achieve a complicated nonlinear input-output relation by synthesizing more than one simple input-output relation.

Fuzzy and robust optimization techniques are primarily applied to address operational risks and tactical planning. For instance, [156] utilized robust optimization methods to manage operational risks in physical and financial supply chain management. In another example, [157] proposed a method that combines fuzzy cognitive maps and BBN to enhance BBN's ability to model operational risks.

In today's business landscape, characterized by the rise of information technology and economic globalization, supplier selection has emerged as a crucial factor in supply chain decision-making. Luan et al. [158] presented a new hybrid algorithm that merges genetic algorithms and ant colony optimization to tackle the issue of supplier selection. However, it should be noted that this method may not yield optimal results in a dynamic marketing environment characterized by uncertain or stochastic demand. Additionally, [159] proposed a supplier selection process for a supply chain that considers various selection criteria for managing supply risks. [160] presented an integrated framework for the evaluation and selection of a strategic supplier in a global sourcing environment. Moreover, [161] introduced a new VIKOR method to handle the MCDM problem.

Some researchers have approached SCRM problems by utilizing automated reasoning techniques that depend on encoding expert knowledge in the form of rules or cases. For instance, [162] employed the association rule mining technique to define risk labels in SCs. However, expert systems are not optimal for all problems, and considerable knowledge is necessary to operate any of these systems effectively.

While ease of rule creation and modulation can be beneficial, it can also be a double-edged sword. A system can be broken or vandalized by a non-knowledgeable user who can easily add worthless rules or guidelines that conflict with existing ones. The absence of facilities for system audit and detection of possible conflicts are reasons for the failure of many systems.

The dynamic and complex nature of SCRM decision-making, especially under uncertainty, has led several researchers to adopt a network-based model to describe the various possible states, their outcomes, and the feasible transitions between them [163]. A SCRM network management process that captures inter-dependencies between risks has been developed in [164]. Additionally, a comprehensive measurement approach for anticipating the complex behavior of risk propagation has been provided by [165].

A multi-agent-based solution has been proposed in [166], where the architecture of each agent includes concurrent individual and collective Belief-Desire-Intention structures to support collaborative objectives. Moreover, [167] proposed a framework structured in two modules based on Petri-net and agent-based modeling techniques for modeling disruptions management. In another study, [168] proposed an Internet of Things-based risk monitoring system for controlling product quality and occupational safety risks in cold chains. They applied a fuzzy logic approach to evaluate the cold-associated occupational safety risk of different cold chain parties.

The diversity of AI techniques and methodologies means that selecting the appropriate one is crucial for effective decision support and managing supply chain risks. While several AI techniques have been applied to SCRM as presented in Table 2.8, there is a lack of holistic frameworks that integrate all risk management process steps while considering a decision maker's risk appetite. Additionally, current frameworks typically focus on optimizing a single objective without modeling the trade-offs between conflicting and interdependent objectives.

While AI has numerous potential benefits in SCRM, there are also several disadvantages to its use. Some of the main disadvantages of AI in supply chain risk management include:

- ***Limited understanding of context:*** AI algorithms are designed to analyze data and identify patterns, but they may lack the ability to understand the context in which the data is being used. This can lead to incorrect predictions and recommendations that may not align with the actual risks and uncertainties in the supply chain.

- ***Data quality issues:*** AI algorithms rely heavily on the quality of the data they are fed. If the data is incomplete, outdated, or inaccurate, the algorithm's output will also be flawed. In some cases, AI can even amplify the effects of bad data by making incorrect assumptions or generalizations.

- ***Lack of human oversight:*** While AI can automate many aspects of risk management, it cannot replace the critical thinking and decision-making abilities of human experts. Relying solely on AI to manage supply chain risks can lead to over-reliance on algorithms and a lack of human oversight, which can increase the likelihood of errors and oversights.

- ***Cybersecurity risks:*** AI systems are vulnerable to cyber-attacks, which can compromise the integrity and security of the data they analyze. Hackers can manipulate AI algorithms to generate false data and misleading predictions, which can lead to significant disruptions in the supply chain.

- ***Cost and complexity:*** Implementing AI in supply chain risk management can be expensive and complex, particularly for smaller organizations with limited resources. The cost of developing, implementing, and maintaining AI systems can be prohibitive, and the complexity of these systems can make them difficult to use and understand for non-experts.

Overall, while AI can be a powerful tool for managing supply chain risks, it is important to be aware of these potential disadvantages and to use AI in conjunction with human expertise and oversight.

Table 2.8: Artificial intelligence approaches applied in SCRM.

Reference	SCRM Process				Problem area	Approche (Empirical/analytical)	Decision Making	Methodology, Techniques and Modeling used
	I	A	M	M				
[158]	•	•	-	-	Supplier selection	Simulation case referring to extant literature	-	Hybrid algorithm of genetic algorithm and ant colony optimization
[169]	•	•	-	-	Credit Risk	Chinese small and medium-sized enterprise	-	Probabilistic neural network (PNN)
[166]	•	•	•	•	Logistics risk management	-	Yes	Multi-agent system
[170]	•	•	-	-	Credit risk evaluation	-	Yes	Expert system design using neuro fuzzy logic
[171]	•	•	-	-	Supply chain risk	Numerical example	Yes	Shannon entropy is used for weighing criteria and fuzzy TOPSIS is applied for ranking suppliers
[168]	•	•	-	•	Cold chain	Cold chain that handled frozen and fresh food	Yes	Fuzzy logic
[156]	•	•	•	-	Operational risks	Case-oriented numerical analysis	Yes	Robust optimization Value-based management
[165]	-	•	-	-	Supply chain disruptions, ripple effect	Numerical example	-	Bayesian network
[167]	•	•	•	-	Disruption management	Air company that shipping goods from China to Brazil	Yes	Petri nets, agent-based systems
[172]	-	•	-	-	Transportation, Disruptions and Risks	-	Yes	Bayesian, Big data
[161]	•	•	-	-	Supplier Selection	Numerical example	Yes	Dempster–Shafer evidence theory VIKOR DS-VIKOR
[160]	•	•	-	-	Supplier selection	An illustrative example	Yes	Bayesian belief network, Decision tree
[159]	•	-	-	-	Supplier selection	Numerical example	Yes	Fuzzy logic, Fuzzy inference system
[162]	•	-	-	-	Supply chain risk	Aluminum company	-	Association rule mining, Big data
[164]	•	•	•	•	Supply chain risk network management	Aerospace industrie	Yes	Bayesian Belief Networks, Fault Tree Analysis
[173]	•	•	-	-	Supply Chain Agility	Subject Matter Experts SMEs	Yes	Brainstorming
[157]	-	•	-	-	Operational risk	Iranian private bank		Bayesian Belief Networks, Fuzzy Cognitive Maps
[174]	•	•	•	-	Oil Spill Management	Prototype case study	Yes	Model-based, Rule-based and Case-based reasoning

I: identification A: assessment M: mitigation M: monitoring

In this way, hybrid methods were born and proposed to remediate the lack and challenge of each method separately and to optimize decision-making and make it more robust and reliable.

2.5.5 Hybrid approaches

Integrated models are highly valued because each method has a unique function. However, choosing the most accurate approach is often a challenging and practical question faced by supply chain managers. An inappropriate integrated model can lead to disastrous consequences and the failure of the system [175].

Managers need to manipulate a wide amount of information during the decision-making process in order to reach a rational decision. This information can often be uncertain, incomplete, and even contradictory to each other.

MCDM techniques are widely utilized and highly effective in aiding decision-making processes amidst uncertainty. Integrated MCDM methods are particularly favored by researchers for their capability to solve intricate problems in this context. However, they have the constraint of capturing sound judgment in decision-making due to the implication of linguistic data. Therefore, it is recommended to integrate fuzzy concepts with AHP to converge the objectives of supply chain managers. Some works can be cited; for example, [76] described a fuzzy AHP and fuzzy TOPSIS integrated approach to quantify SCRs. Their approach had the advantage of not just considering the likelihood of risk events in analyzing SCRs, but also accounting for their impact. However, the method fails to consider risk inter-dependencies and cannot be used to conduct time-varying analysis. In a separate study, an orders of magnitude AHP-based ex-ante SCR assessment model was developed by [176]. Also, [177] offered a method for quantifying SC risks and integrated AHP with the TOPSIS technique using the neutrosophic set to better deal with uncertainty, vagueness, and inconsistency of information.

In supplier selection problems, [178] applied fuzzy AHP to identify performance and risk-based decision criteria for supplier selection. Multi-criteria supplier selection models incorporating two different types of risk models were developed by [83]. Additionally, [179] presented a decision support system to model risks for procurement processes.

The study conducted by [175] proposed a decision support model for selecting logistics providers based on quality function deployment and TOPSIS for the agricultural supply chain in France. [180] developed a risk assessment model that enables a structured analysis of the aggregative risk associated with implementing various green initiatives in the fashion industry supply chain. [181] applied the fuzzy DEMATEL method to identify the interactions between supply chain resilience criteria. Furthermore, [182] proposed a fuzzy FMEA based on the VIKOR method and fuzzy set theory to prioritize failure modes. Additionally, [183] proposed an MCDM method using DEMATEL based on ANP with FVIKOR to judiciously select suppliers based on important criteria.

The Analytic Network Process (ANP) is a generalized structure of the Analytic Hierarchy Process that overcomes some obstacles, such as the failure to consider interactions among factors. [184] established a risk assessment model using fuzzy-grey comprehensive evaluation and AHP.

According to the available scholarly sources, it has been acknowledged that classical fuzzy sets may not consistently provide satisfactory results and can be inadequate in addressing the imprecision of concepts related to subjective assessments made by human decision-makers. Conversely, Intuitionistic Fuzzy sets are recognized as advantageous instruments for tackling the inherent ambiguity in decision makers' judgments, particularly in intricate environments where information or data regarding the problem is limited. Hence, as documented in Boran et al. [185], the integration of both classical and Intuitionistic Fuzzy sets in hybrid approaches can offer substantial advantages and maximize the potential benefits.

SCRM researchers have fundamentally mistreated the significance of sustainability issues. For example, [186] tried to bridge sustainability and SCRM but without evaluating SCRM. [187] used FAHP to prioritize risks in green SC. The analysis of the results indicates that operational category risks are the most important risks in green supply chain (GSC). Additionally, [188] proposed a model that can measure effectiveness, efficiency, and productivity in an uncertain environment and submitted a ranking model based on the fuzzy inference system for sustainable supplier selection.

The hybridity of AI applications associated with other qualitative or quantitative methods is available in the literature review, as presented in Table 2.9. Decision trees and neural networks have been tested by [189] for accounts receivable risk analysis. Another emerging field is process mining, applied to compliance checking in [190]. The results of the literature can contribute to supporting decisions in these practical problems [191]. Integrated methodologies have received relatively less focus in the existing literature. For instance, [17] categorized SCRM research appearing between 2003 and 2013 and found that among 159 quantitative-based articles, 119 articles used individual methods, and only 40 articles proposed integrated methods. Certain techniques can be integrated to enhance the performance of the original methods or to overcome their limitations. Consequently, integrated methods will likely play a dynamic and vigorous role in the area of SCRM in the future.

A hybrid approach in SCRM can be advantageous in several ways. Firstly, it can provide a more comprehensive and accurate representation of the supply chain risk landscape by leveraging the strengths of different techniques and methodologies. For example, a hybrid approach that combines simulation modeling with machine learning can provide a more accurate prediction of supply chain disruptions.

Secondly, a hybrid approach can facilitate better decision-making by providing a more holistic view of the risks and their impact on the supply chain. By integrating different techniques and methodologies, a hybrid approach can capture the various interdependencies and trade-offs between different risks and objectives, which can help decision-makers to make more informed and effective decisions.

Thirdly, a hybrid approach can enhance the flexibility and adaptability of the SCRM process. By incorporating different techniques and methodologies, a hybrid approach can be customized to suit the specific needs and requirements of different organizations and supply chains. This can enable organizations to better manage and respond to changing risk scenarios and emerging threats. Overall, a hybrid approach can offer several advantages over a single-method approach in SCRM, including improved accuracy, better decision-making, and increased flexibility and adaptability.

Table 2.9: Hybrid approaches applied in SCRM.

Reference	SCRM Process I	A	M	M	Problem area	Approches (Empirical/analytical)	Decision Making	Methodology, Techniques and Modeling
[183]	•	-	-	-	Supplier selection	Welding industry	Yes	MCDM,F-VIKOR, DEMATEL-ANP
[178]	•	•	•	-	Supplier selection	-	-	Fuzzy AHP, Fuzzy TOPSIS
[186]	•	•	-	-	Sustainability	The oil industry in iran	Yes	Fuzzy MCDM, TOPSIS, Critic
[176]	•	•	-	-	Supply chain risk management	Telecommunications equipment and services company in China	Yes	Orders-of-magnitude AHP, Risk matrix
[83]	•	•	-	-	Supplier selection	Global IT company	-	Value-at-risk, Miss-the-target, MCDM, Goal Programming
[76]	•	•	•	-	Supply chain risk management	The Indian textile and steel industry	Yes	Fuzzy AHP, Fuzzy TOPSIS
[192]	•	•	-	-	Green SC, Sustainability, Risk analysis	Four companies	-	Fuzzy AHP
[179]	•	•	•	•	Supplier selection, Spot market	Real case of purchasing flash memory	Yes	Monte Carlo simulation, Goal programming
[193]	•	•	•	-	Risk mitigation strategies	Electronic manufacturing company 'XYZ' in India	-	Grey theory, DEMATEL
[194]	•	•	-	-	Sustainable supply chain management	Electronics firms listed in the base data of the stock market in Taiwan	Yes	MCDM, Interval-valued triangular fuzzy number
[188]	•	•	-	-	Sustainable supplier selection	Azar Resin Chemical Industrial	Yes	Fuzzy productivity value
[177]	•	•	•	-	Supply chain risk management, Risk assessment	Real case study	Yes	Cognitive map, MCDM, Neutrosophic AHP TOPSIS
[184]	•	•	-	-	Risk assessment	Chinese oil and gas companies	-	Fuzzy-grey comprehensive evaluation, AHP
[175]	•	•	-	-	Logistic provider	Agricultural supply chain in France	Yes	Fuzzy linguistic variables, Quality function deployment
[195]	-	•	-	-	Supply chain resilience	-	-	Hybrid fuzzy-probabilistic approach

I: identification A: assessment M: mitigation M: monitoringo

2.6 Overview of decision support system for SCRM

In this section of the thesis, we will provide an in-depth analysis of Decision Support Systems (DSS) in the context of SCRM. Specifically, we will examine how DSS can aid in the decision-making process to mitigate supply chain risks and improve SCRM performance. Our work will be based on the proposition of a DSS for Supply Chain Risk Management, which is specifically designed to help evaluate and assess risks in the supply chain.

The DSS utilizes advanced technologies to provide real-time data analysis and visualization tools to aid decision-making in SCRM. It enables organizations to identify potential risks in the supply chain, evaluate their impact, and take appropriate measures to mitigate them. The system also provides a platform for communication and collaboration between various stakeholders in the supply chain, including suppliers, distributors, and customers, to enhance the overall risk management process.

2.6.1 Decision support systems

The concept of a DSS has been defined as a computer-based system that consists of three interacting components, according to some scholars [196]. These components are not standalone entities, but rather work together to support decision-making processes, The three components of a DSS as defined by [196] are as follows:

- ***Language system:*** This component serves as a mechanism to facilitate communication between the user and other components of the DSS. It provides a user-friendly interface that allows the user to input and receive information in a manner that is easy to understand and use.
- ***Knowledge system:*** This component acts as a repository of problem domain knowledge and is embodied in the DSS as either data or procedures. The knowledge system is responsible for storing information related to the problem at hand, such as data on suppliers, inventory levels, and pricing information. It may also include procedures for analyzing and interpreting data to aid in decision-making.
- ***Problem-processing system:*** This component serves as a link between the other two components and contains one or more of the general problem-manipulation capabilities required for decision-making. It processes the information provided by the user through the language system and uses the knowledge system to generate solutions to the problem at hand. The problem-processing system may include mathematical models, algorithms, or other tools for analyzing and interpreting data. It also provides feedback to the user through the language system, allowing them to refine their inputs and obtain more accurate results.

DSS are computer-based tools designed to assist decision-makers in semi-structured decision-making tasks. According to Scott Morton [197], DSS aim to support rather than replace the judgment of decision-makers by providing them with relevant information and tools to aid their decision-making process. DSS can assist in improving the quality of decision-making by providing a structured and systematic approach to decision-making, and by enabling decision-makers to analyze and evaluate different scenarios and alternatives.

DSS are particularly useful in situations where decisions involve multiple criteria or factors that need to be considered, such as in supplier selection, risk management, and resource allocation. By providing decision-makers with access to relevant information and analysis tools, DSS can help reduce the level of uncertainty and ambiguity associated with decision-making.

While DSS can improve decision-making quality, they are not intended to replace human judgment entirely. Decision-makers still need to exercise their judgment and expertise in interpreting the information provided by DSS and making decisions based on their own experience and knowledge.

The foundation of the idea of decision support is based on the harmony between human judgment and computer processing. It is primarily a tool for formalizing decision-making processes and is used to tackle complicated problems by relying on models and data. However, it should be noted that it does not replace the decision-maker, but rather assists them in making informed decisions.

2.6.2 Decision-making levels

In order to effectively manage a supply chain, decision making is divided into three levels based on the time horizon for which decisions are made. These levels include strategic, tactical, and operational decision-making. At each level, different types of decisions are made based on the time horizon, scope of the decision, and level of detail involved. One critical aspect of decision-making at each level is risk management, as the potential for disruptions, uncertainties, and variability in the supply chain can have significant impacts on overall performance. Therefore, it is important to consider risk mitigation strategies at each level of decision-making to ensure the overall success and resilience of the supply chain. Some issues and work related to each decision level are listed in Figure 2.4.

- ***Strategic level:*** At the strategic level, all major decisions are consolidated. These decisions involve long-term plans (ranging from 6 months to several years) and provide direction and guidance for action, such as identifying new business partners, choosing suppliers and subcontractors, designating new areas for inventory storage in a distribution center, creating a new product, configuring and operating the supply chain, and establishing financial goals. This level involves making high-level decisions that set the direction of the supply chain. It is the responsibility of top-level managers and focuses on the big picture. At the strategic level, risk mitigation involves considering alternative scenarios and building flexibility into plans. Managers should evaluate the risks associated with different supply chain configurations and develop contingency plans in case of unexpected events. For example, companies may use scenario planning to assess the potential impact of geopolitical risks, changes in regulations, or natural disasters.

- ***Tactical level:*** The level of tactical decisions involves decisions that need to be implemented in the medium-term (ranging from a few weeks to a few months) to execute the company's strategy. These decisions focus on managing the company's resources and involve planning activities based on the available resources for a specific time period.

  The tactical level involves translating strategic decisions into actionable plans that can be executed by middle managers. It focuses on optimizing supply chain performance in the medium-term. Risk mitigation at this level involves balancing conflicting objectives such as cost, customer service, and inventory levels.

  Managers should use analytics and modeling tools to analyze data and optimize supply chain performance. They should also collaborate with suppliers and customers to align demand and supply and reduce the risk of disruptions. For example, companies may use predictive analytics to forecast demand and adjust production plans accordingly.

- ***Operational level:*** At the operational level, decisions are more focused in terms of scope and time, typically limited to daily or weekly decisions. Tactical decisions made at this level are aimed at creating detailed production or scheduling plans that are applicable at the workshop or logistics area level.

  The operational level involves executing plans on a day-to-day basis and ensuring that the supply chain runs smoothly. It is the responsibility of front-line managers and workers and focuses on short-term execution. Risk mitigation at this level involves developing processes and procedures that ensure that the supply chain runs smoothly.

  Managers should establish clear communication channels and response protocols to address unexpected events. They should also invest in technology and automation to improve efficiency and reduce the risk of errors. For example, companies may use real-time tracking and monitoring systems to track shipments and proactively identify potential disruptions.

The impact of a decision within a company can take various forms, and they can be broadly classified into two families: short-term impact and long-term effects. The former influences the physical resources available to the company, while the latter can lead to a change in the company's operating strategy. For example, if an important customer makes a request that the company cannot satisfy, it may result in losing the customer, leading to regrettable long-term effects on its sales, competitiveness, and brand image.

Decisions taken internally typically result in changes in the company's immediate environment, including customers and direct suppliers. However, as these decisions spread, their effects can extend to all partners in the supply chain. Therefore, it is crucial to consider the potential impacts of decisions on all stakeholders, including partners in the supply chain, to ensure long-term success and sustainability.

2.6.3 Comparison between the steps of a DSS and the SCRM

The decision-making process involves a sequence of predefined steps, consisting of four main phases: problem definition, alternative generation, alternative selection, and implementation of the chosen alternative.

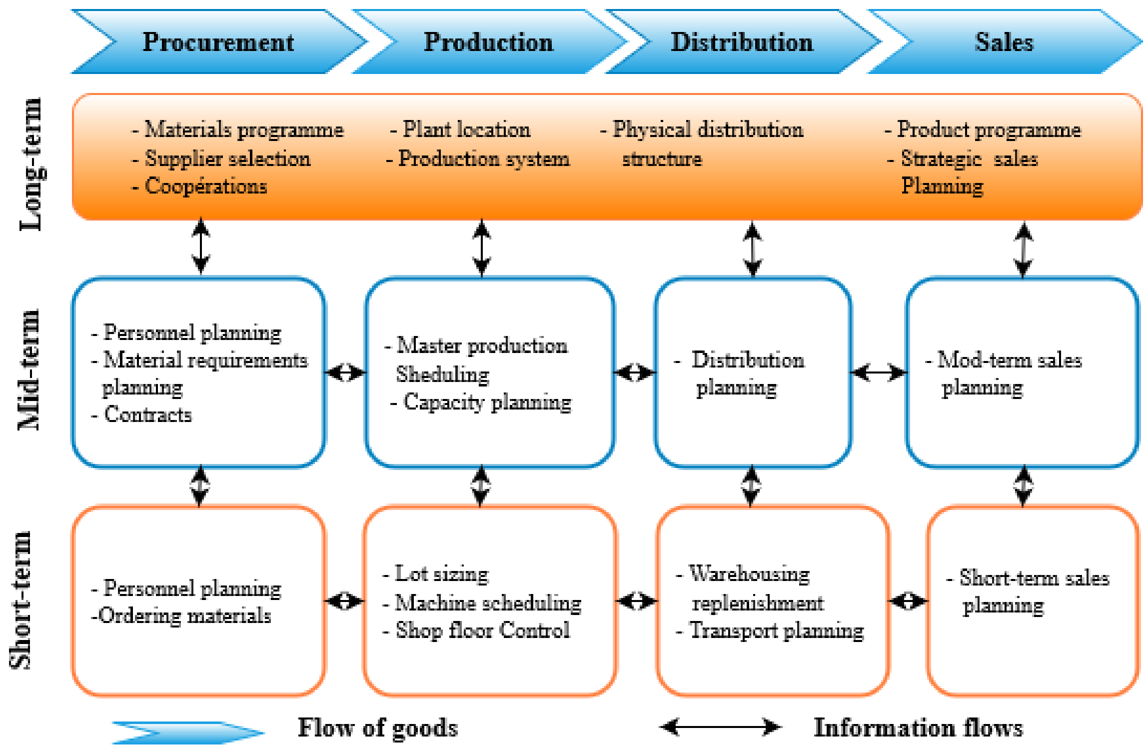


Figure 2.4: Decision levels in the supply chain.

The first stage of the decision-making process is the generation phase, during which all possible alternatives are identified and selected for later comparison. This step should be carried out carefully to exclude impossible solutions and ensure all necessary information is collected.

The second stage of the process is the sorting phase, where the potential solutions are classified according to predetermined criteria. Each solution is evaluated based on its performance in terms of meeting the decision maker's objectives. The subjectivity of the decision maker plays a significant role in this stage through the weighting of selection criteria and comparison of performance with personal preferences.

The third stage of the process is the choice phase, which is often the most challenging due to the conflicting nature of different objectives and uncertainties. Once the choice is made, it is important to document the information gathered to provide feedback that can be utilized in future decisions.

Although there is significant overlap between the decision support system process and the SCRM procedure, there is currently no unified decision support methodology that integrates the numerous existing methods, approaches, and techniques to assist managers in the risk management procedure.

Although there are notable differences between a DSS and SCRM, they both share similarities in their decision-making approach as mentioned in Figure 2.5. Both involve a systematic process that follows several steps. In a DSS, the steps include data collection and analysis, model development, solution generation, solution validation, and solution implementation. Similarly, the SCRM process involves identifying risks, assessing the likelihood and poten-

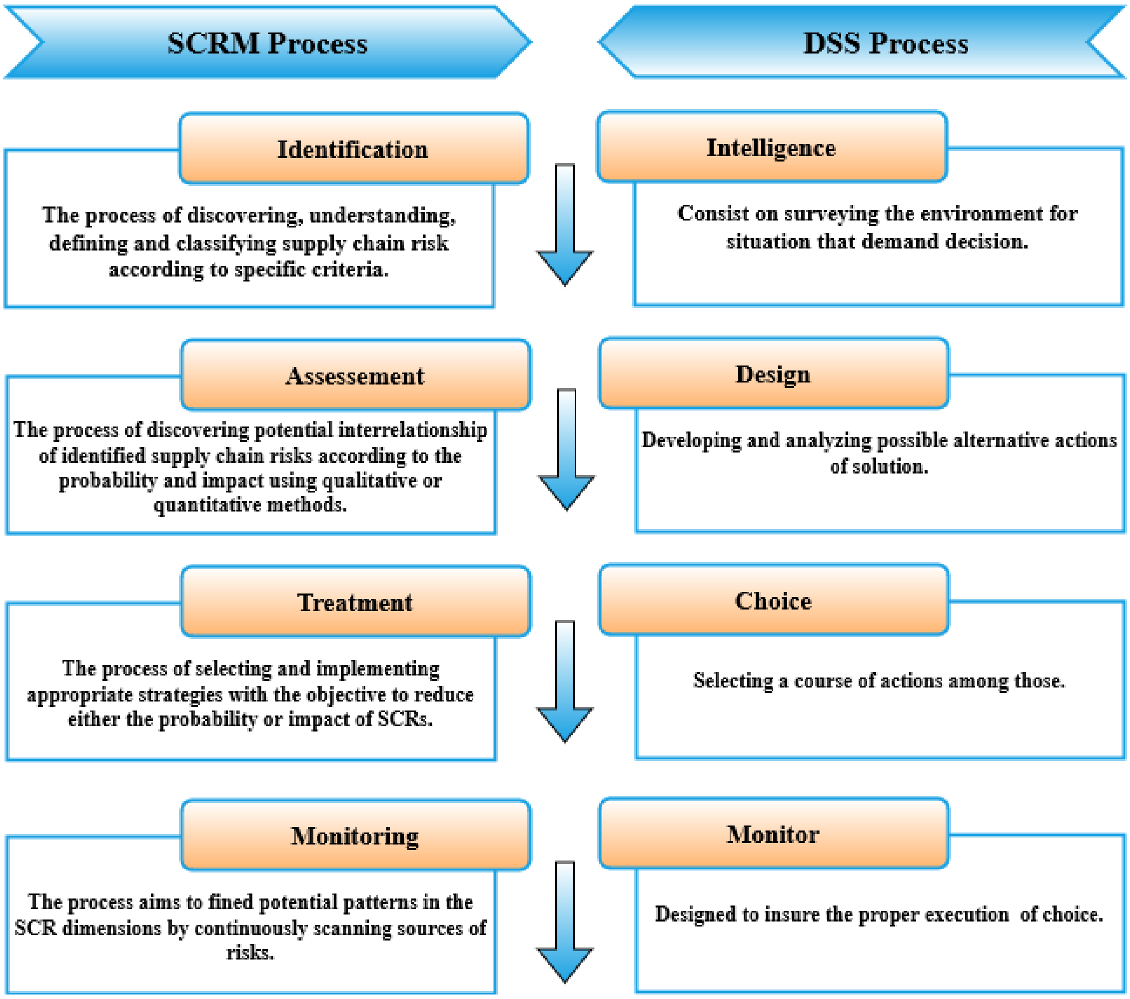


Figure 2.5: Comparison between the decision support system process and the SCRM process.

tial impact of those risks, developing strategies to mitigate those risks, implementing those strategies, and monitoring their effectiveness.

While a DSS is designed to support decision-making across a wide range of business functions, SCRM specifically focuses on managing risks in the supply chain. Moreover, while a DSS can support decision-making at all levels of an organization, SCRM is primarily concerned with operational and tactical decision-making within the supply chain. Despite these differences, both DSS and SCRM can help organizations make informed decisions that minimize risk and maximize performance. By leveraging data and analytical tools, organizations can gain valuable insights into their supply chain operations and make more effective decisions to manage risks and enhance overall performance.

2.6.4 Literature mapping through bibliometric network

Literature mapping through bibliometric network analysis is a method that allows for the visualization of relationships between articles and their authors. This method involves the use of citation analysis and data mining to identify key articles, authors, and research topics within a given field. By mapping out these relationships, researchers can gain a better understanding of the evolution of research in a particular field and identify areas where additional research is needed. This approach has been used in various fields, including supply chain management, to track the growth and development of research over time. By applying this method to the study of decision support systems in supply chain risk management, researchers can gain insights into the most influential articles and authors in the field and identify emerging research trends.

Figure 2.6 illustrates the trend in the number of articles mentioning decision support systems in the context of supply chain risk, sorted by year of publication from 2003 to 2023. The graph reveals a gradual increase in the research community's interest in decision making and decision support in the supply chain over time. Boolean logical operators (AND/OR) were utilized to refine the search by combining keywords. The search query employed the terms "supply chain risk*" AND ("decision support" OR "decision support system" OR "decision support systems" OR "decision making") to retrieve articles from the Scopus database. The selection process involved screening the titles and abstracts of the articles to identify the most relevant manuscripts for review. A total of 8,774 articles published in 160 different journals were selected and reviewed. By the end of 2022, the number of published articles on this topic had reached 1,870, as depicted in Figure 2.6. This clearly demonstrates the growing interest of the scientific community in this field of research.

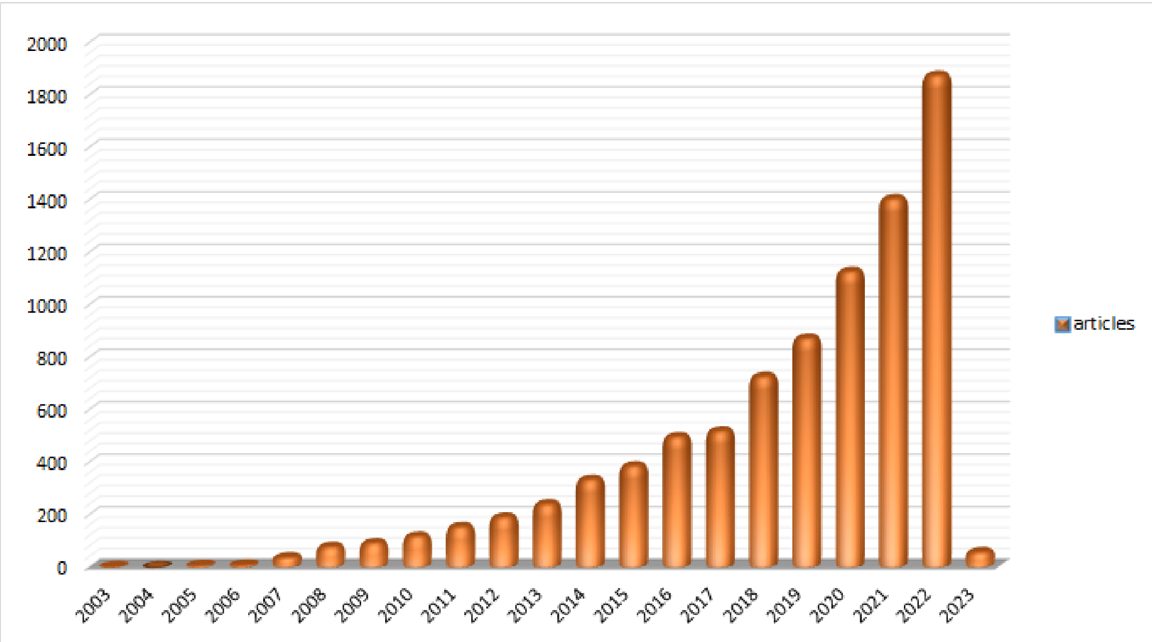


Figure 2.6: Distribution of the number of articles dealing with DSS in SC

The papers that were analyzed had been published across 160 distinct academic journals. These journals are predominantly indexed by Scopus or are housed in reputable libraries, including Springer, Elsevier, Taylor & Francis, and Emerald, as indicated in Table 2.10.

To do the bibliographic analysis, the articles chosen from the Scopus database were imported into the VOSviewer® 1.6.18 software in CSV format.

VOSviewer is a bibliometric mapping and network analysis tool that allows researchers and practitioners to visualize and analyze the relationships between scientific publications,

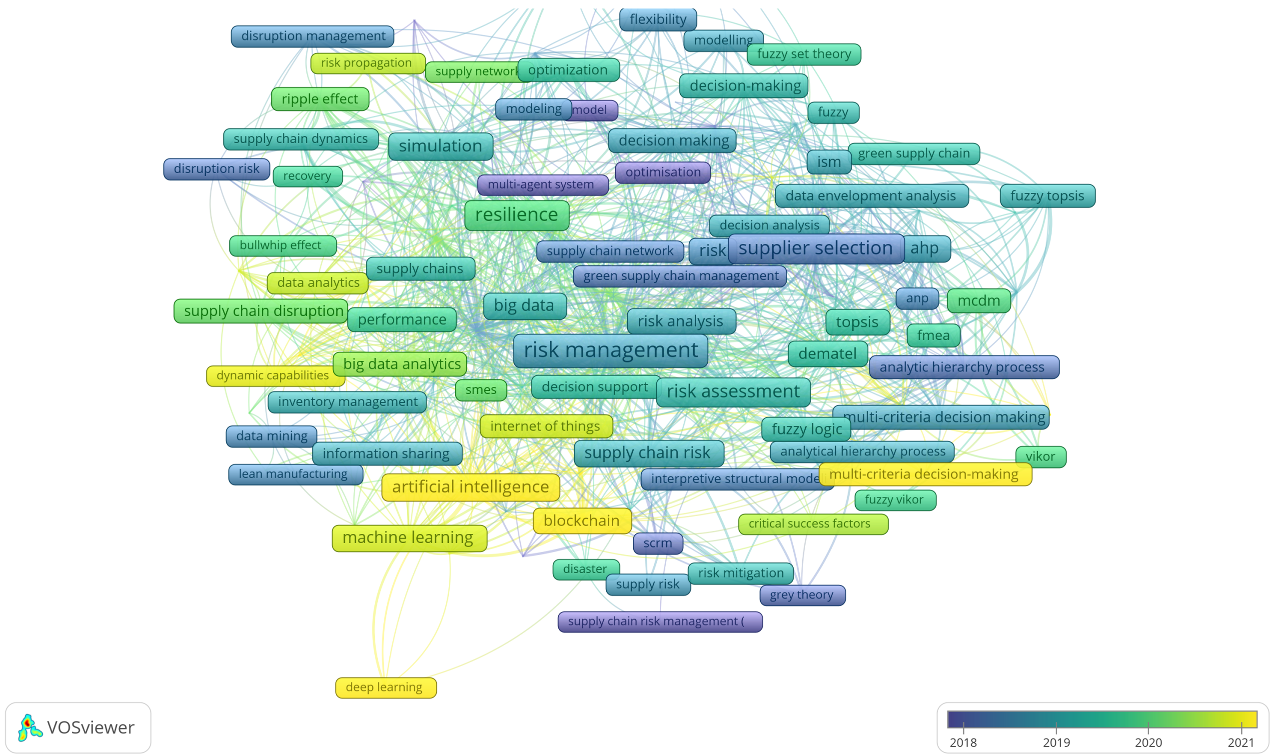


Figure 2.7: VOSviewer network of co-word on DS models for SCRM.

Table 2.10: Main papers published on DSS by journal and publisher (2003 to 2023).

Journal	Impact factor*	No. of papers	Publisher
International Journal Of Production Research	2,78	340	Taylor and Francis.
International Journal of Production Economics	2,81	243	Elsevier
Journal Of Cleaner Production	1,92	183	Elsevier.
Computers And Industrial Engineering	1,78	151	Elsevier.
Annals Of Operations Research	1,17	129	Springer Netherlands
Benchmarking	0,89	125	Emerald Group Publishing.
International Journal Of Logistics Management	1,5	101	Emerald Group Publishing.
Supply Chain Management	2,39	95	Emerald Group Publishing.
Production Planning And Control	1,66	92	Taylor and Francis.
Transportation Research Part E Logistics And Transportation Review	2,84	92	Elsevier.
International Journal Of Logistics Systems And Management	0,36	76	Inderscience Enterprises.
Industrial Management And Data Systems	1,01	74	Emerald Group Publishing.

authors, institutions, and keywords. VOSviewer provides a comprehensive platform for mapping and analyzing the structure and evolution of scientific fields and subfields, as well as for analyzing collaboration patterns and author productivity.

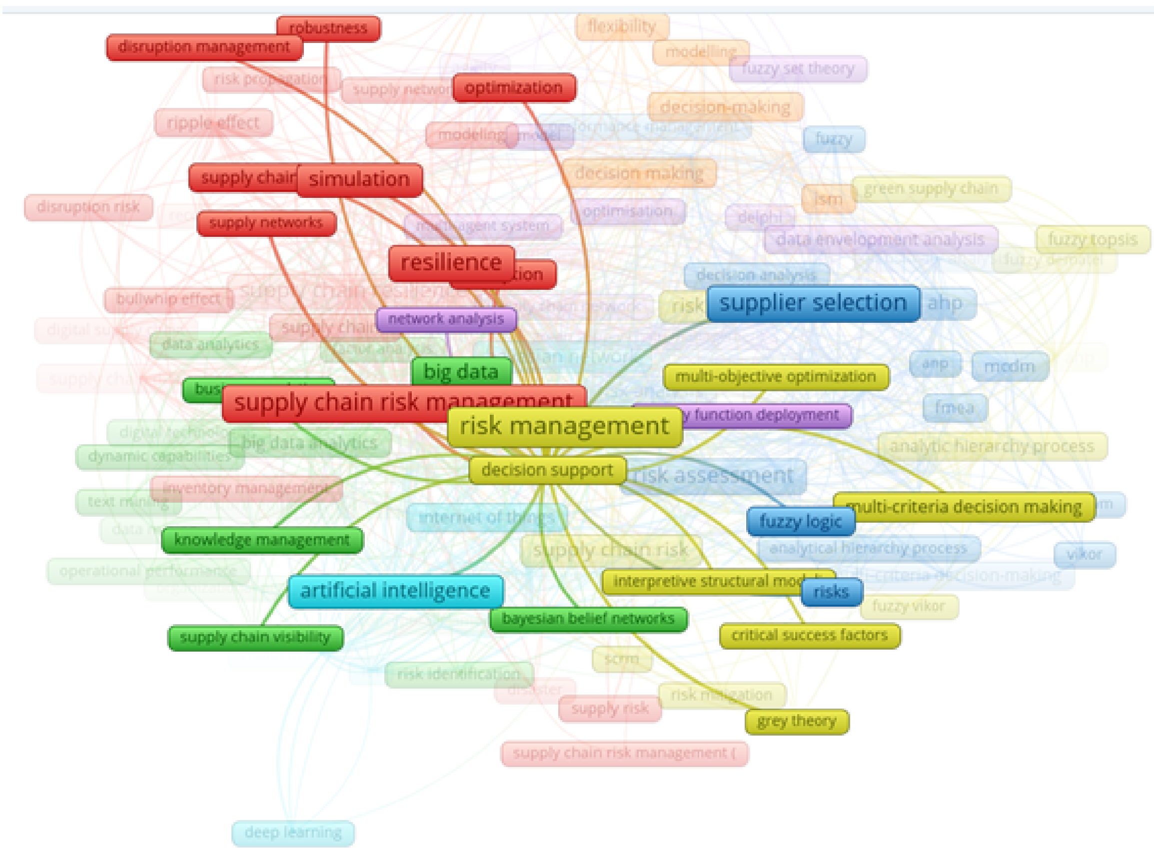


Figure 2.8: Highlighting of the most important decision support methods by Vosviewer.

VOSviewer is a tool that functions by gathering data from multiple sources, including bibliographic databases like Scopus and Web of Science. It then creates a network map that displays the connections between scientific entities, such as authors, institutions, and keywords. These entities are represented by nodes and the connections are represented by edges. VOSviewer provides several tools for analyzing the network, including measures of centrality, community detection, and cluster analysis. The tool is customizable and is widely used in bibliometrics, information science, and science of science research.

The choice to use VOSviewer was based on its ability to handle large amounts of data and provide a range of visualization, analysis, and search options. The nodes in a bibliometric network can represent anything from authors to journals to keywords, and the edges represent the connections between them as presented in [198]. The VOSviewer program places the nodes in a way that reflects their degree of relatedness, with closer nodes indicating a stronger relationship. Overall, VOSviewer is a useful tool for exploring scientific fields and analyzing the relationships between scientific entities in a network perspective. First, we conducted a mapping exercise of decision-making models and support systems for SCRM from 2003-2023. We utilized the co-word analysis method, which allows for the identification and construction of a discipline's identity. In total, 7274 keywords were identified from the selected CSV files using VOSviewer's "co-correlation" map, "all keywords" analysis unit, and "complete count" approach. To streamline the co-word network, we limited the number of terms to 200, with each keyword requiring at least 10 citations to be included. We excluded keywords that were not directly related to SCRM decision-making models and support systems, resulting in a list of representative keywords. We grouped these keywords into clusters based on their total co-occurrence link strength, as shown in Figure 2.7 and Figure 2.8. The figures display co-word networks in different colors, representing clusters of the most frequently used decision-making methods in SCRM.

When we used the co-word technique to map the literature, we discovered that the most frequently used methods for multicriteria decision making are MCDM (n = 95), Analytical Hierarchy Process-AHP (n = 117), Artificial intelligence (n = 73), Simulation (n = 75), Topsis (n = 54), Fuzzy Logic (n = 52), Sensitivity Analysis (n = 20), Bayesian belief networks (n = 52), vikor (n = 12), and several others.

Overall, our analysis using co-word analysis has revealed that a wide range of decision-making methods and support systems have been used in the field of Supply Chain Risk Management. Among these, multi-criteria decision-making, Analytical Hierarchy Process, and Artificial Intelligence have emerged as the most commonly used methods. While these methods differ in their approach and application, they share the goal of enabling organizations to make informed decisions that minimize risk and maximize performance in the supply chain. By identifying these key methods, our study can help researchers and practitioners to better understand the landscape of decision-making in SCRM and provide insights for future research in this area.

2.6.5 Literature review

To reduce complexity, decisions are made even in completely uncertain situations. The fundamental challenges in decision making include optimality, multiple objectives, risk, uncertainty, and complexity. In recent years, there has been a significant shift in the focus of DSS towards risk assessment. Both industry experts and scholars are advocating for the development of DSS to assist businesses in evaluating their SCRs and selecting appropriate mitigation strategies [52].

To summarize, the research on DSS for SCRM is still in its early stages. For instance, [199] has created an AHP model to aid the automotive industry in selecting suppliers, with decision-making issues addressed through expert choice software. [76, 200] have used structured techniques to evaluate risk probability employing AHP and fuzzy-TOPSIS. [97] has also established a method that combines fuzzy AHP with fuzzy TOPSIS algorithm to aid in decision-making. Although AHP can be an appropriate option, it is insufficient to link customer values to the decision-making process.

An original DSS for the design, management and control of warehousing systems with solid Database Management System (DBMS) architecture have been developed by [201], the benefits due to the adoption of that DSS were summarized as a dashboard of key performance indicators. Adding to [179] had proposed a novel decision support framework which helps the buyer to make optimal and robust procurement decision.

As per [120], it is important to combine various decision support techniques into a strong system that can help professionals dealing with complex decisions involving multiple stakeholders and objectives amidst uncertainty. Additionally, the importance of analytical MCDM tool has been confirmed by [202]. Another study by [35] introduced a two-step DSS methodology for mitigating SCRs.

Some academic articles have used game theory to tackle the SCRM problem, particularly when considering competition between two supply chain plans, as mentioned in reference [64]. For example, reference [203] developed a comprehensive decision support system framework that includes the identification, assessment, and analysis of risk networks. In addition, reference [204] applied game theory to study the competition between two closed-loop supply chains that involve manufacturers, retailers, and recyclers in uncertain environments.

Recently, there has been a push to advance the field of SCRM. For instance, in [205], an intelligent purchasing decision support system was proposed for small retailers. In addition, [206] conducted a comprehensive analysis of strategies and decision-making practices related to the impact of terrorism risks on SCRM and security. Furthermore, [144] developed a multi-phase, intelligent decision support system that is based on knowledge and is designed to manage operational risks across the complete supply chain. It should be noted that their study primarily concentrates on the operational decision-making stage.

Table 2.11 displays a summary of DSS for SCRM mentioned in this section with respect to the SCRM process, approaches, industry type treated in a case study and methodology.

From the summary it can be note that most studies were mainly focused on the assessment of the SCR profile but did not improve the selection of effective mitigation measures to abridge the risk of this risk [76]. It can be mentions that there is not an effective DSS that able the supply managers to select appropriate mitigation actions when a threat of risks occurs. So they just focus on one stage of SCRM process as [189, 207, 208].

Overall, it has been noted that numerous papers have focused on either an individual or an integrated decision-making model, without necessarily developing an effective DSS [175]. Each research concentrate on a single problem and the most treated is the supplier selection as presented in table 2.11 [29, 209, 210, 211].

Some works [29, 209] take into consideration the relationship between profit and cost. But most of the works doesn't make an evaluation of the chain's performance and also doesn't show the increase in profits and the reduction of the overall costs of the SC after the application of their methodologies as [212]. Then, It can be saying that is an area that still lacks work and deserves more interest because it is profitable.

One idea related to the lack of real-time reaction to risks is the absence of up-to-date information in decision-making processes. Many businesses have systems in place to collect data on risks, but this information is often not updated frequently enough to be useful in real-time decision making. This can lead to delayed reactions to emerging risks and missed opportunities to mitigate them.

For example, if a business only updates its risk assessment once a year, it may miss important changes in the risk landscape that occur between assessments. In contrast, a system that provides real-time risk monitoring and analysis can help businesses quickly identify and respond to emerging risks. Such a system can also help businesses evaluate the effectiveness of their risk mitigation strategies and adjust them in real-time based on actual information, rather than relying on outdated data.

Table 2.11: Decision Support Systems (DSS) used in SCRM.

Reference	SCRM Process				Approche (Empirical/analytical)	Problem area	Methodology	DSS (S, T, O)
	I	A	M	M				
[199]	•	-	•	-	Automotive industry	Supplier selection	AHP+ MCDM	S
[35]	•	•	•	-	Offshore-wind industry	Decision framework	Decision trees	-
[202]	•	•	-	-	Office buildings	Facilities management	Fuzzy MCDM	O
[203]	•	•	-	-	-	Supply uncertainty	Game theory	S
[179]	•	•	•	•	Semiconductor	Supplier selection & order allocation	Monte Carlo simulation and Goal programming	-
[211]	•	•	•	-	Confectionary company	Supplier selection	fuzzy-AHP, fuzzy TOPSIS, MCDM	S
[189]	-	•	-	-	-	Accounts receivable	Data mining	-
[212]	•	•	•	•	IT organization	Risk Mitigation	Software agents, knowledge mapping	O
[209]	•	•	-	-	-	Supplier selection & order alocation	Simulation, optimisation model	-
[144]	•	•	•	-	Electronics company in South Korea	Operational risk management	Knowledge-based DSS, Swarm optimization, PSO	O
[210]	-	-	-	•	Numerical application	Supplier selection	Mixed integer linear programming	S
[120]	•	•	-	-	Bioenergy industry	Supplier selection and order allocation	Combined AHP-QFD	S
[207]	•	•	-	-	Multimodal green logistics	Multimodal green logistics	DEA, AHP	O
[208]	•	•	-	-	Airbus Defense and Space	Crisis management	Multi-agent system	S
[29]	•	•	•	•	Automotive	Supply side risks	Linear programming	-
[213]	•	•	•	-	An example application	Supply chain network topology	Simulation	O
[214]	•	•	•	-	-	Critical materials	-	-
[215]	•	•	•	-	Case from the Australian textile industry	Uncertainty of an inventory system	Simulations	O
[204]	•	-	-	-	Battery market	Uncertain environment	Game theory	S and T
[216]	-	-	•	-	Numerical examples	Dual sourcing	Mathematical	O

I: identification A: assessment M: mitigation M: monitoring S: Strategic T: Tactic O: operational

2.7 Conclusion

Although some authors denounce "the hope of mechanizing decision-making", the representation of the decision-making process remains an important issue to better understand and thus better help decision-makers in their daily work.

But what then is the role of this standardization? Identification - assessment - treatment, called risk management, if not a rule that ensures that the components of the decision process are in the right order and each one is the "best possible".

Starting from the principle that "the decision begins where the calculation ends", we have concluded that any decision related to the management of cooperation in supply chains contains a mandatory risk component. The risk management process is therefore considered as an approach that must be followed in order to make "good" decisions.

The starting point of our study was the definition of supply chain risk management. We have tried to enrich and complete this definition by bringing not only an intra-organizational but also, and more importantly, a cross-organizational view in the context of a supply chain.

This chapter has a dual purpose. On the one hand, it allows us to present the current state of the art on the notions of decision-making, risk and risk management in the supply chains. On the other hand, based on this state of the art, it allows us to conclude on the role of DSS to support the management of collaboration within supply chains.

In the context of SCM, the tools used to identify and characterize risks, and classify them into different categories, are not fundamentally different from general approaches such as expert opinion, brainstorming, risk matrix, simulation, among others. However, the challenge arises when dealing with uncertainty, contradictory and incomplete information, which are common in SCRM. Therefore, in this study, a novel approach will be adopted to address this challenge, by using neutrosophic logic as the main tool for dealing with uncertainty and incomplete information. Neutrosophic logic is an extension of fuzzy logic that has been developed to handle information that is simultaneously indeterminate, contradictory, and imprecise. A detailed explanation of neutrosophic logic and its application in SCRM will be presented in the next chapter of the thesis. The main objective is to collect and analyze uncertain, inaccurate, and contradictory information in real-time, to facilitate effective risk assessment and decision-making.

Chapter 3

Methodological tools

Chapter 3

Methodological tools

Contents

3.1 Introduction

THIS chapter presents the methodological tools essential for the development of the approaches proposed in the context of this thesis.

Mono-criteria optimization aims to determine an optimal solution, which maximizes or minimizes the objective considered. However, in the majority of decision-making scenarios, this model is insufficient to capture the issues we encounter, because the decision-maker frequently tries to accomplish a number of goals that may be at odds with one another.

The first section of this work provides a detailed explanation of Neutrosophic logic and its significance in handling uncertain and contradictory information. Neutrosophic logic is a valuable tool that can be used to model and analyze fuzzy and ambiguous data in various fields, such as medicine, engineering, and finance. In the following section, we introduce the Analytic Hierarchy Process (AHP), which is a popular multi-criteria decision-making technique that is widely used to address complex decision-making problems. We explain the fundamental concepts and principles of the AHP approach and the reasons behind our decision to use the Neutrosophic AHP approach, which combines the strengths of both Neutrosophic logic and AHP to handle complex decision-making problems involving hazy and amorphous data. The Neutrosophic Data AHP approach has been extensively applied in various fields and has proven to be effective in addressing complex decision-making problems. By combining these two approaches, we can provide decision-makers with a more reliable and accurate analysis of alternatives, and help them arrive at better-informed decisions. In the subsequent chapters, we will demonstrate the effectiveness of this approach in practical decision-making situations.

3.2 Neutrosophic logic

We know that in classical double-valued logic, the variable takes one of two values 0,1 , i.e. true, false only, but with the passage of time and the development of science, it has been observed that true and false alone are not enough to represent all logical forms, so scientist Lotfi Zadeh in 1965 introduced the concept of fuzzy set theory [217] to deal with these problems . Then, at the end of the eighties, many ideas appeared in this field, which called everyone to pay attention to it, What distinguishes the fuzzy set from the classic group is that it allows an element to belong partially, while the classical group element belongs to it or does not belong to it at all, and after that, Atanasoff in 1983 [218] introduced intuitionistic fuzzy set as a generalization of fuzzy sets, where Atanasoff added to the definition of the fuzzy group as a New component, the degree of non-membership, fuzzy groups give the degree of membership of an element of a group (and the degree of non-membership =1 - degree of membership), while the intuitionistic fuzzy set intuitively give the degree of membership and the degree of non-membership each of them independently of the other, the condition is that the sum of these two scores is not greater than one. The figure 3.1 accompanying this work illustrates the progression of logics over time.

Here is the definition of Fuzzy Set and Intuitionistic Fuzzy Set.

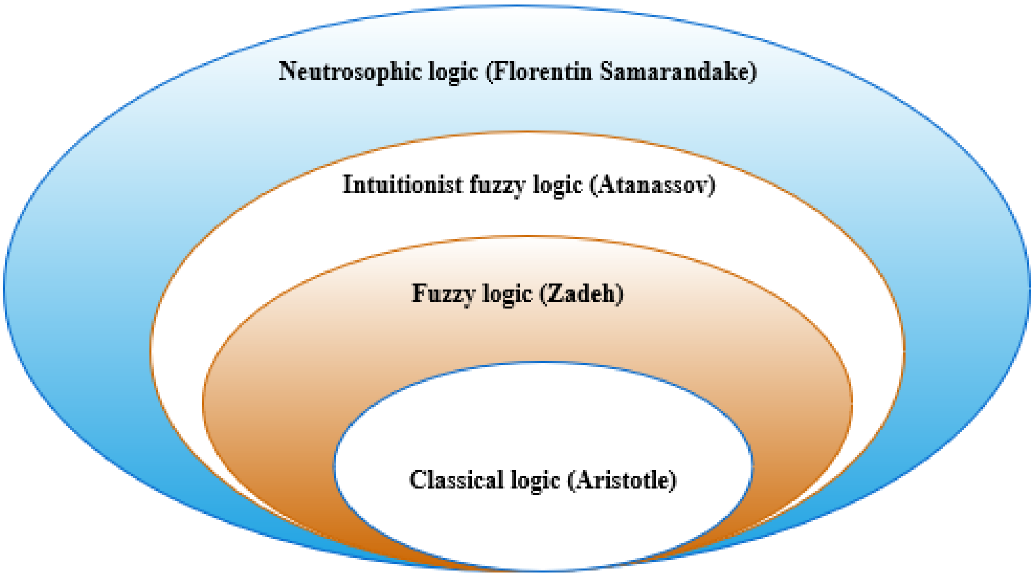


Figure 3.1: The progression of logics

3.2.1 Fuzzy set

According to [219], the basic idea of fuzzy logic is to define the truth value (T) of an assertion by a number which varies between 0 and 1 progressively, unlike classical binary logic which only manipulates the values 0 and 1. The theory of fuzzy subsets used by fuzzy logic is different from classical and binary set theory, fuzzy logic is a set of mathematical principles for the representation and manipulation of knowledge based on degrees of membership T(x) included in [0,1], This logic is based on the theory of fuzzy sets invented by Lotfi Zadeh [217].

Let X be a non-empty finite set, the fuzzy set A of X has the form:

$$A = \{(x, \mu_A(x)); x \in X \ \ \& \ \ \mu_A(x) \in [0,1]\} \tag{3.1}$$

$Wherefunction\ \mu_A : X \rightarrow [0,1].$

It represents the degree of membership of the elements x $(x \in X)$ in group A.

- If it was $\mu_A(x_0) = 1$, then we say: x_0 belongs to A.
- If it was $\mu_A(x_1) = 0$, then we say: x_1 does not belongs to A.
- If it was $\mu_A(x_2) = 0.4$, then we say that the membership value of x_2 in A is 0.4

When it is always equal to zero or one we get the classical group in X.

3.2.2 Intuitionistic fuzzy set

The basic idea of intuitionistic fuzzy logic is to characterize each logical assertion in a 2D space, where each dimension of the space represents, respectively, the truth (T) and the false (F) of the assertion under consideration, where T, F are the real subsets.

A collection of mathematical principles has been formulated for the purpose of representing and manipulating knowledge, utilizing degrees of membership represented by the function T(x), as well as non-membership denoted by the function F(x), both of which are contained within the range [0,1]. This logic has been based on the theory of intuitionist fuzzy sets, which was introduced by Atanassov in 1988 [218].

Let X be a non-empty finite set, the intuitionist fuzzy set A of X has the form:

$$A = \{(x, \mu_A(x), V_A(x)); x \in X \ \ \& \ \ \mu_A(x) \in [0,1], V_A(x) \in [0,1]\} \tag{3.2}$$

$Where\ \mu_A : X \to [0,1].$

$Where\ V_A : X \to [0,1].$

Define, in order, the degree of membership and the degree of inorganicity of element x in group A, and it is:

$$0 \leq \mu_A(x) + V_A(x) \leq 1\ So \tag{3.3}$$

$$\pi_A(x) = 1 - (\mu_A(x) + V_A(x)) \tag{3.4}$$

is called the degree of frequency for x in A, with $0 \leq \pi_A(x) \leq 1.$

In addition to the explanation of intuitionistic fuzzy sets, it is worth noting that intuitionistic fuzzy sets have an advantage over fuzzy sets in that they allow for a more flexible and nuanced representation of uncertainty. With fuzzy sets, an element can only belong partially or not at all, while with intuitionistic fuzzy sets, an element can also have a degree of non-membership, which represents the degree to which the element is not a member of the set. This additional degree of non-membership allows for a more nuanced representation of uncertainty, making intuitionistic fuzzy sets particularly useful in decision-making scenarios where uncertainty is a significant factor.

In 1995, Florentin Smarandache, a Romanian-American mathematician and philosopher, introduced neutrosophic logic [220] as an extension of fuzzy logic, specifically intuitive fuzzy logic. Smarandache introduced a new component to the degrees of belonging and non-belonging called the degree of indeterminacy.

The benefit of adopting neutrosophic logic is that it makes a distinction between absolute truth, which is a truth in all conceivable worlds, rated as 1^+, and relative truth, which is a truth in one world only, designated by 1, where $1^+ > 1$. And similarly, neutrosophic logic distinguishes between the absolute falsehood, denoted 0^-, and the relative lie, marked 0, in the same situation, where $0 > 0^-$.

We can express it in the form:

$^{-}0 = 0 - \xi$, $1^+ = 1 + \xi$

Where ξ is a very small positive number.

- In neutrosophic logic, the sum of the components is not necessarily 1 as in classical and fuzzy logic, but any number between $^{-}0$ and 3^+, which allows neutrosophic logic to be able to deal with paradoxes, propositions which are true and false at the same time: thus $\boldsymbol{NL(paradox) = (1, I, 1)}$. Fuzzy logic cannot do this because in fuzzy logic the sum of the components must be 1.
- In neutrosophic logic, in a simple way, each logical variable x is described by an ordered triple. $\boldsymbol{x = (t, i, f)}$ where $\boldsymbol{t}$ is the degree of truth, $\boldsymbol{f}$ is the degree of false, and $\boldsymbol{i}$ is the level of indeterminacy. As featured in[221].

  In which:

  1. Neutrosophic logic preserves consistency with classical logic and fuzzy logic in the particular case when: $\boldsymbol{t + i + f = 1}$.
  2. In the case of incomplete information about the variable it has: $\boldsymbol{t + i + f < 1}$.
  3. In the case of contradictory information about the same variable then: $\boldsymbol{t + i + f > 1}$.

The table 3.1 presents an in-depth comparison of various types of logic, highlighting their similarities and differences. More generally, Samarandakha defined the neutrosophic components by form, as described in the reference [221].

Suppose a company is trying to evaluate the feasibility of a new project. The company has gathered some information about the potential market demand for the project, but the information is incomplete and contradictory.

Incomplete Information: The company has surveyed a sample of potential customers and found that 30% of them are interested in the project, but they are unsure about the level of interest among the broader population. They estimate that there is a 30% chance that the true level of interest is higher, a 10% chance that it is lower, and a 50% chance that it is the same as the sample.

Using neutrosophic logic, the company can represent the degree of truth, indeterminacy, and falsehood for the market demand variable as follows:

$(\text{market demand}) = (0.3, 0.5, 0.1)$

The sum of the truth, indeterminacy, and falsehood values is less than 1, which satisfies the first rule of neutrosophic logic for incomplete information.

Contradictory Information: The company has also gathered some expert opinions about the potential market demand for the project, but the opinions are conflicting. One expert believes that there is a high level of interest in the project, while another expert believes that the project is unlikely to be successful. The company estimates that there is a 50% chance that one expert is right, a 30% chance that they are both partially right, and a 40% chance that they are both wrong.

Using neutrosophic logic, the company can represent the degree of truth, indeterminacy, and falsehood for the expert opinions variable as follows:

(expert opinions) = (0.5, 0.3, 0.4)

The sum of the truth, indeterminacy, and falsehood values is greater than 1, which satisfies the second rule of neutrosophic logic for contradictory information. The company can then use these neutrosophic tuples to combine the information and make a decision about the feasibility of the project. For example, the company might define a variable called (feasibility) and use the neutrosophic operator AND to combine the market demand and expert opinions variables:

(feasibility) = (market demand) AND (expert opinions)

The resulting neutrosophic tuple for (feasibility) will capture the uncertainty, incompleteness, and contradiction in the information that the company has gathered and provide a more nuanced and comprehensive view of the feasibility of the project.

Also, let's take the example of a production company that uses raw materials from various suppliers. The company must ensure that the raw materials it purchases are of good quality and meet safety standards. However, the company may receive contradictory or incomplete information about the quality of the raw materials provided by some of its suppliers.

In this case, neutrosophic logic can be used to evaluate the risk associated with using these raw materials in the company's production process. Each raw material can be considered as a logical variable with a degree of truth, a degree of falsehood, and a level of indeterminacy.

For example, for a given raw material, the degree of truth can be evaluated at 0.7, which means that the company has received information indicating that the raw material is of good quality at 70%. The degree of falsehood can be evaluated at 0.1, which means that the company has received information indicating that the raw material is not of good quality at 10%. The level of indeterminacy can be evaluated at 0.2, which means that the company has not received clear information about the quality of the raw material at 20%.

Using neutrosophic logic, the company can evaluate the risk associated with using this raw material by taking into account these degrees of truth, falsehood, and indeterminacy. For example, if the degree of truth is low and the level of indeterminacy is high, the company may decide not to use this raw material in its production process in order to reduce the risk associated with the quality of the finished product. If the degree of truth is high and the level of indeterminacy is low, the company may decide to use this raw material but take additional measures to monitor the quality of the finished product.

3.3 Neutrosophic components

In this section, we briefly retrospect some basic definitions that will be used in our proposal.

Let **T, I, F** be normal or non-normative real subsets of the non-normative domain $]^{-}0, 1^{+}[$ with:

$supT = t_{sup}$, $infT = t_{inf}$

$supI = i_{sup}$, $infI = i_{inf}$

$supF = f_{sup}$, $infF = f_{inf}$

And will have:

$n_{sup} = t_{sup} + i_{sup} + f_{sup} \leq 3^{+}$

$n_{inf} = t_{inf} + i_{inf} + f_{inf} \geq^{-} 0$

And therefore:

$^{-}0 \leq n_{inf} \leq n_{sup} \leq 3^{+}$

And these groups T, I, F do not have to be domains, they can be any partial groups, and these groups can be continuous or discontinuous, made up of one or more elements, finite, countable or uncountable, assembly or intersection of partials groups, ...

From truth, falsity, and indeterminacy, we can divide T into partial components, denoted by $T_1, T_2, \ldots, T_m$, and likewise, we divide I into partial components $I_1, I_2, \ldots, I_r$, and F into partial components $F_1, F_2, \ldots, F_p$.

Such that the sample size $n = p + r + m$.

And thus it becomes:

$(T, I, F) = (T_1, T_2, \ldots, T_m; I_1, I_2, \ldots, I_r; F_1, F_2, \ldots, F_p)$

The ambiguity and inaccuracy of information, whether in knowledge of truth, in the absence of determination or in error, is the reason why the components T, I and F are in subsets.

- For example: In the context of neutrosophic logic, the statement ***"Tomorrow it will rain"*** does not have a fixed truth value. It could have a truth value of 40%, an indeterminate value of 50%, and a false value of 45% at time t1. However, this truth value can change at a later time, for instance, at time t2, it could become 50% true, 49% indeterminate, and 30% false due to new evidence or sources. Furthermore, the same proposition may have a truth value of 100%, an indeterminate value of 0%, and a false value of 0% at time t if it actually rains on that day.
- In other examples: the proposition ***"It's raining"*** can have different truth values in different places. For instance, in Oum el Bouaghi, it might be 0% true, 0% indeterminate,

and 100% false, while in Constantine, the truth value could be (1, 0, 0). This highlights how truth values are influenced by contextual factors and can vary based on the situation.

- Additionally, it should be noted that truth values can also vary depending on the observer, thereby highlighting the role of subjectivity as another parameter of the functions or operators T, I, F. For instance, the proposition ***"John is smart"*** could be assigned different truth values by different observers. According to John's boss, it might be (0.35, 0.67, 0.60), while John himself might assign it a truth value of (0.80, 0.25, 0.10). Meanwhile, John's secretary might assign it a truth value of (0.50, 0.20, 0.30), underscoring the subjective nature of truth values.

T, I and F are called neutrosophical components, representing the values of truth, indeterminacy and falsehood referring to neutrosophy, neutrosophical logic, neutrosophical set, neutrosophical probability, neutrosophical statistics respectively. This representation is closer to the reasoning of the human mind. It characterizes and captures imprecision of knowledge or linguistic inaccuracy perceived by various observers (this is why **T, I, F** are subsets and not necessarily unique elements), uncertainty due to incomplete knowledge or errors of acquisition or stochasticity (this is why the subset **I** exists), and fuzziness due to the absence of clear outlines or boundaries.

In fact, neutrosophic logic can be seen as a more accurate representation of the world we find ourselves in. Few things are absolute, in fact mathematics is one of the few areas where something is known with certainty. The indeterminate input recognizes that the values given for the true and false inputs are generally not known with certainty.

To represent statements that are partially true, partially false, and partially indeterminate, neutrosophic logic uses a system of neutrosophic components. Each component includes three parts: the set of objects that possess the attribute being considered (truth), the set of objects that do not possess the attribute being considered (falsehood), and the degree of indeterminacy. By using these components, neutrosophic logic can handle complex and ambiguous information in a more nuanced way than traditional logic.

Table 3.1: Comparison of different types of logic.

Logic Type	Basic Idea	Set Membership	Truth Value	Negation	Conjunction	Disjunction	Implication
Classical Logic	Assumes truth is binary and absolute	Elements either belong or do not belong to a set	True or False	$\neg p =$ True if $p =$ False $\neg p =$ False if $p =$ True	$p \wedge q =$ True if p and q are True; otherwise False	$p \vee q =$ True if either p or q is True; False if both are False	$p \to q =$ True if p implies q; False otherwise
Fuzzy Logic	Allows for partial truths and degrees of membership	Elements have a degree of membership between 0 and 1	Truth value is a degree of membership	$\neg p = 1 - \mu(p)$, where $\mu(p)$ is the degree of membership of p	$p \wedge q = \min(\mu(p), \mu(q))$	$p \vee q = \max(\mu(p), \mu(q))$	$p \to q = \min(1, 1 - \mu(p) + \mu(q))$
Intuitionistic Fuzzy Logic	Allows for hesitancy and uncertainty in decision making	Elements have degrees of membership and non-membership between 0 and 1	Truth value is a pair of degrees of membership and non-membership $(\mu(p), \nu(p))$	$\neg p = (\nu(p), \mu(p))$	$p \wedge q = (\min(\mu(p), \mu(q)), \max(\nu(p), \nu(q)))$	$p \vee q = (\max(\mu(p), \mu(q)), \min(\nu(p), \nu(q)))$	$p \to q = (\max(1 - \mu(p), \nu(q)), \min(1 - \nu(p), \mu(q)))$
Neutrosophic Logic	Allows for incomplete, indeterminate, and inconsistent information	Elements have three values: true, indeterminate, and false, denoted by (T, I, F)	Truth value is a triplet of values (T, I, F)	$\neg p = (F, I, T)$	$p \wedge q = (\min(T_p, T_q), \min(I_p, I_q), \min(F_p, F_q))$	$p \vee q = (\max(T_p, T_q), \max(I_p, I_q), \max(F_p, F_q))$	$p \to q = (\min(T_q + F_p, 1), \min(I_q + I(p \to q), 1), \min(F_q + T_p, 1))$

Note: T_p, I_p, and F_p denote the true, indeterminate, and false values of p, respectively, and similarly for T_q, I_q, and F_q.

3.4 Neutrosophic set

A neutrosophic set is a mathematical concept that was introduced by Florentin Smarandache in the 1990s. It combines the ideas of uncertainty, indeterminacy, and neutrality and provides a framework for handling multiple conflicting values or uncertain information. In neutrosophic sets, an element can have truth, indeterminacy, and falsity degrees, representing different degrees of uncertainty and conflict. The concept has applications in various fields, including decision making, artificial intelligence, and information fusion.

3.4.1 Definition 1 (Neutrosophic Set)

Consider a space of points (objects) denoted by X, where a generic element in X is represented by x. In this context, a neutrosophic set A in X is defined by three membership functions: a truth-membership function denoted as T_A, an indeterminacy-membership function denoted as I_A, and a falsity-membership function denoted as F_A. These functions are used to characterize the degree of membership of x in A with respect to truth, indeterminacy, and falsehood.

$$A = \{(x, T_A(x), I_A(x), F_A(x)); x \in X\} \tag{3.5}$$

$T_A(x)$, $I_A(x)$ and $F_A(x)$ are real standard or non-standard subsets of $]^{-}0, 1^{+}[$ as presented in Figure 3.2. That is

$T_A : X \to]^{-}0, 1^{+}[$

$I_A : X \to]^{-}0, 1^{+}[$

$F_A : X \to]^{-}0, 1^{+}[$

No limitations apply to the sum of $T_A(x)$, $I_A(x)$ and $F_A(x)$.

$^{-}0 \leq supT_A(x) + supI_A(x) + supF_A(x) \leq 3^{+}$

3.4.2 Definition 2 (The complement of a Neutrosophic sets)

The complement of a neutrosophic set A, which is denoted as c(A), is a concept used in neutrosophic set theory. It is defined as the set of all elements in the universe that do not belong to A. The complement of a neutrosophic set can be used to represent the opposite or negation of a given set. It is worth noting that the complement of a neutrosophic set does not necessarily have the same truth-membership, indeterminacy-membership, and falsity-membership functions as the original set. Instead, they are calculated using a complement function. Complements of neutrosophic sets are useful in many applications, including decision making and data analysis. For example, in medical diagnosis, the complement of a set of symptoms can be used to represent the absence of those symptoms and aid in determining a patient's condition. The complement c(A) is defined by:

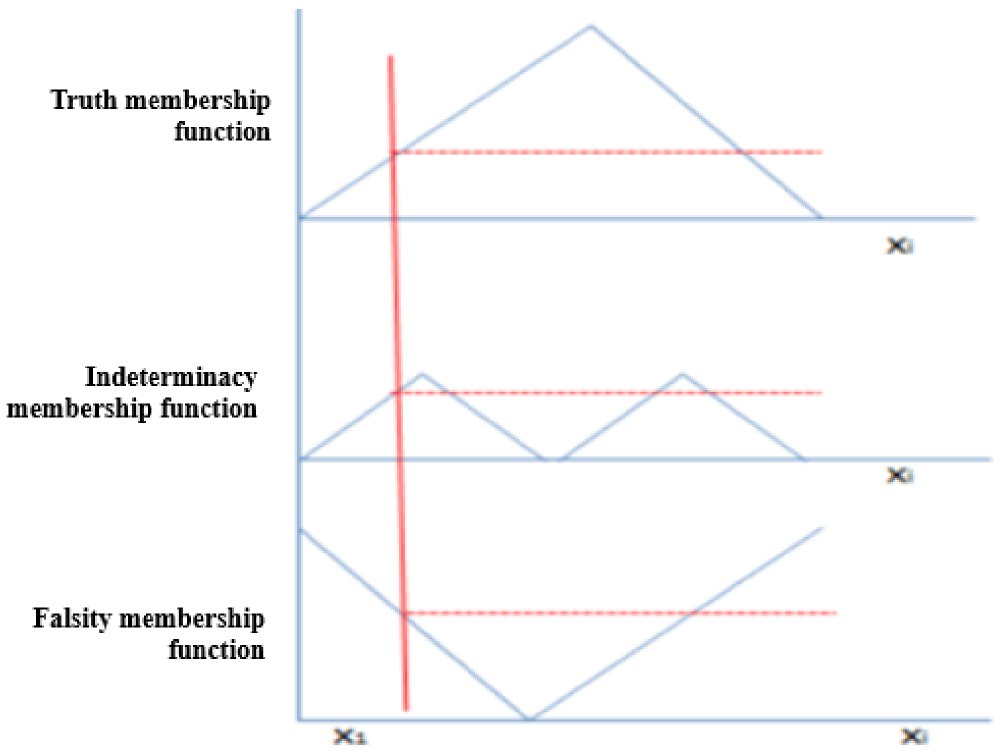


Figure 3.2: Neutrosophication process[3]

$$T_{c(A)}(x) = \{1^+\} - T_A(x),$$

$$I_{c(A)}(x) = \{1^+\} - I_A(x),$$

$$F_{c(A)}(x) = \{1^+\} - F_A(x),$$

for all x in X.

3.4.3 Definition 3 (Containment of a Neutrosophic sets)

In neutrosophic set theory, the concept of subset inclusion is an important one. A neutrosophic set A is said to be a subset of another neutrosophic set B, denoted as $A \subseteq B$, if and only if every element in A also belongs to B. More specifically, this means that for every x in X, the truth-membership function, $T_A(x)$, is less than or equal to the truth-membership function, $T_B(x)$, the indeterminacy-membership function, $I_A(x)$, is less than or equal to the indeterminacy-membership function, $I_B(x)$, and the falsity-membership function, $F_A(x)$, is greater than or equal to the falsity-membership function, $F_B(x)$. It is worth noting that this definition of subset inclusion in neutrosophic sets is more general than that of classical sets, as it accounts for the degree of membership of each element rather than just whether or not it belongs to the set. The notion of subset inclusion is essential in various applications of neutrosophic set theory, including fuzzy control systems, decision-making, and pattern recognition.

A neutrosophic set A is contained in the other neutrosophic set B, if and only if:

$infT_A(x) \leq infT_B(x)$, $supT_A(x) \leq supT_B(x)$

$infF_A(x) \geq infF_B(x)$, $supF_A(x) \geq supF_B(x)$

3.4.4 Definition 4 (Union of a Neutrosophic set)

In neutrosophic set theory, the concept of set union is used to combine two neutrosophic sets A and B into a new neutrosophic set C, denoted as $C = A \cup B$. The truth-membership, indeterminacy-membership, and falsity-membership functions of C are related to those of A and B as follows: for each element x in X.

$T_C(x) = T_A(x) + T_B(x) - T_A(x) * T_B(x)$

$I_C(x) = I_A(x) + I_B(x) - I_A(x) * I_B(x)$

$F_C(x) = F_A(x) + F_B(x) - F_A(x) * F_B(x)$

Intuitively, this means that the degree of truth-membership, indeterminacy-membership, and falsity-membership of each element in C is the maximum of the corresponding degrees in A and B.

The concept of set union is useful in many applications of neutrosophic set theory, such as decision-making, image processing, and data analysis. For example, in decision-making, set union can be used to combine the opinions or preferences of multiple decision-makers into a single, comprehensive decision. In image processing, set union can be used to combine different image segmentation results to obtain a more accurate segmentation. It is worth noting that the definition of set union in neutrosophic sets is different from that in classical set theory, as it takes into account the degree of membership of each element.

3.4.5 Definition 5 (Intersection)

In neutrosophic set theory, the intersection of two neutrosophic sets A and B is defined as the set of elements that belong to both A and B. The intersection of A and B is denoted as $C = A \cap B$, and its truth-membership, indeterminacy-membership, and falsity-membership functions are related to those of A and B as follows: for each element x in X.

$T_C(x) = T_A(x) * T_B(x)$

$I_C(x) = I_A(x) * I_B(x)$

$F_C(x) = F_A(x) * F_B(x)$

Intuitively, this means that the degree of truth-membership, indeterminacy-membership, and falsity-membership of each element in C is the minimum of the corresponding degrees in A and B.

The concept of set intersection is useful in many applications of neutrosophic set theory, such as decision-making, image processing, and data analysis. For example, in decision-making, set intersection can be used to find the common ground or agreement among multiple decision-makers. In image processing, set intersection can be used to identify the common regions between different image segmentation results. It is worth noting that the definition of set intersection in neutrosophic sets is different from that in classical set theory, as it takes into account the degree of membership of each element.

3.5 Single valued neutrosophic set

In this section, we present the notion of single valued neutrosophic set (SVNS). SVNS is an instance of neutrosophic set which can be used in real scientific and engineering applications.

3.5.1 Definition 6 (Single Valued Neutrosophic Set)

This section introduces the concept of a single valued neutrosophic set, which is a specific type of neutrosophic set that has practical applications in scientific and engineering fields. Unlike general neutrosophic sets, which allow for multiple degrees of truth, indeterminacy, and falsity for each element, SVNS assigns a single value for each of these three components. Specifically, for a given SVNS A, each element x in the universe of discourse X has a unique truth-membership value $T_A(x)$, a unique indeterminacy-membership value $I_A(x)$, and a unique falsity-membership value $F_A(x)$, with the condition that $T_A(x) + I_A(x) + F_A(x) = 1$ for all x in X.

SVNS is particularly useful in applications where precise and unambiguous values are required, such as decision-making, risk analysis, and forecasting. For example, In risk analysis, SVNS can be used to assess the probability and severity of different types of risks in a precise and consistent manner. In forecasting, SVNS can be used to predict future trends and events with a high degree of certainty. Overall, the concept of SVNS extends the utility of neutrosophic sets to practical applications where precise values are essential.

When X is continuous, a SVNS A can be written as

$$A = \int_x \langle T(x), I(x), F(x)\rangle / x, x \in X \tag{3.6}$$

When X is discrete, a SVNS A can be written as

$$A = \sum_{i=1}^{n} \langle T(xi), I(xi), F(xi)\rangle / xi, xi \in X \tag{3.7}$$

3.5.2 Complement SVNS

The complement of a single valued neutrosophic set A is denoted by c(A) and is defined by

$T_{c(A)}(x) = F_A(x)$

$I_{c(A)}(x) = 1 - I_A(x),$

$F_{c(A)}(x) = T_A(x),$

for all x in X.

3.5.3 Containment SVNS

A single valued neutrosophic set A is contained in the other single valued neutrosophic set B, $A \subseteq B$, if and only if:

$T_A(x) \leq T_B(x)$

$I_A(x) \leq I_B(x)$

$F_A(x) \geq F_B(x)$

for all x in X.

3.5.4 Union SVNS

The union of two single valued neutrosophic sets A and B is a single valued neutrosophic set C, written as $C = A \cup B$, whose truth membership, indeterminacy-membership and falsity membership functions are related to those of A and B by:

$T_C(x) = max(T_A(x), T_B(x))$

$I_C(x) = max(I_A(x), I_B(x))$

$F_C(x) = min(F_A(x), F_B(x))$

for all x in X.

3.5.5 Intersection SVNS

The intersection of two single valued neutrosophic sets A and B is a single valued neutrosophic set C, written as $C = A \cap B$, whose truth-membership, indeterminacy-membership and falsity-membership functions are related to those of A and B by

$T_C(x) = min(T_A(x), T_B(x))$

$I_C(x) = min(I_A(x), I_B(x))$

$F_C(x) = max(F_A(x), F_B(x))$

3.5.6 Difference SVNS

The difference of two single valued neutrosophic set C, written as $C = A \backslash B$, whose truth-membership, indeterminacy-membership and falsity-membership functions are related to those of A and B by:

$T_C(x) = min(T_A(x), F_B(x))$

$I_C(x) = min(I_A(x), 1 - I_B(x))$

$F_C(x) = max(F_A(x), T_B(x))$

for all x in X.

The proposed method using SVNS can be extremely useful in real-time risk data analysis. With the ability to manage incomplete and contradictory information, it can help in identifying potential risks and taking preventive measures in a timely and efficient manner. Moreover, the method's ability to consider the degree of membership, non-membership, and indeterminacy of the information can provide a more comprehensive understanding of the risks involved. This can be particularly beneficial in critical areas such as finance, healthcare, and transportation, where real-time risk management can save lives, prevent financial losses, and maintain public safety.

3.6 The classic AHP method

Decision analysis is a systematic approach to making decisions that involves assessing and evaluating different options based on various criteria or objectives. It involves identifying the problem, gathering and analyzing information, generating alternatives, and selecting the best course of action. The figure 3.3 proposed by [4] depicted the three main components of decision analysis methods: multi-criteria decision-making, decision support systems, and single objective decision-making.

Multi-criteria decision-making is a technique used to evaluate multiple criteria or objectives that are important to a decision. In MCDM, different criteria are considered and weighted based on their relative importance, and alternatives are evaluated based on how well they meet these criteria. The result is a ranking of alternatives based on their overall performance on the different criteria.

A decision support system is a computer-based tool that helps decision-makers analyze information and data to support decision-making. A DSS typically includes a database, analytical tools, and a user interface that allows decision-makers to interact with the system and explore different scenarios.

Single objective decision-making is a simpler form of decision-making where a single objective or goal is considered. In this method, alternatives are evaluated based on their ability to meet the objective, and the alternative that best meets the objective is chosen.

Unlike conventional single-criteria methods, multi-criteria decision-making methods do not aim to determine an optimal solution that optimizes all criteria simultaneously. Instead, they seek to find the best compromise solution that meets the most important criteria while still satisfying the other criteria to an acceptable degree.

MCDM is commonly used in operations research and is divided into two broad categories: multi-attribute decision-making (MADM) and multi-objective decision-making (MODM). MADM involves establishing a preference ranking of alternatives based on several conflicting attributes, while MODM involves identifying the set of optimal solutions that satisfy multiple objectives.

In summary, MCDM is a valuable tool for decision-making in complex scenarios where multiple criteria need to be evaluated. It does not provide a single optimal solution but rather a best-compromise solution that balances the different criteria. In our proposition, we have utilized two decision analysis methods, namely the Neutrosophic logic as a decision support system and the Analytic Hierarchy Process as a multi-criteria decision-making method.

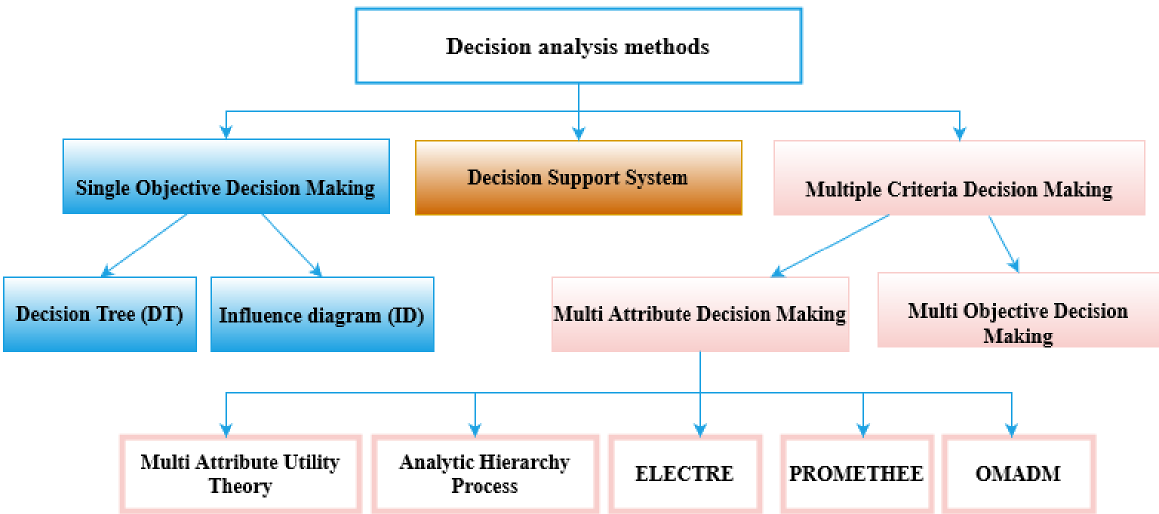


Figure 3.3: Classification of Decision Analysis Methods [4]

The Analytic Hierarchy Process (AHP) theory is a method adopted in multi-criteria decision making that relies on the use of quantitative methods in the decision-making process to select the optimal alternative among a group of alternatives based on multiple criteria. As this theory has been proven to be successful and highly effective in solving complex problems and making multi-criteria decisions, numerous studies have been conducted worldwide to address the issue of differentiating and choosing between a set of alternatives.

This theory was developed and defined by Professor Thomas Saaty [222] as "The theory of constructing indicators using pairwise comparisons which depends on the opinion of experts and decision-makers within the limits of a specific scale". By using this technique, a complex issue can be broken down into a hierarchy where binary combinations are established at each level.

3.6.1 Strengths of the analytic hierarchy process method

The reasons for the popularity of the AHP method are:

- AHP helps capture both subjective and objective evaluation measures. While providing a useful mechanism for checking the consistency of evaluation measures and alternatives, the AHP reduces bias in decision-making.
- The AHP method supports consensus group decision-making by calculating the geometric mean of individual pairwise comparisons.
- AHP is uniquely positioned to help model situations of uncertainty and risk as it is able to derive scales where measurements typically do not exist.
- The AHP method has the advantage of decomposing a decision problem into its constituent parts and constructing hierarchies of criteria. Then, the importance of each element (criterion) becomes clear. In addition, the identification of priorities which makes it possible to consider the relative priority of each criterion in order to obtain the best alternative according to the identified objective.
- Interdependence which makes it possible to consider the interdependence of the elements of a problem without insisting on linear reasoning (the elements of each level of the hierarchical structure are dependent).
- Consistency that keeps a logical consistency of the judgments used to determine priorities.

3.6.2 The steps of the AHP method

Due to its simplicity, ease of use and great flexibility, Since the development of Analytical Multilevel Decision Making, AHP has been widely studied and used in almost all applications related to multi-criteria decision making.

The three main elements of AHP are hierarchy building, priority analysis, and consistency checking. First, decision makers need to decompose complex multi-criteria decision problems into their components where each possible attribute is organized into several hierarchical levels. Second, decision makers must compare each cluster of the same level in pairs based on their own judgments. More precisely, two criteria of the second level are compared at the same time with respect to the objective, while two attributes of the same criteria at the third level are compared at the same time with respect to the corresponding criterion.

Because the comparisons are based on personal or subjective judgments, some inconsistencies may occur. To ensure the consistency of judgments, the third element, called the consistency check, which is considered one of the most significant advantages of the AHP, is integrated to measure the degree of consistency between pairwise comparisons by calculating the consistency ratio. If the consistency ratio exceeds the threshold, decision makers should review and revise the pairwise comparisons. Once all pairwise comparisons are made at all levels and found to be consistent, the judgments can be synthesized to determine the ranking of each criterion and its attributes. The overall AHP process is shown in Figure 3.4.

In this chapter, we will provide an overview of the AHP method, with a focus on practical application through the use of examples to enhance clarity. To analyze a decision using the AHP method, the following steps need to be followed:

3.6.2.1 Step 1: Establish the hierarchical structure

The first step in an AHP analysis is to establish a hierarchy for the decision. In this case, we start with the starting point for the application of this method by identifying the problems and the objective, then the selection of the best criteria and the alternatives in relation to the higher level of the hierarchy, which is the objective. The first step is then to decompose the complex problem into a hierarchical structure with the following levels (see Figure 3.5):

- ***Level 0***: Define the goal.
- ***Level 1***: Define the decision or analysis criteria.
- ***Level 2***: Define the characteristics of each criterion or option under study.

The advantages of this hierarchical decomposition are obvious. By structuring the problem in this way, it is possible to better understand the decision to be made, the criteria to be applied, and the alternatives to be evaluated. This step is crucial. For more complex problems, it is possible to bring in experts to ensure that all criteria and possible alternatives have been considered. Also note that for complex problems, it may be necessary to include additional levels in the hierarchy, such as sub-criteria.

3.6.2.2 Step 2: Performing the pairwise comparison

All the criteria will not have the same importance. Therefore, the second step in the AHP process is to derive the relative priorities (weights) of the criteria. Relative because the identified priority criteria are measured against each other, as we will see in the following discussion. Obviously, the importance or weight of each criterion will be different. Therefore, we must first derive the relative priority of each criterion with respect to each of the others through pairwise comparisons, using a numerical comparison scale developed by Saaty as shown in Table 3.2.

The comparison can lead to the design of a matrix model called a judgment matrix. The judgment matrix is a numerical representation of the relationship between two items (pairwise

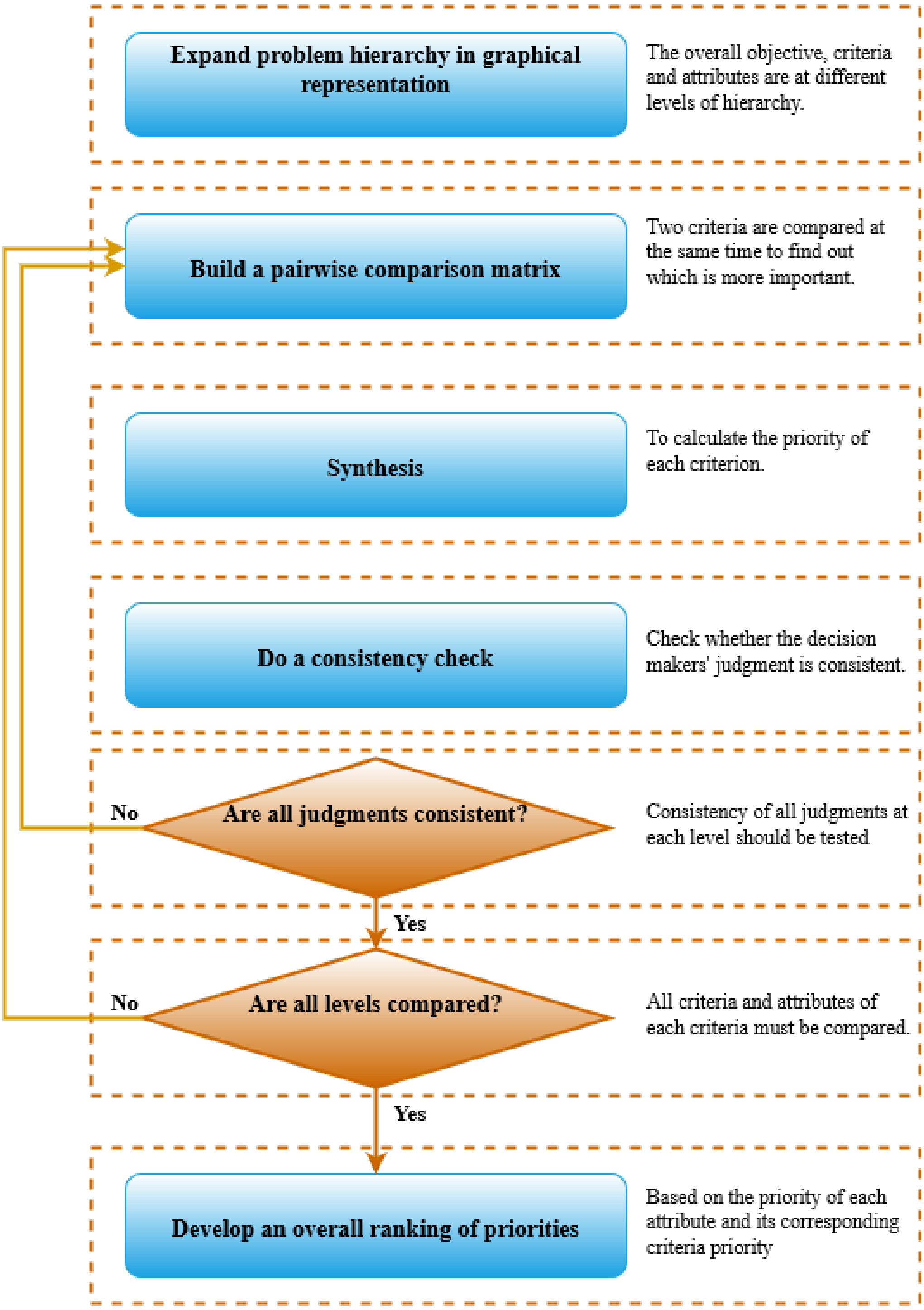


Figure 3.4: The process of the AHP method.

comparison) that share a common parent and is used to assess the relative importance of one item over another indicated by the following procedure:

- Compare the relative importance of all the elements belonging to the same level of the hierarchy taken two by two, compared to the element of the level immediately above.
- For each comparison we must choose the most important criterion and express our

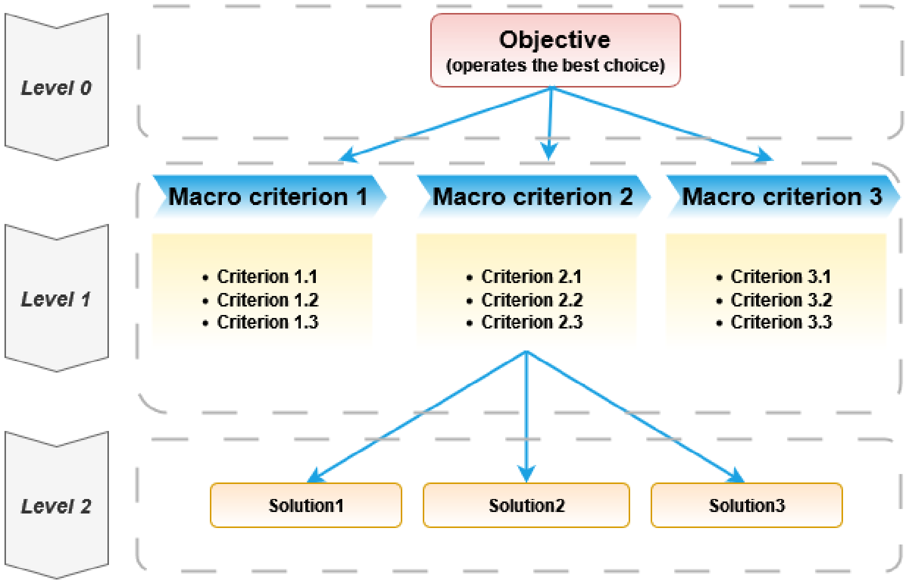


Figure 3.5: An overview of problem hierarchy.

judgment as to its importance.

- The measure to determine the relative importance could be expressed by scale from 1 to 9 (According to Table 3.2 of Saaty)

Table 3.2: Saaty scale of the AHP method.

Weighting	**Degree of preference**
1	Equal importance
2	low importance
3	Fairly moderate importance
4	Moderate importance
5	Fairly strong importance
6	Strong importance
7	Very strong importance
8	Extreme importance
9	Capital importance

Establishment of the comparison judgment matrix

We transform the criteria comparison table 3.2 into a matrix called the judgments matrix, by transcribing the values of the evaluations of the table in each corresponding column. The set of all these judgments can be represented by a square matrix of order n x n.

The comparison matrices thus obtained will have the following property:

- $A = a_{ij}$, where A is the square matrix of order n x n and a_{ij} represents the pairwise comparison of the criteria i and j.

- $a_{ii} = 1$, as a criterion always has the highest possible priority compared to itself.
- $a_{ji} = \frac{1}{a_{ij}}$, as the comparison between criteria i and j is reciprocal, and therefore, a_{ji} is the reciprocal of a_{ij}.

Priority vector calculation

The priority vector calculation step in the AHP method involves calculating the relative importance of each element in the hierarchy based on the evaluations obtained in the previous step. This step is critical because the priority vector determines the relative weights or priorities of each criterion, sub-criterion, or alternative in the decision-making process.

To calculate the priority vector, we first normalize the judgments matrix to obtain a priority matrix. This is done by performing column sums and then dividing the elements of the matrix by the column sum. The resulting matrix has each column summing up to 1, which enables comparison between the different criteria.

Next, we calculate the average of the elements in each row of the priority matrix. This gives us the priority weights of each criterion, sub-criterion, or alternative. The resulting vector is known as the priority vector, and it represents the relative importance of each element in the hierarchy.

The priority vector can also be interpreted as the degree to which each element contributes to the overall goal or objective of the decision-making process. The larger the value of a particular criterion, sub-criterion, or alternative in the priority vector, the more important it is in achieving the overall objective.

Calculation of the eigenvalue λ_{max}

The calculation of the eigenvalue λ_{max} is an essential step in the AHP method. It is used to determine the consistency of the judgments made during the pairwise comparisons process in the previous steps.

To calculate λ_{max}, we multiply the judgments matrix A by the priority vector x. The resulting vector is a weighted sum of the columns of A, with the weights given by the priority vector x. In other words, we are computing the weighted sum of the values in each row of the judgments matrix A, with the weights given by the priority vector x.

The resulting scalar value is called the eigenvalue λ_{max}, which represents the maximum eigenvalue of the matrix A. It is used to assess the consistency of the judgments made by the decision-makers during the pairwise comparisons process. The larger the value of λ_{max}, the more consistent the judgments are.

Calculation of consistency Ratio (CR)

Since the numerical values are derived from the subjective preferences of individuals, it is impossible to avoid certain inconsistencies in the final matrix of judgments. The question is to what extent inconsistency is acceptable?

According to the result that given a pairwise comparison matrix A, its maximum eigenvalue, λ_{max}, is equal to n if and only if the matrix is consistent (and greater than n otherwise), Saaty [223] proposed the Consistency Index:

$$CI(A) = \frac{\lambda_{max} - n}{n - 1} \tag{3.8}$$

However, numerical studies showed that the expected value of CI of a random matrix of size n+1 is, on average, greater than the expected value of CI of a random matrix of order n. Consequently, CI is not fair in comparing matrices of different orders and needs to be rescaled.

For this, AHP calculates a consistency ratio (CR) comparing the consistency index (CI) of the matrix in question (the one with our judgments) to the consistency index of a random type matrix (RI). A random matrix is a matrix in which the judgments have been entered at random and therefore it is expected to be highly inconsistent. Saaty [5] provides the calculated RI value for matrices of different sizes as shown in Table 3.3.

Table 3.3: Values of RI_n.

n	**$\mathbf{RI_n}$**
3	0.5247
4	0.8816
5	1.1086
6	1.2479
7	1.3417
8	1.4057
9	1.4499
10	1.4854

In AHP the consistency ratio CR is defined as :

$$CR(A) = CI(A) \backslash RI_n. \tag{3.9}$$

Saaty [5] showed that a consistency ratio (CR) of 0.10 or less is acceptable for further AHP analysis. If the consistency ratio is greater than 0.10, it is necessary to revise the judgments to locate the cause of the inconsistency and correct it (See table 3.4). If $RC \leq 0.1$ or $RC \leq 10\%$, the matrix is considered sufficiently consistent, in the case where this value exceeds 10%, the judgments may require certain revisions.

Table 3.4: Acceptable consistency ratios [5].

Matrix size(n)	**Acceptable Consistency Ratio**
3	0.05
4	0.08
5+	0.10

3.6.2.3 Step 3: Derive local priorities for alternatives

In step 3 of the AHP method, local priorities for alternatives are derived against each criterion separately. This step involves comparing alternatives pairwise against each criterion, and then deriving a priority vector for each criterion.

To begin this step, the decision maker should create a matrix for each criterion, with the alternatives in the rows and the criterion in the column. Then, the decision maker should compare each pair of alternatives against the criterion, assigning a value that represents their relative importance or performance. This can be done using the same scale as in step 2, typically a 1 to 9 scale.

After obtaining all pairwise comparisons for each criterion, the same process as step 2 should be followed to calculate the priority vector for each criterion. The column sums are calculated, and the matrix is normalized to derive the priority vector. The consistency of each matrix should also be checked and adjusted as necessary.

Once the priority vector for each criterion is obtained, they can be combined using the weighted arithmetic mean method to calculate the overall priority of each alternative. This involves multiplying the priority vector of each criterion by its weight and then summing them up.

As with step 2, it is important to ensure that the consistency of each criterion matrix is acceptable before deriving the priority vector. If inconsistencies are found, they should be addressed and the pairwise comparisons should be revised until a consistent priority vector can be obtained.

3.6.2.4 Step 4: Derive global priorities (summary of the model)

All the alternative priorities obtained are combined as a weighted sum - to take into account the weight of each criterion - to establish the overall priorities of the alternatives. The alternative with the highest overall priority is the best choice.

3.6.2.5 Step 5: Make a final decision

Overall, step 5 involves using the results from the previous steps to make an informed decision or to rank the alternatives based on their relative importance. The decision-maker should carefully consider the results of the analysis and the sensitivity analysis before making a final decision.

3.6.3 Limits of the AHP method

However, the AHP method has limitations that must be taken into account when using it.

- There is a limited number of studies that critically evaluate the Analytic Hierarchy Process The use of the Saaty scale in AHP often has shortcomings, such as the problem of inconsistency resulting from pairwise comparisons. This inconsistency can arise when the decision maker struggles to distinguish the relative importance between two alternatives, resulting in difficulty in assigning a value to them, such as determining whether an alternative is 6 or 7 times more important than another. Moreover, the AHP method may face difficulty in handling cases where one alternative is significantly larger than another, such as Variant A being 25 times larger than Variant C, due to scale restrictions. This limitation leaves the decision maker with no other option but to create an inconsistency, and consequently, they have to be concerned about the inconsistency ratio.

- The Analytic Hierarchy Process (AHP) involves decomposing the decision problem into a number of subsystems, requiring a significant number of pairwise comparisons to be made both within and between them. However, this approach has a disadvantage in that the number of pairwise comparisons required can become exceedingly large $(\frac{n(n-1)}{2})$, resulting in a time-consuming task.

  As the number of alternatives or criteria increases, performing pairwise comparisons in AHP becomes more confusing and leads to a higher level of inconsistency. Consequently, the comparisons may need to be repeatedly sent back to the decision maker for improvement. The issues with AHP become more serious when the decision maker begins manipulating the values of pairwise comparisons in an attempt to eliminate inconsistency, rather than performing a fair comparison between items.

It is important to note that, contrary to common belief, the system does not determine the decision to be made, but rather the results are to be interpreted as a preference scheme of alternatives according to the degree of importance of the different criteria taken into consideration. In other words, we can assess which alternative is best compatible with our criteria using the AHP technique.

The AHP method's incapacity to cope with subjectivity and ambiguity in human judgment or conduct is another significant flaw in the approach. On the other hand, the advantage of the fuzzy set model and other fuzzy-based models is their ability to effectively capture the fuzziness of criteria and other decision characteristics. As a result, Van Laarhoven and Pedrycz's Fuzzy Analytic Hierarchy Process (FAHP) technique was developed [224], where each pairwise comparison judgment is represented as a fuzzy number which is described by a membership function. Many studies have been conducted to examine the reliability and credibility of the FAHP. But the fuzzy number does not describe the degree of non-membership and it is not a solution when decision makers hesitate to define membership.

Fuzzy AHP is a method for multi-criteria decision making that uses fuzzy numbers to represent the subjective preferences of decision-makers. It deals with uncertainty and vagueness by assigning a membership function to each alternative, indicating the degree to which it satisfies each criterion. On the other hand, Neutrosophic AHP incorporates both uncertainty and conflicting information by using neutrosophic sets. In Neutrosophic AHP, each element can have three degrees of truth, indeterminacy, and falsity, representing different levels of uncertainty and conflict. This allows for more nuanced decision making, as it can handle situations where the information is both uncertain and conflicting. In summary, while fuzzy AHP handles uncertainty by assigning membership functions, neutrosophic AHP handles both uncertainty and conflicting information by using neutrosophic sets.

The neutrosophic AHP method has the same advantages of the classic AHP alongside the following advantages:

- It allows for the effective description of the decision-preferences maker's and judgmental values.
- Fuzziness and uncertainty are handled more effectively by neutrosophic logic than by fuzzy AHP and intuitionistic fuzzy AHP approaches because it takes into account three separate degrees: "degree of belonging, degree of indeterminacy, and degree of non-belonging."

Previous study on NAHP as [225], has demonstrated how useful it is when used to address various MCDM issues. However, all of this study only considers expert judgments, which can be quite subjective, and real facts can override the significance of a criterion determined by an expert. Furthermore, experts may not agree on a criterion's importance since one expert may disagree with another expert's assessment of its significance.

Neutrosophic Data Analytic Hierarchy Process (NDAHP), a new AHP technique based on the SVNS model, is suggested by [226] as a solution to this issue. The primary distinction between the NDAHP approach and the NAHP method is that the NDAHP derives the criteria weightings from actual data as opposed to depending on expert opinion. As a result, the NDAHP model's outcomes will be more accurate because the value and weighting of each criterion and alternative are established objectively using actual data sets.

3.7 Neutrosophic Data AHP

In this section, a risk quantification method for supply chain management is proposed, building upon the approach presented in Tey et al. [226]. This method offers a significant advantage as it utilizes an integrated method to automatically assign weights to different risk factors, rather than relying on subjective assessments. This feature is one of the key strengths of the proposed method.

To begin, an organization is required to develop a comprehensive risk hierarchy that encompasses all potential threats to the enterprise, considering various aspects of the supply chain. This thorough examination enables the identification of vulnerable areas that require attention. Subsequently, the risks are classified based on criteria such as ***severity***, ***occurrence***, and ***detectability***, as outlined in the study.

Unlike traditional AHP methods where subjective weights are assigned by expert in the domain or decision-makers, the proposed neutrosophic data AHP method automatically determines the weights through an integrated approach. This automated weight assignment process enhances the objectivity and reliability of the risk assessment, making it a powerful aspect of the proposed method.

By incorporating this neutrosophic data AHP framework, decision-makers benefit from an effective and systematic approach to assess and prioritize risks within the supply chain. The integrated weight assignment mechanism adds robustness and credibility to the risk quantification process, assisting organizations in implementing appropriate risk management and mitigation strategies.

Step 1 NDAHP:

In the initial step of the Neutrosophic Data Analytic Hierarchy Process (NDAHP), the first task involves acquiring problem datasets from reliable sources. These datasets serve as the foundation for the subsequent analysis, it is essential to ensure that the problem datasets used for analysis are derived from actual and real-time sources. By extracting data from real-time datasets, the NDAHP can capture the most up-to-date information and reflect the current state of affairs accurately. This ensures that the decision-making process is based on relevant and reliable data, enhancing the effectiveness and validity of the analysis. To effectively handle the data and account for its inherent uncertainties, a transformation process is applied. This process converts the cross-data into single-valued neutrosophic sets (SVNS) based on the definition provided in Wang et al. [227].

SVNS are a specific type of neutrosophic sets characterized by three essential membership functions: the truth membership function $T_A(x)$, the indeterminate membership function $I_A(x)$, and the falsity membership function $F_A(x)$. Each of these functions is bound between 0 and 1, signifying the degree of membership or non-membership of an element within the set. Importantly, these membership functions are subject to the constraint that their sum does not exceed 3, ensuring a valid and coherent representation of uncertainty.

The SVNS, represented by the set A and described by the formula mentioned in Equation 3.10, play a vital role in the subsequent stages of the NDAHP. These sets capture the nuanced characteristics of the dataset, considering the degrees of truth, indeterminacy, and falsity associated with its elements. By employing SVNS, decision-makers can account for and effectively handle the inherent uncertainties and ambiguities present in the dataset.

According to the proposal, the utilization of SVNS can streamline the process of neutrosophic set application. To convert cross-data into SVNN, it is imperative to first normalize the matrix through the use of equations (3.11) and (3.12). These equations, which were introduced by Nirmal and Mahata [228], facilitate the normalization process for beneficial and non-advantageous criteria, respectively.

Following the methodology proposed by Nirmal and Mahata [228], the concept of beneficial and non-beneficial criteria is utilized to assess the criteria's desirability in the Neutrosophic Data Analytic Hierarchy Process (NDAHP). Beneficial criteria are those in which higher values are more desirable, such as the degree of risk detection, indicating a positive impact on the decision-making process. On the other hand, non-beneficial criteria are characterized by a preference for lower values, such as the severity and occurrence of risks, as lower values indicate a better outcome in terms of risk mitigation.

To quantify and represent these criteria, the resultant values of R_{ij}, derived from the pairwise comparisons, are employed. These values serve as the basis for determining the corresponding Single-Valued Neutrosophic Numbers (SVNNs) using equations (3.13) (for beneficial criteria) and (3.14) (for non-beneficial criteria). These equations capture the transformation process, allowing for the representation of the criteria's characteristics and their impact on the decision hierarchy within the NDAHP framework.

$$A = \{(x; T_A(x), I_A(x), F_A(x) : x \in U\} \tag{3.10}$$

$$R_{ij} = \frac{(a_{ij} - a_j^{min})}{(a_j^{max} - a_j^{min})}, \ i = 1 \ldots m, \qquad j = 1 \ldots n \tag{3.11}$$

$$R_{ij} = \frac{(a_j^{max} - a_{ij})}{(a_j^{max} - a_j^{min})}, \ i = 1 \ldots m, \ j = 1 \ldots n \tag{3.12}$$

$$(t_p, i_p, f_p) = (R_{ij}, 1 - R_{ij}, 1 - R_{ij}) \tag{3.13}$$

$$(t_p, i_p, f_p) = (1 - R_{ij}, R_{ij}, R_{ij}) \tag{3.14}$$

Step 2 NDAHP: Pairwise comparison

The subsequent step in the Neutrosophic Data Analytic Hierarchy Process involves comparing the Single-Valued Neutrosophic Numbers (SVNNs) associated with each criterion to determine their relative levels of importance. This comparison is carried out using equation (3.15), which was introduced by Tey et al. [226]. Notably, the power of this method lies in equation (3.15), as it eliminates the need for expert opinion in comparing values.

$$a_{ij} = \frac{\theta_i - \theta_j + 1}{2} \tag{3.15}$$

$$x + y = (T_x + T_y - T_x.T_y, I_x.I_y, F_x.F_y) \tag{3.16}$$

$$x \times y = (T_x.T_y, I_x + I_y - I_x.I_y, F_x + F_y - F_x.F_y) \tag{3.17}$$

$$\frac{x}{y} = \left(\frac{T_x}{T_y}, \frac{(I_x - I_y)}{(1 - I_y)}, \frac{(F_x - F_y)}{(1 - F_y)}\right) \tag{3.18}$$

$$\lambda x = (1 - (1 - Tx)\lambda, (I_x)\lambda, (F_x)\lambda)), \ \lambda > 0 \tag{3.19}$$

$$x^\lambda = \left((T_x)^\lambda, 1 - (1 - I_x)^\lambda, 1 - (1 - F_x)^\lambda\right), \lambda > 0 \tag{3.20}$$

$$\frac{x}{\lambda} = \left(1 - (1 - T)^{\frac{1}{\lambda}}, I^{\frac{1}{\lambda}}, F^{\frac{1}{\lambda}}\right), \ \lambda > 0 \tag{3.21}$$

$$x - y = \left(\frac{(T_x - T_y)}{(1 - T_y)}, \frac{I_x}{I_y}, \frac{F_x}{F_y}\right) \tag{3.22}$$

$$S(A_j) = \frac{3 + t_j - 2i_j - f_j}{4} \tag{3.23}$$

In equation (3.15), the SVNN values of criterion i and criterion j are represented as θ_i and θ_j, respectively, while the SVNN value representing their comparison in the comparison matrix is denoted as a_{ij}. The comparison values a_{ij} are calculated using equations (3.21) and (3.22), which consider the properties and concepts related to SVNNs.

By utilizing equation (3.15) and the calculated a_{ij} values, the NDAHP enables a systematic and quantitative comparison of criteria without relying on subjective expert opinions. This approach enhances the objectivity and consistency of the decision-making process, eliminating potential biases and discrepancies that can arise from individual judgments.

Step 3 NDAHP: Consistency Checking

Verifying the consistency of the matrix is crucial to ensure the accuracy and reliability of the subsequent results. By evaluating the consistency ratio of the matrix, we can determine whether the data is reliable and consistent. This is particularly important when dealing with complex decision-making processes, as even minor inconsistencies or errors can significantly impact the final outcome. Therefore, incorporating consistency checking into the decision-making process can help prevent errors and inaccuracies, ultimately leading to more informed and effective decisions.

The objective of this stage is to evaluate the consistency and suitability of the matrix. Specifically, the matrix is deemed consistent and eligible for subsequent processing if the consistency ratio (CR) value is below 0.1. If the CR value exceeds this threshold, the data is regarded as inconsistent and must be reconstructed. The formula for computing CR, as presented by [226], has been incorporated into our approach.

Assuming a given SVNS $A = (a_{ij})\ n \times n$ where each a_{ij} corresponds to a neutrosophic number (T_{ij}, I_{ij}, F_{ij}), and a consistency matrix $C = (c_{ij})\ n \times n = (T'_{ij}, I'_{ij}, F'_{ij})_{n \times n}$.

- For $j > i + 1$, where k = i + 1.
- For $j = i + 1$, $c_{ij} = (T_{ij}, I_{ij}, F_{ij})$, where $k = i + 1$.
- For $j < i$, $c_{ij} = (T'_{ij}, 1 - I'_{ij}, F'_{ij})$, where $k = i + 1$.

Utilizing the aforementioned equation will yield the consistency index (CI) of the data in matrix form. Subsequently, the decision maker is required to employ equation 3.24 in order to obtain the consistency ratio (CR).

$$T'_x = \frac{\sqrt[j-i-1]{T_{ik} \times T_{kj} \times T_{i(j-1)} \times T_{(j-1)j}}}{\sqrt[j-i-1]{T_{ik} \times T_{kj} \times T_{i(j-1)} \times T_{(j-1)j}} + \sqrt[j-i-1]{(1-T_{ik}) \times (1-T_{kj}) \times (1-T_{i(j-1)}) \times (1-T_{(j-1)j})}}$$

$$I'_x = \frac{\sqrt[j-i-1]{I_{ik} \times I_{kj} \times I_{i(j-1)} \times I_{(j-1)j}}}{\sqrt[j-i-1]{I_{ik} \times I_{kj} \times I_{i(j-1)} \times I_{(j-1)j}} + \sqrt[j-i-1]{(1-I_{ik}) \times (1-I_{kj}) \times (1-I_{i(j-1)}) \times (1-I_{(j-1)j})}}$$

$$F'_x = \frac{\sqrt[j-i-1]{F_{ik} \times F_{kj} \times F_{i(j-1)} \times F_{(j-1)j}}}{\sqrt[j-i-1]{F_{ik} \times F_{kj} \times F_{i(j-1)} \times F_{(j-1)j}} + \sqrt[j-i-1]{(1-F_{ik}) \times (1-F_{kj}) \times (1-F_{i(j-1)}) \times (1-F_{(j-1)j})}}$$

$$CR = \frac{1}{2(n-1)(n-2)} \times \sum_{i=1}^{n} \sum_{j=1}^{n} (|T'_{ij} - T_{ij}| + |I'_{ij} - I_{ij}| + |F'_{ij} - F_{ij}|) \tag{3.24}$$

Step 4 NDAHP: Relative weight

Once the consistency of the matrix has been verified and deemed acceptable, the next step in the Neutrosophic Data Analytic Hierarchy Process involves computing the weighting of the criteria. In this method, the criterion weighting is represented in the form of Single-Valued Neutrosophic Numbers (SVNNs), and the calculations are performed using equations from [225], specifically equations (3.16) to (3.21), which incorporate concepts and properties related to SVNNs.

Given two SVNNs $x = (T_x, I_x, F_x)$ and $y = (T_y, I_y, F_y)$, and λ representing the number of alternatives or criteria, the criterion weighting calculation is performed using these operations:

- A matrix is constructed, where each element represents an SVNN obtained from the pairwise comparisons of criteria.
- Equation (3.16) is utilized to compute the summation of the SVNNs in each column of the matrix. This yields a new matrix A with dimensions of $1 \times n$, where n represents the number of criteria.
- Applying equation (3.18), each element of the matrix A is divided by the corresponding element of the comparison matrix B. This results in a square matrix A_0 with dimensions of $n \times n$.
- The weighting is then calculated row by row. For each SVNN that represents a criterion, the mean value is computed using equations (3.16) and (3.21). This process yields the criterion weights, which indicate the relative importance of each criterion in the decision-making process.

By employing these operations and equations, the NDAHP facilitates the computation of criterion weighting in a systematic and rigorous manner. The use of SVNNs allows for a comprehensive consideration of the inherent uncertainties and complexities associated with the decision problem. The resulting criterion weights provide valuable insights for prioritizing criteria and informing subsequent analyses within the NDAHP framework.

Step 5 NDAHP: Getting Broad Classification

At this stage, the decision-maker is required to repeat steps 1 through 4 of the process to calculate the weighting of the sub-criteria and alternatives. Once the weighting of the criteria, sub-criteria, and alternatives has been determined, the overall weighting can be computed. It is important to note that the resulting total weight is represented as a Single-Valued Neutrosophic Number (SVNN).

To transform the SVNNs into crisp values, equation (3.23) from [226] is employed. This equation allows for the conversion of the SVNNs into a more conventional numerical representation. For each alternative, denoted as A_j, the membership values for truth, indeterminacy, and falsity are represented by t_j, i_j, and f_j, respectively.

By applying equation (3.23), the decision-maker can obtain crisp values that reflect the degree of truth, indeterminacy, and falsity associated with each alternative. This transformation allows for a more straightforward interpretation and comparison of the alternatives based on their membership values.

Step 6 NDAHP : Broad Classification Establishment

In this step, the alternatives are given weights based on the results of step 5. The weights are then arranged in descending order to facilitate the decision-making process.

After the weighting of alternatives is obtained, the decision maker needs to establish a broad classification of the alternatives based on the weights. This is important because it allows the decision maker to focus on a smaller set of alternatives that are more likely to lead to the desired outcome.

The broad classification can be established by ranking the alternatives in descending order of their weights. The alternatives with the highest weights are considered the most desirable and are placed at the top of the list. Conversely, the alternatives with the lowest weights are considered the least desirable and are placed at the bottom of the list. The decision maker can then focus on the top alternatives and make a final selection based on their specific needs and preferences.

It is important to note that the broad classification should not be the final decision. It is only the beginning of the decision-making process, and the decision maker should continue to evaluate and compare the top alternatives until a final selection is made. The Neutrosophic Decision Analysis with Hybrid Pairwise Comparison (NDAHP) method provides a systematic approach to help decision makers make more informed and reliable decisions as demonstrated in [276].

3.8 Conclusion

Risk management in supply chains, and specifically risk assessment, is a complex issue that involves a multitude of conflicting criteria. It is evident that the single-criteria approach is insufficient to tackle this challenge, and therefore a shift to the multi-criteria paradigm is necessary. Additionally, decision makers in today's supply chains may have ambiguous and imprecise criteria, preferences, and assessments, further complicating the decision-making process.

The process of making decisions in risk assessment not only involves accurate and inaccurate information but also uncertain information, which is represented by a degree of ignorance between truth and falsehood. In order to model this type of information more effectively, this chapter revisits the fundamental principles of neutrosophic logic, specifically Single-Valued Neutrosophic Sets (SVNS). The chapter introduces the fundamental principles of the techniques used to address multi-criteria issues, including multi-criteria analysis methods for decision support and the Analytic Hierarchy Process method. The chapter also discusses the Neutrosophic AHP and Neutrosophic Data AHP methods.

These theoretical concepts serve as the foundation for the development of the multi-criteria fuzzy approaches presented in the subsequent chapters of this thesis. The next chapter focuses on the first multi-criteria decision support approach, which is dedicated to solving the risk management problem in a fuzzy environment. To achieve this, the approach combines an analytical model with multi-agent systems to better control the risks that arise in supply chains in real-time.

Chapter 4

NeutroMAS4SCRM

Chapter 4

NeutroMAS4SCRM

Contents

4.1 Introduction

This chapter describes a type of system or approach that uses multiple, distributed agents to manage and mitigate the risks associated with a supply chain. The term "distributed" refers to the fact that the agents are spread out or distributed throughout the supply chain, allowing for a more comprehensive and decentralized approach to risk management. The use of "agent-based" refers to the utilization of intelligent agents, which are software entities that are capable of autonomous decision-making and problem solving. The overall goal of this type of architecture is to improve the efficiency and effectiveness of supply chain risk management by leveraging the capabilities of distributed agents.

In recent years, Multi-Agent Systems (MAS) have gained significant attention as a promising solution for complex and dynamic problems. MAS are composed of multiple autonomous agents that interact with each other and the environment to accomplish tasks. The agents are capable of making decisions and carrying out actions independently, allowing for decentralized problem solving.

One of the key benefits of MAS is their ability to handle complex and dynamic problems effectively. Unlike traditional centralized systems, MAS can adapt to changing conditions, as the agents can work together and make decisions based on the current state of the system. Furthermore, the communication and cooperation between agents result in emergent and adaptive behavior, making MAS highly resilient and flexible. Another important feature of MAS is the autonomy of the agents. This autonomy allows the agents to act independently, making decisions and carrying out actions without the need for central control. This decentralized structure enables MAS to solve complex problems more effectively, as the agents can work together and make decisions based on local information.

In addition to the potential of MAS to solve complex and dynamic problems, their ability to react in real time is another important advantage. MAS are designed to operate in dynamic and changing environments, where they must be able to respond quickly and adapt to changing conditions. This real-time capability is particularly important in the context of SCRM, where supply chain disruptions can occur at any time and require immediate action.

In SCRM, MAS can be used to monitor supply chain operations in real time, identify potential risks and disruptions, and take proactive steps to mitigate those risks. For example, a MAS could monitor weather patterns and alert supply chain managers of potential disruptions to shipping routes, or detect delays in the delivery of raw materials and adjust production schedules accordingly.

The advantages of MAS are driving supply chain managers to integrate the MAS model into their SCM system as a risk management and decision-making tool. The design, implementation, and validation of MASs involve the implementation of coordination and negotiation strategies, as well as reasoning protocols that enable good decision-making in the agent environment.

This chapter outlines our contribution to the development of a multi-agent system for risk management in supply chains, specifically, our NeutroMAS4SCRM. The proposed sections introduce the concepts of agents, agent interactions, and communication protocols among agents in our NeutroMAS4SCRM system. The NeutroMAS4SCRM system represents a promising approach to SCRM, and the concepts introduced in this chapter lay the foundation for further research and development in this area.

4.2 The notion of Agent

In recent years, there has been a strong and rapid development of research on agents and multi-agent systems, as there is no universally accepted definition of an agent in the literature. It is therefore interesting to compare different definitions in order to have a good representation of the concept. The definition proposed by J. Ferber [229] highlights several characteristics.

An agent is defined as a physical or virtual entity:

- That is capable of acting within an environment.
- That can directly communicate with other agents.
- That is driven by a set of tendencies in the form of individual goals or a satisfaction function, or even survival, which it seeks to optimize.
- That has its own resources, where resources refer to the sum of knowledge and means available to agents in order to act within their environment.
- That is capable of perceiving (but to a limited extent) its environment. That only has a partial representation of this environment (and possibly none at all).
- That possesses skills and offers services.
- That can possibly reproduce.
- Whose behavior tends to satisfy its goals, taking into account the resources and skills it has, and based on its perception, representations, and communications it perceives.

For Michael Wooldridge [230], an agent is a computer system capable of autonomously and flexibly acting in an environment. By flexibility, it means:

- ***Reactivity:*** A reactive system maintains a constant connection with its environment and responds to changes. A reactive system is able to detect and respond to changes in its environment in a timely and appropriate manner. This may involve using sensors or other means of monitoring the environment to detect changes, and then taking action based on predefined rules or algorithms.
- ***Proactivity:*** A proactive system generates and satisfies goals. Its behavior is not solely driven by events. a proactive system is able to take initiative and act independently of external stimuli. This means that it is not solely reactive, but is able to generate its own goals and take action to achieve them. Proactivity may involve using heuristics or other decision-making mechanisms to select actions that are likely to lead to desired outcomes.

- ***Social abilities:*** A social system is able to interact and cooperate with other systems in its environment. This may involve exchanging information, coordinating actions, or negotiating agreements with other agents in order to achieve shared goals. Social abilities may be based on predefined rules or protocols, or may involve more complex forms of communication and cooperation, such as trust-building and reputation management.

In addition to the aforementioned properties, we can identify others derived from definitions that appear in the literature, such as:

- ***Reasoning:*** An agent is able to reason about its environment and make decisions about what actions to take based on its goals and the current state of the world. This may involve using logic or other reasoning mechanisms to generate plans or strategies for achieving goals, or evaluating the potential consequences of different actions.
- ***Learning:*** An agent is able to improve its performance over time by learning from experience. This may involve using machine learning or other techniques to analyze data and adapt to changes in its environment, or learning from interactions with other agents or humans.
- ***Mobility:*** In some applications, it may be desirable to allow agents to move from one location to another in a network. Mobility may be necessary in order to perform certain tasks or to better coordinate with other agents in the environment. It may also require mechanisms for preserving the agent's state during node jumps, so that it can continue to function seamlessly even as it moves from one location to another.

4.3 Multi-Agent Systems (MAS)

Among the different definitions of multi-agent systems, we will retain the one by Ferber [229] who defines it as a system composed of the following elements:

- An environment $\boldsymbol{E}$ This can be a physical or virtual space where agents operate. It can have a fixed or dynamic structure, and agents may have different degrees of control over the environment.
- A set of objects $\boldsymbol{O}$. These objects are located, i.e. for any object, it is possible at a given moment to associate a position in $\boldsymbol{E}$. These objects are passive, i.e. they can be perceived, created, destroyed, and modified by the agents.
- A set of agents $\boldsymbol{A}$, which are special objects representing the active entities of the system.
- A set of relationships $\boldsymbol{R}$ that link objects (and therefore agents) to each other.
- A set of operations $\boldsymbol{Op}$ allowing agents from $\boldsymbol{A}$ to perceive, produce, consume, transform and manipulate objects from $\boldsymbol{O}$.
- Operators responsible for representing the application of these operations and the reaction of the world to this attempt at modification, which will be called the laws of the universe.

4.3.1 Characteristics of multi-agent systems

The following are the key characteristics of MAS, which are essential to understanding the behavior and function of these systems:

- ***Autonomy:*** The agents in MAS are autonomous, meaning that they have the ability to act independently, without the need for central control. This autonomy allows the agents to make decisions and carry out actions based on local information and situations, rather than relying on a central authority.
- ***Decentralized Decision-Making:*** In MAS, the decision-making process is distributed among the agents, which allows for efficient problem-solving and improves system performance. This decentralization results in a robust and adaptive system, as agents can make decisions and carry out actions independently, without relying on a central authority.
- ***Emergent and Adaptive Behavior:*** The communication and cooperation between agents in MAS result in emergent and adaptive behavior. This behavior allows MAS to be flexible and resilient in the face of changing conditions and to handle complex problems more effectively than traditional centralized systems.
- ***Cooperation:*** The agents in MAS are capable of communicating and cooperating with each other, which is essential for solving complex problems collectively. The cooperation between agents in MAS can lead to improved problem-solving and increased efficiency compared to traditional centralized systems.
- ***Complexity:*** MAS are complex systems that can handle complex and dynamic problems effectively. The decentralized structure and autonomous agents result in a complex system that can handle complex problems more effectively than traditional centralized systems.

In conclusion, the key characteristics of MAS are essential to understanding their behavior and function. The decentralization of decision-making, autonomy of agents, emergent and adaptive behavior, cooperation between agents, and complexity of the system, make MAS a promising solution for solving complex and dynamic problems in various domains and applications. As the field of MAS continues to evolve and mature, it is expected that these characteristics will become increasingly important and that MAS will play a crucial role in a variety of domains and applications in the future.

4.3.2 Communication languages between Agents

Effective coordination between agents in a multi-agent system leads to improved task completion compared to a single agent. However, for the coordination of the activity of a heterogeneous group of autonomous agents, a common language must be used for communication. The use of a common communication language requires that all agents understand its vocabulary in all aspects, including syntax which specifies the mode of symbol structuring, pragmatics for interpreting symbols, and ontology for the use of common vocabulary words.

4.3.3 Typology of agents

The typology of agents in a MAS refers to the categorization and classification of agents based on certain characteristics. These characteristics can include their level of autonomy, their objectives, and their behavior. In this section, we will provide a detailed definition of the different types of agents in a MAS and illustrate their characteristics using figures.

- ***A Simple Reflex Agent:*** is a type of agent that operates in a straightforward manner. It responds to a specific stimuli within its environment in a predetermined manner, without having a perception of previous events or actions. This is due to the absence of memory or history as presented in Figure 4.1, and this type of agent is considered to be relatively uncomplicated.

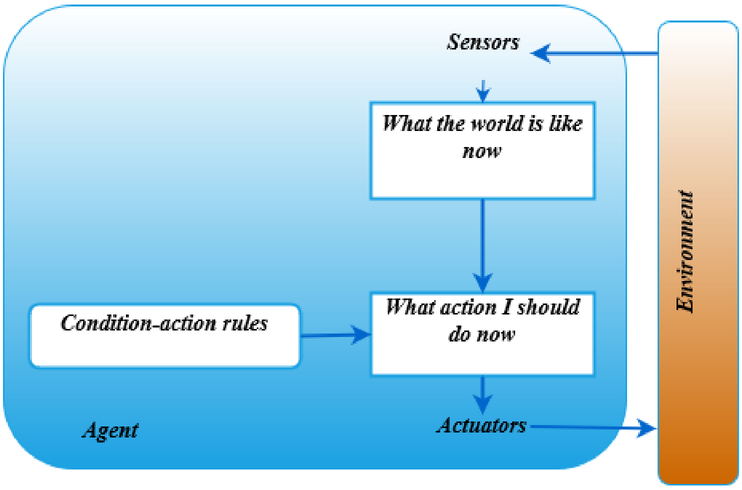


Figure 4.1: The composition of a simple reflex agent

- ***Model-Based Reflex Agent:*** This type of agent does not have a complete perception of its environment as presented in Figure 4.2. To address this, the agent is equipped with a general model that represents the theoretical evolution of its environment. It reacts in the same way as a simple reflex agent, however, in implementing its actions, it relies on the view provided by its model.

- ***Goal-based agent:*** This type of agent as presented in Figure 4.3 focuses on achieving a specific goal or set of goals, and may use planning or reasoning techniques to generate a sequence of actions that lead to the desired outcomes. The current state of the environment model may not always provide enough information to make effective action selections, so the agent may need to reason about possible future states and their consequences. Decisions made by this type of agent may have a more long-term impact, as they are based on a desired outcome rather than a short-term objective.

- ***Service-based agent:*** This type of agent is based on a service function that is incorporated into part of the environment model as presented in Figure 4.4. The service function may provide information, resources, or capabilities that the agent can use to achieve its goals more efficiently or effectively. For example, a service-based agent in a transportation

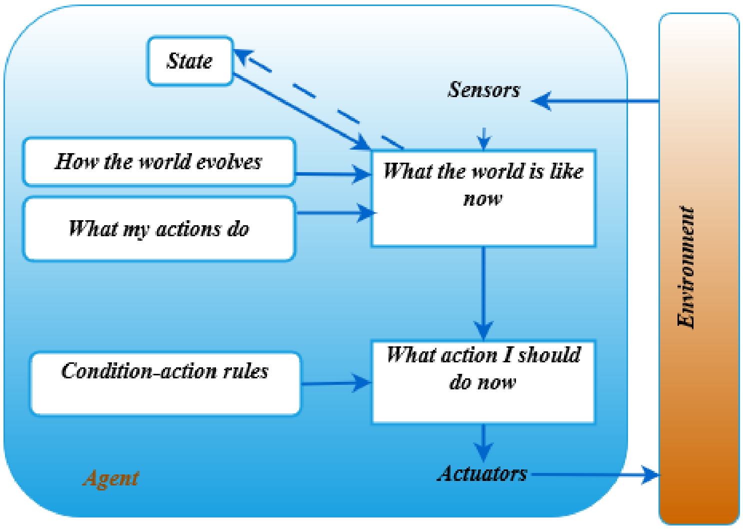


Figure 4.2: The composition of a model-based reflex agent

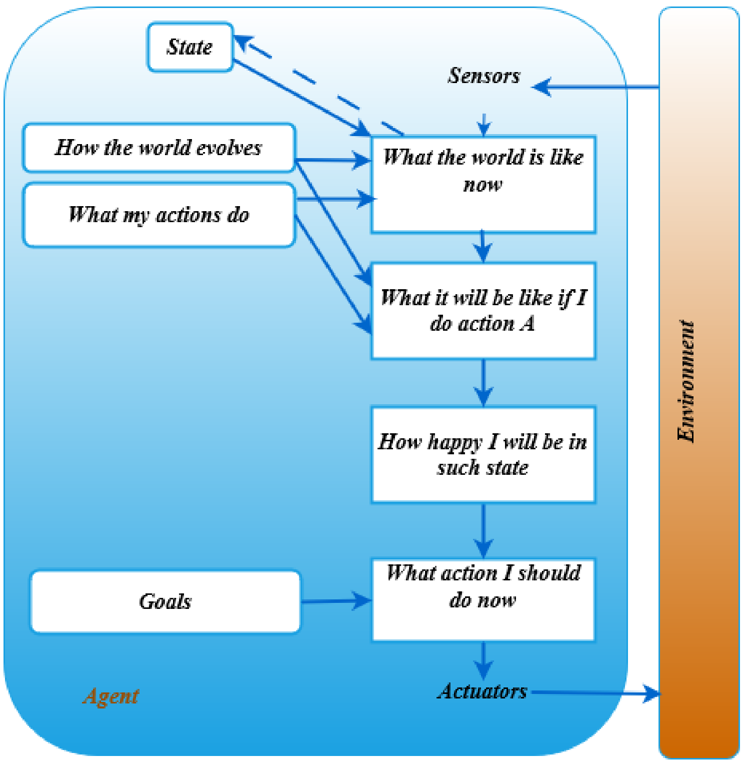


Figure 4.3: The composition of a Goal-based agent

system may use a traffic monitoring service to avoid congested routes or a weather service to plan for inclement conditions. The service function may be provided by another agent, a middleware component, or an external service provider.

- ***Knowledge-based agent (cognitive agent):*** This type of agent as shown in Figure 4.5 is generally used for gathering information related to the environment. It may use

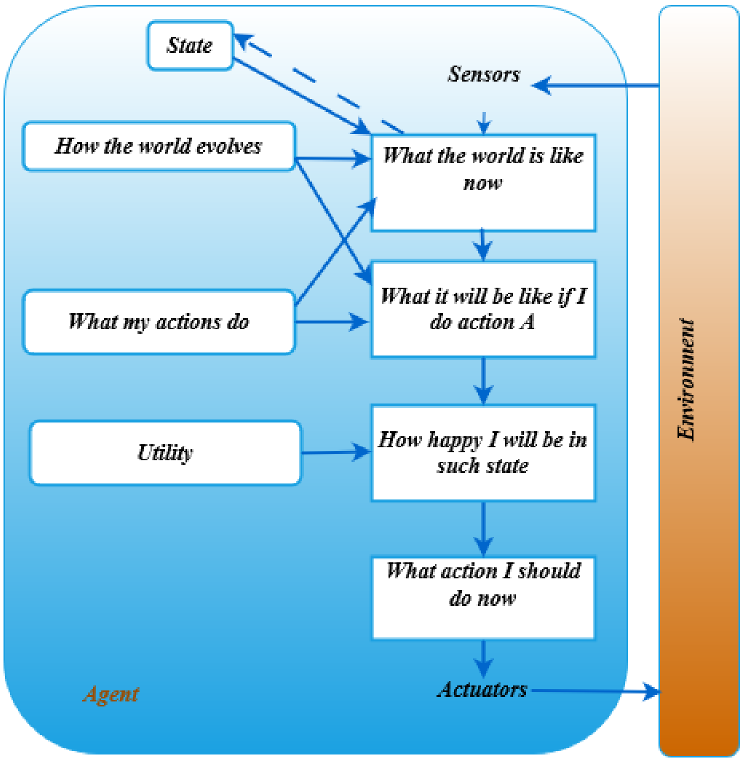


Figure 4.4: The composition of a Service-based agent

machine learning, natural language processing, or other techniques to analyze data and extract useful knowledge. The knowledge may be stored in a knowledge base, which the agent can use to make better decisions or communicate with other agents. A cognitive agent may also use reasoning or planning techniques to infer new knowledge or solve problems based on the available knowledge. The main focus of this type of agent is to preserve and utilize knowledge to improve performance or adapt to changing environments.

4.4 An overview of the MAS studies in the SCRM context

Over the past few years, MAS have emerged as a promising solution for SCM challenges. Software agents, which are sophisticated autonomous software entities that interact and behave collaboratively, are at the heart of MAS. In order to enable demand and supply processes, the application of MAS in collaborative SCM systems requires the modeling of communication and cooperation between agents. Some studies have explored this topic, including [153, 166, 231, 232].

The bullwhip effect, a phenomenon of demand variability amplification that causes excessive fluctuations in supply chain inventory levels and costs, is one of the issues that has received considerable attention in SCM literature. Several studies have focused solely on bullwhip effects, including [233]. Other research has gone beyond the bullwhip effect and examined the ripple effect, where disruptions in one part of the supply chain can have cas-

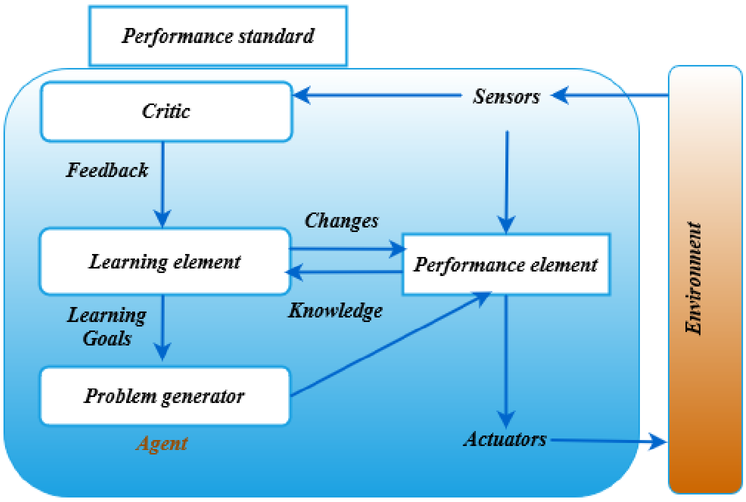


Figure 4.5: The composition of a Knowledge-based agent

cading effects throughout the entire system. For example, [56] used simulation to study the ripple effect in a multi-echelon supply chain during a natural disaster.

There has been limited research on the use of MAS in managing uncertainty within SCM. For instance, [234] proposed a model for a multinational SCM system that considers uncertainties on both the supply and demand sides. [235] reviewed the use of multi-agent modeling techniques and simulations in SCM, while [236] focused on SCM issues related to uncertain customer demands and supplier disruptions. SCRM deals with the challenges of managing uncertainty in a constantly changing environment. Other research studies aim to develop resilient and adaptable supply chains, including the works of [109, 237, 238, 239]

There are studies in the literature that deals with the overall problems of risk management in the SC and other works handles the problems in specific areas. For example, [240] had analyzed the impact of alternative production-sales policies on the diffusion of a new generic product. Adding to [241] had evaluated the short-term security of natural gas supply with a contracts-based simulation model by representing different parts of the SC. [242] had treated multi-risk disaster management. Also [243] had presented an agent-based computational framework for studying a complex multi-product, multi-county SC subject to demand variability, production and distribution capacity constraints.

In the last 20 years, a lot of research has been focused on coordinating the decision-making process and communication channels within supply chains. Several methods have been identified, such as revenue-sharing, sales rebates, quantity flexibility, buy-back, and quantity discounts, which have proven to be effective in achieving this coordination. A detailed analysis of this body of literature was provided by [244]. Additionally, [166] introduced a decision-making process for individual agents, along with the necessary tools to determine their individual and collective actions. In another study, [242] presented a multi-agent based decision support system for real-time disaster management that considers multiple risks simultaneously.

Software agents are distinct from other types of software technology because they have the ability to display proactive behavior, which is achieved through their independent decision-making abilities. By assigning a goal to an agent and allowing it to engage in conversations with other software agents, the agent can gather data in a proactive manner and decide when it is necessary to generate alert messages. This advanced functionality of agents was highlighted in a study by [245].

In our analysis, we found that there are relatively few studies that have specifically focused on using Agent-Based Modeling and Simulation (ABMS) for SCRM. Some examples of these studies include: [246], who developed a framework for ABMS of supply chain disruptions and focused on refining the agent process; [247], who created a framework for designing a multi-agent based DSS for managing and mitigating risks in manufacturing supply chains; and [248], who presented a multi-agent simulation model for managing risks in construction projects. Additionally, agent-based simulation has been utilized to model supply chain disruptions and their impact on supply chain performance in several studies, such as those by [142, 249, 250].

A significant advantage of MAS is their ability to break down complex problems into smaller, more manageable sub-problems. This is particularly beneficial for modeling supply chains as networks made up of independent businesses that engage in negotiations, production, and distribution of products and services. This feature was highlighted in a study by [251], emphasizing the usefulness of MAS in representing and managing the intricacies of SC operations.

The concept of a Holon refers to a system that is composed of smaller subsystems while also being a part of a larger system. Holonic agent concepts have been an active area of research, with current efforts concentrating on applying these concepts to larger systems such as complex supply chains [252] and transportation management [253]. Additionally, foundational steps for establishing the infrastructure required for creating agents have been discussed in [254].

Almost every decision to be made in the SCRM are affected by supplier evaluation and selection. For example, [255] studied the application of agent technology on a combined problem of sustainable order allocation and supplier selection proposing data base agent that is provided with an algorithm for evaluating suppliers. A simulation–optimization approach for multi-period news-vendor problem with multiple unreliable suppliers and multiple news-vendors have been proposed in [236] . Adding to [256] had implemented an agent-based negotiation model for supplier selection of multiple products with synergy effect and the last decision was taken according to the negotiation functions. [257] had developed supplier assessment methodology to be applied as the decision making procedure by the supplier evaluation agent. Also, [258] had defined a semantic-augmented MAS architecture.

The profit of the enterprise was taken in consideration in the development of some works as [236] however other works are interested in lower costs [259]. The assortment of problems such as inventory management in the SC with the focal on minimizing the overall cost are discussed by [260]. Inventory control where each local agent had optimized a local cost function for decision-making have been studied in [259]. Also [231] had discussed cost collaborative management.

The majority of conventional SC models concentrate on creating policies for SC agents that aim to either increase their anticipated overall profits or decrease their expected overall expenses. While the focus on maximizing expected profit or minimizing expected cost is suitable for decision makers who are not risk-averse, traditional SC models do not adequately address the needs of risk-averse planners, as they do not propose methods to mitigate the possibility of unfavorable profit outcomes. Hence, it is essential to integrate the concept of risk aversion into traditional SC models.

The findings in this part are based on a review of journal articles that mainly apply MAS in SCRM. The literature review was conducted in two phases: identification of the journal articles and compartmentalization of the papers by addressing different issues.

SCRM involves an extensive variety of topics. So this causes difficulties in categorizing the nature of the papers. Although there are some survey of the state of the art close to our work as [117, 261] but a readily classification of SCRM issues with DSS and MAS wasn't available in the current literature. Moreover, each paper uses different terms.

A summary of previous research on risks, DSS and MAS in SCRM are categorized in table 4.1. The table outlines the scope of application for each research. which are classified into 5 issues: process SCRM, approaches, problem area, methodology and DSS level.

The benefits of a multi-agent SCRM model for risk management are a plurality. The learning competence via algorithms and the real-time adaptability that is established in the model can prompt a more efficient reaction to data asymmetries amongst SC partners. This in turn can lead to more effective SCRM and synchronization of SC processes [247]. Agent technology offers the essential capability for resolving distributed problems and the independence to achieve proactive system behavior. Moreover, agent technology possesses adaptable communication capabilities, which constitute a fundamental characteristic that existing technological approaches based on contemporary technologies lack.

The outcomes and their implications empower the SCR managers to combine the MAS model to their SCM system as a choice help tool.

The table 4.1 provides a comprehensive overview of studies that have used MAS for SCRM, demonstrating the effectiveness of this approach in addressing specific problems such as supplier selection, order allocation, and inventory control. However, the integration of DSS with MAS in SC remains limited, with only 36% of works utilizing this combination.

To overcome this limitation, an appropriate DSS integrated with the risk management process and MAS is required, which can assist decision-makers throughout all risk management phases and provide solutions at each step. It is worth noting that the majority of MAS research in SCRM is led by computer science researchers, which emphasizes software architecture rather than an in-depth analysis of the problem at hand.

Furthermore, MAS has a unique ability to model and monitor complex phenomena by using a bottom-up technique that examines the micro-level behavior of individual agents to comprehend macro-level emergent behavior. This capability is especially useful for modeling complex SCRM problems that are challenging to explain through empirical research or analysis.

Lastly, while most works that utilize DSS with MAS rely on mathematical models, there is a need to explore the potential of artificial intelligence to construct a real smart system for

SCRM. By doing so, researchers and practitioners can unlock new possibilities for addressing the complexity of SCRM and enhancing decision-making.

4.5 The proposed multi-agent approach for risk management in supply chains

Our multi-agent approach to risk management in SCs is a promising tool for solving SCM problems. This approach leverages the advanced capabilities of software agents to proactively collect data, make decisions, and generate alerts. The ability to assign an agent a goal and its advanced communication abilities allow the agent to operate independently, helping to decompose complex problems into more manageable sub-problems. This is especially useful for representing supply chains as networks of autonomous companies negotiating, producing, and delivering products and services.

The role of a MAS in real-time supply chain risk management is to provide a decentralized and distributed decision-making framework that enables effective collaboration and coordination among different agents involved in the supply chain. By implementing the MAS, the following benefits can be achieved:

- Improved risk assessment: MAS can collect and analyze data from various sources in real-time and provide a comprehensive view of the risk levels in the supply chain.
- Faster decision-making: MAS enables agents to make decisions independently and quickly, reducing the response time to potential risks.
- Increased flexibility: MAS allows for changes in the supply chain structure, such as the introduction of new suppliers, without disrupting the entire system.
- Better coordination: MAS enables agents to exchange information and coordinate their actions, leading to a more efficient and synchronized supply chain.
- Enhanced transparency: MAS provides a clear and transparent view of the supply chain operations, enabling better monitoring and control.

In summary, the MAS approach enables supply chain organizations to proactively manage and mitigate risks in real-time, resulting in improved supply chain performance and resilience.

To develop an agent-based SCRM concept, a suitable software engineering methodology is necessary. In the following, a suitable methodology is selected and adapted to the needs of agent-based risk management in supply networks. We specifically describe the different components (agents) of our NeutroMAS4SCRM system and their interactions by showing the established relationships between the various agents.

Table 4.1: Multi-Agent System works in supply chain risk management.

Reference	SCRM Process				Approche (Empirical/analytical)	Problem area	Methodology	DSS (S,T,O)
	I	A	M	M				
[255]	•	•	-	-	Case study: electronics sector	Sustainable supplier selection, Order allocation	Database Agent, Supplier Agent, Decision Maker Agent & Order Allocator Agent	O
[262]	-	•	-	-	Simulation	Bullwhip effect ,heterogeneous retailers	Enterprise Agent + 9 functional agents	O
[263]	•	•	-	-	Tourism service SC	Customer satisfaction	Hotel agent & Travel agency agent	-
[242]	•	•	-	-	-	Multi-risk Disaster management	-	S
[236]	•	•	•	-	Newsvendor problem numerical example	Uncertain customer demands & suppliers' disruption events	Agent-based approach & Optimization	-
[232]	•	•	•	-	Valorpneu Network	The interactions & Business interoperability	Each company is modeled as an agent	O
[258]	•	-	-	-	Marine company	Supplier selection	5 types of agents or modules	O
[259]	-	-	•	-	Procter & Gamble's home-care products	Inventory control	local agent	O
[238]	-	•	-	-	Timber SC in Southern Ontario	Supply risks	Truck agent, Sawmill agent & Forest agent	O
[250]	•	•	•	•	Lube oil supply chain.	Disruption management	Agent-based simulation framework	O
[166]	•	•	•	-	Prototype	Logistics risk management	Agent BDI	-
[256]	•	-	-	-	Simulation	Supplier selection	Seller agent & Buyer agent	-
[246]	•	•	•	-	Manufacturing electronic firm in Taiwan	SC Disruption	Agent-based SC Framework	O
[264]	•	-	-	-	The aquatic SC	Logistics management, Supply quality risk	-	-
[262]	•	•	-	-	-	Partial information sharing, Bullwhip effect	-	O
[153]	-	•	-	-	Numerical experiments.	Cooperative advertising	Agent manufacturer & Agent retailer	-
[265]	-	-	•	-	Natural disasters	Natural disasters, Emergency decision making	Multi-agent negotiation	-
[142]	•	-	-	-	The Austrian intermodal transport network	Intermodal transport network disruption	Agent-based traffic micro simulation model	-
[234]	-	-	-	•	Automotive SC	Lateral transshipments, Multi-location inventory systems	-	-
[249]	-	-	-	•	Simulation model	Supply disruptions	Consumer agent with 4 different states	-
[241]	-	•	-	-	The Colombian gas markets	Supply security	-	S
[56]	•	-	-	•	AnyLogistix multi-method simulation	Ripple effect	Anylogic Agent	O
[247]	•	•	•	-	-	Demand & supply problem	5 software agents	-
[248]	•	•	•	-	Nursing training institute construction (South-West, France)	Construction project	Risk agents	S
[251]	•	•	-	-	-	Supplier selection	WS, DDF & DF Agents	-
[231]	•	•	•	-	-	Cost collaborative management (CCM)	Adaptive multi-agent architecture for CCM in SC	O
[266]	•	-	-	-	Newsvendor	Suppliers & retailers problems	2 agents (supplier & retailer)	O
[257]	•	•	-	-	Real-world case study: a medium-to-large industry (vehicle tires & rubber products)	Supplier evaluation & selection	Supplier évaluation agent	O
[109]	-	-	•	-	Simulation	Retail stockouts	Consumer Agents, Product Agents & Store Agents	-

I: identification A: assessment M: mitigation M: monitoring S: Strategic T: Tactic O: operational

4.5.1 Approaches

4.5.1.1 Macro and Micro perspectives

Agent-Oriented Software Engineering (AOSE) is a software engineering methodology specifically developed for the design and development of Multi-Agent Systems. Unlike traditional software engineering methodologies, AOSE takes into account the unique characteristics of agents, such as autonomy, proactivity, and social ability. Agents are autonomous entities that can perceive their environment, reason about it, and take actions to achieve their goals. They can interact with other agents and external systems to achieve a common objective.

The goal of AOSE is to provide a systematic and rigorous approach to developing MASs. AOSE involves the use of formal methods, such as modeling languages and verification techniques, to ensure that the designed MASs meet their requirements and are correct and reliable. It provides a set of guidelines and best practices for developing MASs, including identifying agents and their roles, modeling agent behavior and interactions, and specifying agent communication protocols.

The basic engineering steps, such as Analysis, Design, and Implementation, are still applicable in the design and development of MASs. However, according to Wooldridge [230], there is a clear differentiation between designing an agent society as a whole, where each agent type is considered as a black box, and further refining each specific type of agent. The former is known as the macro perspective of AOSE, which deals with the overall architecture of the MAS, while the latter is referred to as the micro perspective of AOSE, which focuses on the individual agent's design and implementation, as illustrated in Figure 4.6. This differentiation allows for a better understanding of the complex interactions between agents and their environment, and facilitates the development of MASs that are efficient, robust, and scalable.

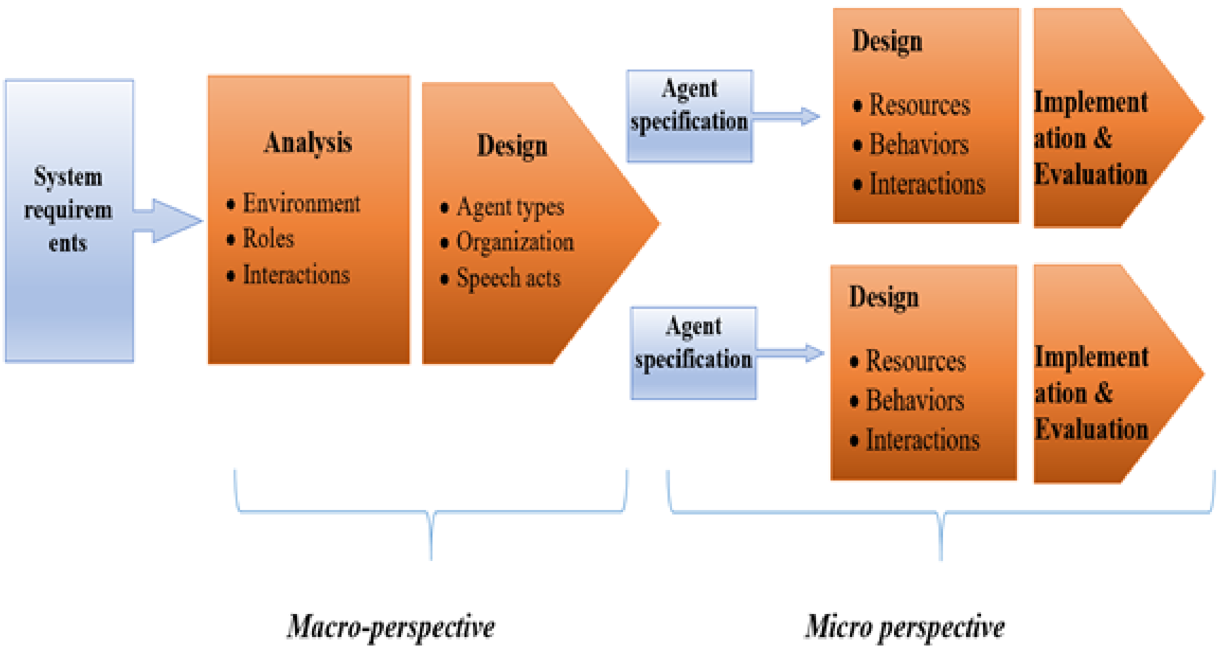


Figure 4.6: Macro- and micro-perspective of Agent-Oriented Software Engineering

The macro perspective of AOSE focuses on the high-level design and organization of agent systems. It involves the definition of the system's architecture, the definition of the interaction protocols between agents, and the assignment of tasks to individual agents. Advantages of the macro perspective include the ability to manage complex systems, and the ability to model large-scale, dynamic systems with multiple agents that interact in real-time. The micro perspective of AOSE, on the other hand, focuses on the internal behavior and decision-making processes of individual agents. This perspective deals with the definition of agents' objectives, the selection of appropriate actions based on their beliefs and goals, and the definition of reactive and proactive behaviors for agents. Advantages of the micro perspective include the ability to design intelligent and adaptive agents that can respond to changing conditions and make autonomous decisions, and the ability to model systems with agents that have different motivations, preferences, and behaviors.

In conclusion, both the macro and micro perspectives of AOSE have their own advantages and challenges. By considering both perspectives, AOSE provides a comprehensive approach to software engineering that takes into account the needs of both system-level and agent-level design.

During the analysis phase within the macro-perspective, three aspects are typically considered according to [230, 267]:

- ***The environment :*** The agent system's surroundings are evaluated, which includes determining the domain and problem that the system will address, as well as identifying any environmental restrictions. The agent system's objectives are established based on the system's specifications.
- ***Key roles*** responsible for the main functions of a system are identified. These functions must be executed to achieve the goals of an agent solution.
- ***Interactions :*** The connections between functions and their corresponding roles are recognized and designed. These models of interaction establish, for instance, which roles must collaborate to attain a goal.

The findings of the analysis stage are utilized in the design stage to specify the types of agents that assume one or more of the identified roles and to establish a structural dependence between agent types (for instance, how many agents of a certain type are created in an agent system). The interactions identified in the analysis phase are structured as agent interactions within such an agent community. The design stage generates a comprehensive model of a multi-agent system that outlines the agent types, their roles, and the primary interactions between them.

In the micro-perspective design phase, these agent specifications are refined with regards to the following aspects, according to Bauer et al. [267]:

- ***Resources:*** Each agent needs several types of resources that it can use to carry out activities. These are its internal knowledge assets, its goals, and external resources that it can employ. External resources provide sensory information (e.g., access to databases, user inputs) or represent effectors that are used to influence an agent's environment (e.g., communication channels or machine control interfaces).

- ***Behaviors:*** The way an individual agent achieves its goals by employing activities that use its available resources is described in an agent's behaviors. A behavior combines several activities that are triggered if certain preconditions apply and lead to a specific outcome (e.g., a modification of an agent's knowledge or environmental situation).
- ***Interactions:*** A detailed description of how an agent interacts with other agents in an agent society and how these interactions are initiated and controlled by an agent's behaviors is summarized in an interaction model.

The final step in AOSE is the implementation of the detailed concept and evaluation of the MAS. In subsequent sections, a specific methodology for designing the agent society and for the micro-perspective is discussed, prototypical implementations are discussed in the next chapter, and an overall evaluation of NeutroMAS4SCRM concept is carried out in this chapter.

4.5.1.2 Methodologies for the development of MAS

Currently, there are a significant number of MAS design tools and methodologies [267]. Each of them is based on its own conceptual foundation and covers a number of aspects that are considered essential. Most of these methodological proposals are inspired by the results of the object-oriented software engineering field. In this section, we present several examples of these methodologies and conclude with some arguments that reinforce our choice of the methodology to use for our MAS application in the logistics chain.

- ***AUML***: The goal of AUML [268] is to extend UML with facilities that enable the description of agents. This formalism aims to recommend a technology for adopting a common semantic, meta-model, and abstract syntax for the analysis and design of agent-based methodologies. This technology must cover the lifecycle of AUML products and work tools and be in accordance with existing FIPA specifications and the Object Management Group (OMG). Currently, UML versions 2.0 and 2.1 have incorporated several concepts of Agent UML, as shown on the official AUML website. Thus, with UML 2.0 and later versions, one can model an agent-oriented application.
- ***M-UML***: Is a modeling language proposed by [269] to represent and describe mobile agents. It provides a standardized approach for modeling the behavior of mobile agents and their interactions with other agents or systems. The language encompasses a range of UML (Unified Modeling Language) diagrams and notation, such as sequence diagrams and activity diagrams, that are adapted to capture the particularities of mobile agents.
- ***GAIA***: [270] is a methodology where the multi-agent system is seen as an organization composed of roles interacting with each other. The methodology starts with a description of the organizational structure of the system, composed of roles and interactions between them. Two phases are distinguished: the analysis phase, which allows the construction of the role model and the interaction model, and the design phase during which the agent, service, and accointance models are created.

  This methodology approaches the design of a MAS without a pre-established agent architecture model. Its use leads to a set of specifications that can be considered at the analysis level. However, the design is very weak, as no computational model is considered.

- ***MaSE*** (Multi-agent System Engineering [271]) is a generic methodology that considers the initial context of the system, assumed to contain a well-defined set of functional requirements, and allows the extraction of a set of hierarchized goals as its starting point. It focuses on the practical aspects of building MAS. This methodology consists of two phases. The analysis phase takes place in three steps: goal capture, use case application, and role refinement. The design phase has four steps: creation of agent classes, construction of conversations, assembly of agent classes, and design of the system.

  MaSE proposes to start with a goal analysis as it considers that goals are more stable in analysis and design than functions, processes, and information structures. This goal analysis and its clear distinction from a traditional functional analysis are the most interesting contributions of MaSE. It also proposes a mechanism for identifying roles and assigning them to agents.

  To finally arrive at a computational model of agents, however, it carries out some simplification when considering that each type of agent corresponds to an object class. On the other hand, certain considerations, such as assuming that there is an initial set of functional needs or determining a well-established set of conversations, limit its applicability to solving problems similar to those dealt with using a classic object-oriented methodology. This results in a set of classes whose behavior is defined by automata, but it is not clear how one could approach the construction of deliberative agents, such as BDI agents, since, for example, it is no longer defined how to manage and control the satisfaction or failure of goals.

The list presented above is not exhaustive. Below, we show some arguments guiding and reinforcing our choice of methodology to use for the modeling phase of our architecture:

Table 4.2: Comparison of Agent-Oriented Tools.

Tool	Abstraction Level	Agent Interaction Model	Mobile Agent Support	Real-time Reaction	Decision Making
AUML	High	Model-based	No	Yes	No
Gaia	High	Model-based	No	No	No
M-UML	High	Model-based	Yes	No	No
MaSE	High	Methodology-based	Yes	No	No
AALAADIN	High	Framework-based	Yes	No	No
Jason	High	Platform-based	No	Yes	Yes
JACK	High	Model-driven	No	No	No
Prométhée	High	Methodology-based	No	No	No
RoboCup	High	Platform-based	No	No	No
Moise	High	Framework-based	No	No	No
Tuple Centers	Low	Paradigm-based	No	No	No
RBSE	High	Methodology-based	No	No	No
ADELFE	High	Methodology-based	No	No	No
Tropos	High	Methodology-based	No	No	No
KQML	Low	Language-based	No	No	No

This table 4.2 provides a comparison of several agent-oriented tools based on key characteristics such as abstraction level, agent interaction model, mobile agent support, real-time reaction, and decision making. Let's go through each criterion:

- ***Abstraction Level:*** This criterion refers to the level of abstraction provided by the tool. It assesses how abstract or detailed the tool's modeling capabilities are. In this table, the tools are categorized as having a "High" abstraction level, indicating that they offer comprehensive modeling capabilities.
- ***Agent Interaction Model:*** This criterion focuses on the approach or model used to represent and facilitate agent interactions within the tool. The table indicates the different interaction models employed by each tool, such as "Model-based," "Methodology-based," "Framework-based," etc.
- ***Mobile Agent Support:*** This criterion assesses whether the tool supports mobile agents, which are autonomous software agents capable of migrating between different execution environments. The table indicates whether each tool provides support for mobile agents with a "Yes" or "No" entry.
- ***Real-time Reaction:*** This criterion evaluates whether the tool enables real-time reaction capabilities for agents. Real-time reaction refers to the ability of agents to respond or react to stimuli in real-time. The table indicates whether each tool supports real-time reaction with a "Yes" or "No" entry.
- ***Decision Making:*** This criterion focuses on the decision-making capabilities of the tool. It indicates whether the tool supports decision-making functionality for agents. The table categorizes each tool as either supporting decision making with a "Yes" or not supporting it with a "No."

The comparison provides a general overview of each tool and can help in selecting the best tool for a particular use case based on the specific requirements.

- There is a significant number of methodologies and design tools for MAS and the community working in the field of agents faces the problem of identifying a common vocabulary to support them. However, there is not yet a mature enough standard methodology that addresses all the necessary aspects for defining an MAS, nor the entire development cycle of this type of software.
- J. Pavón, one of the authors of the INGENIAS methodology, states in [272] that despite the existence of many agent-based applications, there is still a lack of experience for designing and constructing MAS at an industrial level. The vast majority of agent-based applications are built without using reusable agent components and are not generalizable. This is why research on methods, tools, and agent platforms is of great importance for the implementation of agent technology outside the purely academic field. In the current situation, few methodologies have brought significant real-life cases to practice and are assisted by tools. Furthermore, existing methodologies only consider some aspects of the lifecycle, usually analysis and design. For implementation, most methodologies are conditioned by the use of a determined agent architecture.

- The agent paradigm can extend to the object paradigm. As a result, an MAS development methodology should take advantage of the experience of the object-oriented approach. Object-oriented methodologies have acquired a high level of maturity and their advantages are widely recognized. A large number of software developers are familiar with them and use a wide range of available tools.

Among the various tools listed in the table 4.2, AUML stands out due to its alignment with the requirements of the system in multiple criteria. First, AUML exhibits a high abstraction level, showcasing its comprehensive modeling capabilities. This means that AUML offers a rich assortment of constructs and features specifically designed to represent and design complex agent systems effectively.

In terms of agent interaction modeling, AUML adopts a model-based approach. This approach provides a structured and standardized method to depict the interactions between agents. By employing this model-based approach, AUML facilitates clear communication and enhances understanding of the system's behavior, enabling smoother collaboration between agents.

Moreover, AUML excels in real-time reaction capabilities, as it supports agents in promptly responding or reacting to stimuli. This real-time responsiveness is of great significance in systems that necessitate timely and dynamic decision-making in response to ever-changing circumstances. With AUML, the system can effectively adapt and make informed decisions in real-time, enhancing its overall performance and agility.

Considering these factors, AUML emerges as a suitable choice for implementing the system due to its high abstraction level, model-based interaction approach, and support for real-time reaction. These qualities make AUML well-suited for designing and developing agent systems that require complex modeling, well-defined interaction patterns, and real-time responsiveness.

It's important to note that the choice of tool ultimately depends on the specific requirements and context of the system being developed. The table provides a comparative overview of different tools, and based on the given information, AUML appears to be a favorable option for the mentioned criteria. However, other considerations such as ease of use, tool availability, and compatibility with existing technologies should also be taken into account when making the final decision.

In order to give a methodological framework to the modeling process, we will subsequently apply the AUML formalism, which contains a large number of concepts related to agents. In fact, UML is a widely known, accepted, and proven standard for modeling object-oriented applications. The fact that the agent paradigm is considered an extension of the object paradigm has led several authors to extend UML to take into account agent concepts. By choosing AUML, our models proposed in this manuscript will be widely disseminated and understood. Other more technical arguments related to the issue we are addressing and that reinforce our choice will be presented in the next chapter.

4.5.2 Agent society in NeutroMAS4SCRM for SCRM

To leverage our NeutroMAS4SCRM proposition, we will begin by presenting the macro perspective of AOSE, which aims to explain the role and type of agents in the system, as well as the interactions between these agents. This approach will enable us to understand how individual agents can work together to form a global system for SCRM.

Using AOSE, we will design an agent society for managing risks in the supply chain. Each agent will have specific tasks, such as risk assessment, decision-making, or communication. The agents will work together to identify and mitigate risks in real-time, thus improving the resilience of the supply chain.

In summary, we will leverage our proposition by using the macro perspective of AOSE to design an agent society for SCRM. The interactions between these agents will enable proactive and real-time risk identification and management, ultimately enhancing the overall resilience of the supply chain.

4.5.2.1 The roles and types of agents

The roles and types of agents are important components in the management of SCRs. In the macro-perspective of AOSE, different types of agents are proposed for managing risks within supply chain networks, along with basic interaction models. The specific roles and responsibilities of these agents can vary depending on the particular requirements and goals of the SCM. However, some common functions that may be assigned to these agents include communication, data collection and analysis, risk evaluation, decision-making, and alert management. Understanding the different roles and types of agents in SCRM is essential for designing and implementing effective systems for managing risks in these networks.

Each company within the network is represented by three agents, as detailed in Figure 4.3. These agents are responsible for real-time risk alert generation and use neutrosophic logic to evaluate potential risks. In addition, they serve as intermediaries for communication and management of internal and external alerts, and are crucial to the proactive collection of SCRM data. The data collected forms the foundation for the analysis and interpretation phase of the SCRM process, where new information is generated through research, selection, and interpretation of data. The resulting information product provides a snapshot of the status of a particular order, represented by a set of SCRM data types. This group of roles is referred to as the order monitoring group.

The functions of agents within the risk management process of businesses:

- Each of the three agents is equipped with an interface for internal and external communication and alert management, in addition to monitoring. The alert management interface allows the agents to receive and respond to alerts related to potential issues or disruptions in the supply chain. These alerts can come from various sources, such as sensors, tracking systems, or manual reports, and may signal a range of issues such as delays in delivery, quality issues, or inventory shortages. By responding quickly and

Table 4.3: The NeutroMAS4SCRM system Agents.

Agent Name	Roles
RiskAppAgent	Agent related to the company's procurement risk management process: • Communication Manager. • Surveillance Manager. • Information collected. • Risk Evaluation (research, iteration of data launch status) + AHP method + surveillance decision. • Risk Alert Manager. • Risk Handling.
RiskFabAgent	Agent related to the fabrication risk management process: • Communication Manager. • Surveillance Manager. • Information collected. • Risk Evaluation (research, iteration of data launch status) + AHP method + surveillance decision. • Risk Alert Manager. • Risk Handling.
RiskDistAgent	The main role of this type of agent is to handle sales risk management procedures: • Communication Manager. • Surveillance Manager. • Information collected. • Risk Evaluation (research, iteration of data launch status) + AHP method + surveillance decision. • Risk Alert Manager. • Risk Handling.

effectively to these alerts, the agents can mitigate risks and ensure that the supply chain network operates smoothly.

- Information Collection: The proactive collection of SCRM data is based on both internal and external requests for such data. This step provides the foundation for the analysis and interpretation phase of the SCRM data process. During this phase, new information is generated through research, selection, and interpretation of data. An information product is created that represents the status of an order through a set of SCRM data types. This group of roles is collectively referred to as the order monitoring group.

- Monitoring Manager: The role of the Monitoring Manager involves managing the beginning and completion of monitoring procedures, responding to clients' status requests, and actively managing alerts. The successful launch of monitoring activities is closely related to effective proactive alert management. Additionally, the Monitoring Manager is responsible for creating an information product by collecting and analyzing SCRM data.

- Alert Management: The process of Alert Management involves the identification and response to critical issues in a timely and effective manner. These alerts are directed

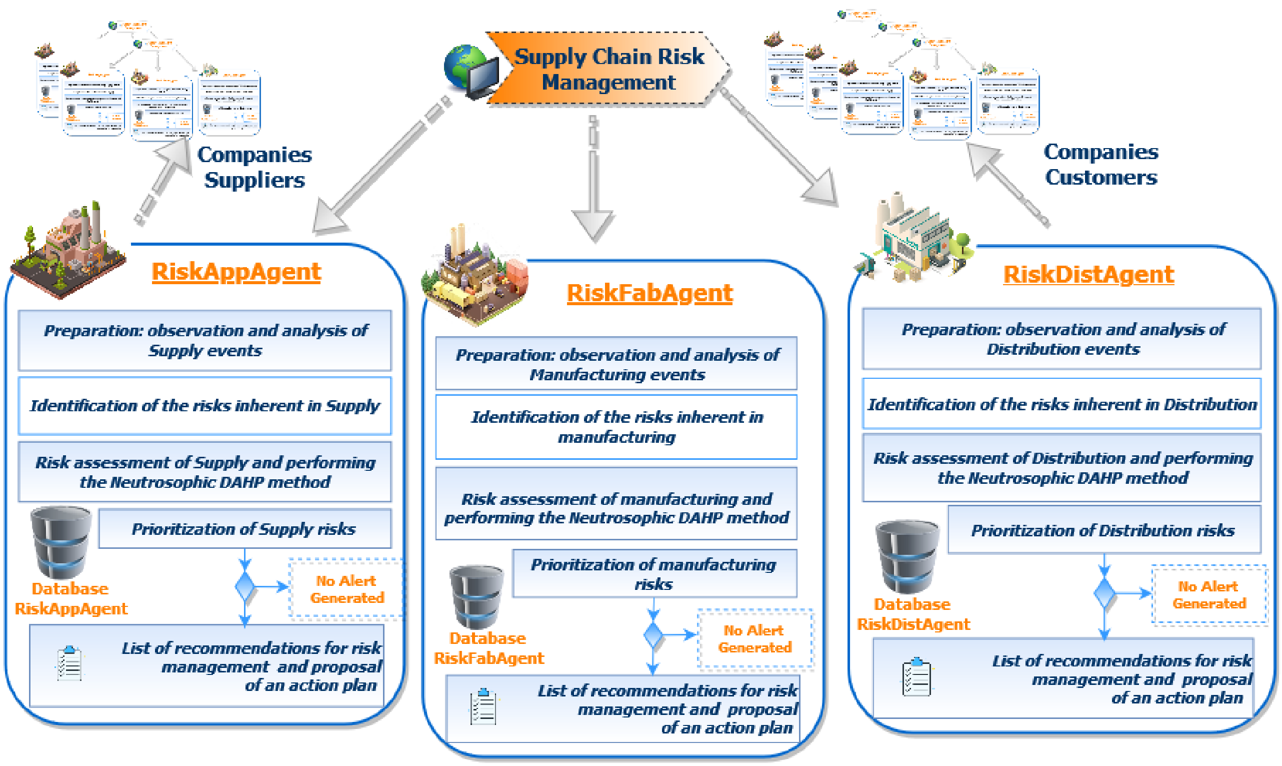


Figure 4.7: Agent societies in a SCRM network

towards both internal stakeholders, such as management teams and employees, as well as external partners in the supply chain network, including vendors, suppliers, and customers. The purpose of Alert Management is to ensure that everyone involved in the supply chain is aware of any potential problems or disruptions that may impact the operations or delivery of goods and services. Effective Alert Management is crucial for maintaining the overall efficiency and productivity of the supply chain network, minimizing the risk of delays, and reducing the costs associated with disruptions.

- Risk handling: Encompasses the crucial step of making informed decisions by considering the findings from the synthesis and sensitivity analysis. Once the risks are identified, treatment plans are initiated, taking into account the severity of each risk. These plans are designed to mitigate and manage the identified risks, safeguarding the overall business operations and minimizing potential adverse impacts. The treatment plans may include a range of strategies such as risk transfer, where insurance or contracts are used to shift the responsibility to external parties, or risk mitigation, which involves implementing proactive measures to reduce the probability or impact of risks. This can include diversifying supplier networks, implementing redundant systems, creating buffer inventory, improving logistics and transportation capabilities, or adopting advanced technology solutions for real-time monitoring and predictive analytics. Additionally, contingency plans are developed to outline specific actions to be taken in response to different risk scenarios, ensuring a swift and coordinated response. Regular monitoring and reassessment of the treatment plans are necessary to adapt to evolving risks and maintain the effectiveness of the risk handling strategy.

Each of the agents depicted in Figure 4.7 aims to collaborate with others to expand the range of potential scenarios for managing risks and mitigating undesirable events that pose a threat to the supply chain. In terms of their responsiveness and ability to process information, these agents are designed to react to incoming stimuli in the form of messages, and they also employ decision-making strategies that utilize the Neutrosophic Data AHP method.

In order to create a concept based on agents, it is necessary to use a suitable software engineering methodology. In the following text, we will outline the distinctive features of agent-oriented software engineering, and choose a methodology that can be customized to meet the requirements of risk management using an agent-based approach in the context of supply chains.

4.5.2.2 The structural design of the agent society

It refers to the way agents are organized and interact with each other in a society. This may include aspects such as the distribution of resources, roles and hierarchical relationships, and mechanisms for coordination and decision making.

Two key dimensions of communication are prominent in the agent-based SCRM concept:

- Inter-organizational communication: This refers to the interaction between businesses and involves the exchange of messages between the distribution agent and the supply agent of each SCRM agent society. These agents serve as the main point of contact for external communication, facilitating communication between different organizations.
- Intra-organizational communication: This refers to the interactions that occur within an SCRM agent society between different types of agents responsible for executing the enterprise system. These interactions play a critical role in ensuring coordination and effective decision making within the organization.

The distinction between these two dimensions of communication highlights the importance of effective communication for the success of SCRM systems. By understanding the communication needs and processes within and between organizations, organizations can design and implement SCRM systems that support the efficient exchange of information and cooperation between agents.

Based on our understanding, the supply chain network is composed of three distinct agents, each of which represents a different company: a RiskAppAgent for service level supply risk management, a RiskFabAgent for production or manufacturing level service risk management, and the last agent, the RiskDistAgent, for distribution level service risk management.

The individual agents are responsible for managing risks in each of the three sectors that comprise the company. They ensure that the company's monitoring initiatives are consistently initiated and that external requests for status updates and alerts are managed effectively. Additionally, the agents provide a comprehensive overview of all the monitored orders within the company. This is crucial for the ongoing assessment of risk levels within the organization and the supply chain as a whole.

If a single agent is responsible for managing different orders, additional planning procedures would be necessary. To avoid this, each order is monitored by several agents, with each agent providing a standard interface to the company's internal data sources. These agents are capable of handling multiple requests from different agents within the supply chain network, and can manage access to their respective data sources. These functionalities are standard features of agent development frameworks like JADE [273], which can be utilized to implement an agent system for Supply Chain Risk Management.

Users can manually access these systems using the application's graphical user interface (GUI). This enables network partners with their own proprietary risk management tracking systems to communicate and exchange data through the interface. However, the most optimal approach to SCRM involves each network partner implementing their own SCRM system. This makes data collection and analysis more efficient at all levels of the supply chain network.

The structural interdependencies between the agents in a SCRM agent society and the main types of knowledge assets that they act upon can be depicted through an abstract model in the form of an AUML class diagram. This provides an overview of the relationship between the agents and their interactions.

Each agent initiates monitoring activities, and each company's distribution agent has access to multiple external supply chain agents from other companies. The distribution agent has a direct connection to the supply chain agent to request data on manufacturing orders, which serves as a gateway to external network partners. The agents can access the SCRM systems of other partners by querying address information since the SCRM process is applicable to each network partner. This results in multiple SCRM systems interconnected in a supply chain network, forming a recursive many-to-many relationship between the companies' agents.

4.5.3 Interactions among agents

4.5.3.1 Basic Interaction Protocol

Interactions among all types of SCRM agents are based on the exchange of requests for supply chain data and activities to be performed for the collection or manipulation of that data. A standardized protocol, the Foundation for Intelligent Physical Agents (FIPA) Request Interaction Protocol [274],is used as the appropriate basic interaction protocol for this exchange that is appropriate for our work.

According to the FIPA specification document (FIPA-00037), the Request protocol is defined as: "A protocol for sending a request from one agent to another with the expectation of a reply. This protocol is used to initiate a conversation between two agents, where the requester agent sends a message to the responder agent asking for some action to be performed. The responder agent sends back a reply, which may be a confirmation of the request, a denial of the request or a counter-proposal." [275]

FIPA Request (refer to Figure 4.8) is a well-established interaction protocol used in agent-based systems that provides a structured and standardized way of exchanging requests and responses between agents [274]. It defines the format and content of requests, the mechanisms

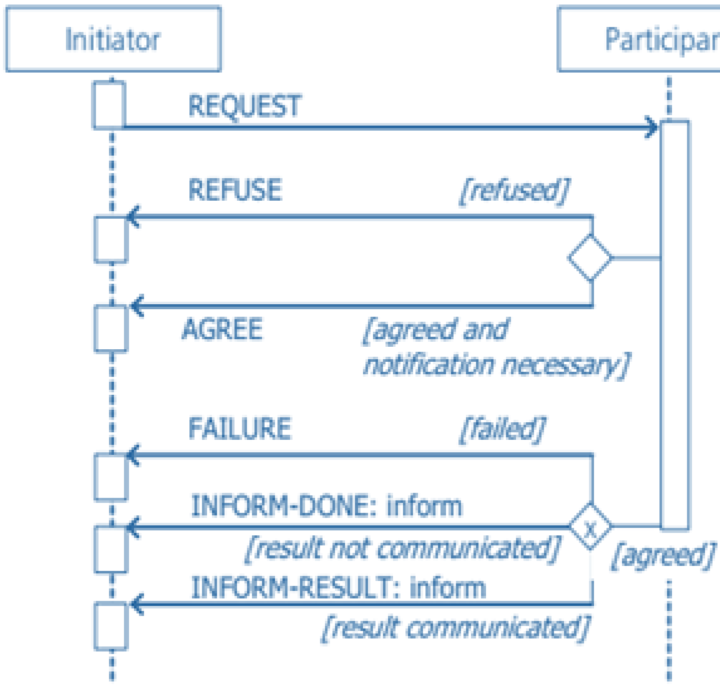


Figure 4.8: The "Request" protocol of interaction in the Foundation for Intelligent Physical Agents.

for handling failure and time-out situations, and the expected responses to requests. The use of this standardized protocol ensures that interactions between SCRM agents are consistent and predictable, even in complex and dynamic environments [274].

Once the activities triggered by the request have been carried out by the participant, it must acknowledge its completion, either by sending a failure message indicating that the request could not be fulfilled, or by sending information as a final response. This information includes either the result of the actions performed in response to the request (inform-result), or a simple confirmation of the successful completion of the request (inform-done), which is sent to the initiator of the request.

In an SCRM agent society, the standard response to a request includes the communication of results, as the exchange of information between agents is critical for the coordination and management of the supply chain. The inform-result message contains the results of the actions performed in response to the request, providing the initiator with the necessary information to make informed decisions and continue to coordinate the supply chain.

Figure 4.9 illustrates the usage of an inform-result message that provides detailed information about the results of actions, which is defined based on the proposed SCRM ontology. Each type of agent decides on an appropriate action based on the type of message, the sender, and the content of the message. In addition to reacting to messages, each agent can proactively decide to take or initiate other actions in the risk management process (e.g., sending an alert).

```
ACLMessage message = new ACLMessage(ACLMessage.INFORM_RESULT);

        message.setSender(new AID("RiskAppAgent@Enterprise3", AID.ISGUID));
        message.addReceiver(new AID("RiskDistAgent@Enterprise2",AID.ISGUID));
        message.setContent("(OrderID=1; OrderType=\"Warehousing\"; "

                        + " PlannedAchievementDate =(xxxx-xx-xx;12:00); "
                        + " ImportantStepID =(( NameofStep;
                        + " PlannedCompletionDate =(xxxx-xx-xx;12:00); "
                        + " CompletionDate =(xxxx-xx-xx;12:00));... "
                        + "RisksTypes=(has_RiskTypeID(34); "
                        + "has_Description(\"XXXX\"); "
                        + "has_RiskOccurenceDate(xxxx-xx-xx;15:50); "
                        + "has_RiskSeverity(3); "
                        + "has_ RiskEventPerturbation =(has_ EventCarrierTypeID
(56); "
                        + "has_DescriptionDetails(\"yyyyy\"); has_Date(xxxx-xx-
xx;15:00);));");
         message.setOntology("SCRM_Ontology");
         message.setConversationId("3");
```

Figure 4.9: Surveillance Result - FIPA Message to the Distribution Agent.

4.5.3.2 Intra-organizational communication

An NeutroMAS4SCRM system within a single company is composed of different types of agents, each serving a specific role in the overall system. These agents work together to achieve the objectives of the NeutroMAS4SCRM system.

The communication between these agents is based on FIPA "Request" interaction protocol. This protocol allows for effective and efficient communication between the agents, allowing them to exchange information and coordinate their activities. In addition, the NeutroMAS4SCRM system also facilitates communication with external entities, such as other companies within the supply chain network.

Figure 4.10 provides a visual representation of the main interactions that occur within the NeutroMAS4SCRM system. It shows how the different agents communicate with each other and highlights the different types of information that are exchanged between the agents. The figure also highlights the communication between the NeutroMAS4SCRM system and external entities, ensuring that all relevant information is available for effective SCM.

In this way, the NeutroMAS4SCRM system can operate as an integrated system, ensuring that all agents are able to effectively collaborate and contribute to the achievement of the system's objectives.

4.5.3.3 Two possible external triggers

The idea of an explanatory AUML interaction diagram for SCRM is to create a visual representation of the system's behavior that enables stakeholders to better understand how it works and how to optimize it for maximum efficiency and effectiveness. It uses the notation of the AUML to illustrate the dynamic behavior of the system and how its components interact with each other.

In this specific scenario, a customer company requests information on a manufacturing order, or a customer informs the distribution agent of an alert. Both pieces of information are transmitted to the Manufacturing agent, which then takes into account any external triggers it may have received and checks for critical states corresponding to the order. The content of the request is based on the ***AgentSCRM*** ontology and follows the syntax introduced in chapter 5, requesting different types of state data and information about disruptive events and risks.

The distribution agent receives requests or alerts from other agents and then starts actively collecting data from internal or external data sources. For example, the client's enterprise resource planning (ERP) system. Based on the SCRM data that the agent receives in the corresponding information message from the External ***RiskAppAgent***, it extracts knowledge on all associated orders. Then, the ***RiskDistAgent*** analyzes and interprets these inputs using its Neutrosophic Data AHP system (see chapter 3) and creates a response (***Inform OF***) to respond to the order state or (***Inform*** (***Alert OF***)) for the evaluation of the criticality of an event or disruptive risk. The results that represent new information created by the distribution agent are stored in its SCRM Data knowledge asset. This response to the request from the external client agent is illustrated in figure 4.10.

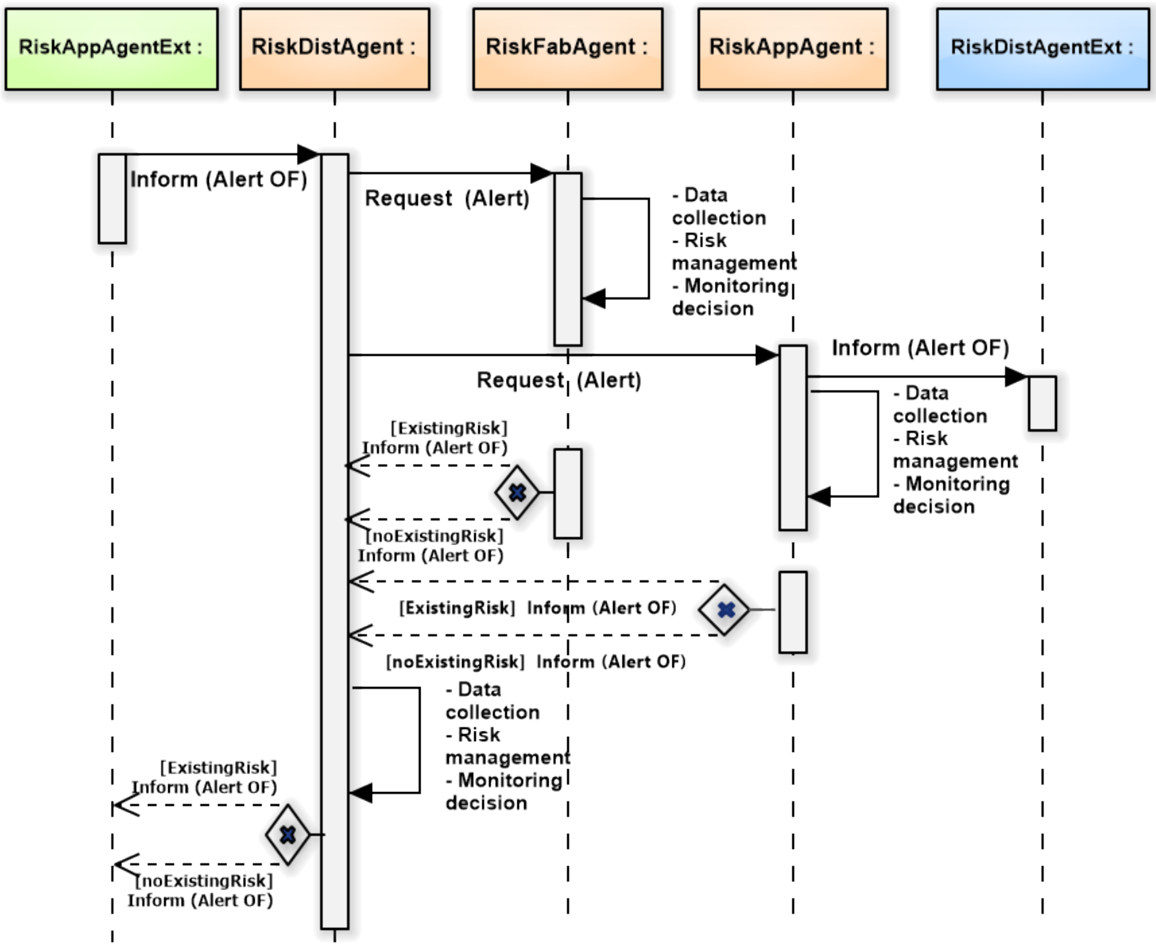


Figure 4.10: An Explanatory AUML Interaction Diagrams for SCRM.

4.5.3.4 Commitment to an ontology

The significance of semantics in communication is emphasized in Chapter 5, where an ontology has been created to outline the relevant semantic concepts and their associations within the AgentSCRM domain. To achieve successful agent interactions, each agent must employ an ontology to clarify the meaning behind its messages. To facilitate communication between all agents in an SCRM society, it is crucial to reach a consensus on a common ontology, which in this scenario is the AgentSCRM ontology. Additionally, the utilization of the AgentSCRM ontology is also required for inter-organizational interactions between SCRM systems, as this helps to eliminate the need for conversions between different semantic interpretations of content and simplifies the implementation process of these systems. Therefore, the basic agent concept in our NeutroMAS4SCRM proposal presumes that all agents must agree to use the same ontology in order to provide clear and transparent interactions without the need for conversion mechanisms. However, in the realistic settings of an inter-organizational supply network, this assumption may not hold and the integration of other risk management solutions may be desired. In such a scenario, mechanisms for matching between different semantics represented by specific ontologies are necessary.

4.5.4 Agent RiskDistAgent

In the field of AOSE, the focus of descriptions regarding society of agents primarily lies on organizational structures and the relationships between all agents involved. However, a comprehensive understanding of each type of agent is also provided, giving a micro-perspective. This comprehensive understanding encompasses the internal resources, behaviors, and interactions with other associated agents as well as AUML models.

In our work, we will solely focus on the distribution agent as the three agents operate under the same principle. The distribution agent is one of the types of agents within the NeutroMAS4SCRM concept, and it plays a crucial role in managing the risks associated with the company's sales process, from demand generation to the delivery of finished products. To effectively perform this role, the distribution agent consists of several components, including a communication module, a reasoning engine, a distribution knowledge base, and a database.

The communication module enables the agent to interact with other agents, while the reasoning engine enables it to make informed decisions based on the information it receives. The distribution knowledge base stores relevant information and data related to the distribution process, while the database serves as a storage system for the agent to access and manipulate data as required.

In conclusion, the detailed concept of the Distribution Agent provides a thorough understanding of its purpose, functions, and components, and plays a critical role in the successful implementation of the NeutroMAS4SCRM concept.

The design of the agents is illustrated in Figure 4.11, which includes the various components and their interconnections.

- *User interface*: The module for user interface allows for communication between the sys-

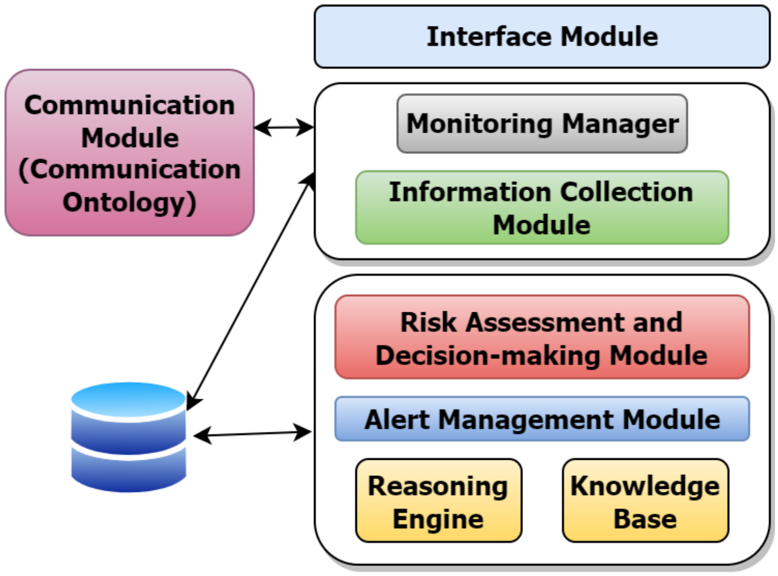


Figure 4.11: Agent Architecture.

tem and the user. It offers the necessary tools for the user to adjust the company's plans in the case of a risk or unfavorable circumstance. Additionally, the interface displays the outcomes of searches and interactions with the "RiskAppAgent" and "RiskFabAgent" agents.

- *The Monitoring Manager*: The Monitoring Manager's primary responsibility is to oversee the initiation of monitoring procedures and generate a knowledge resource by collecting and analyzing SCR data. This data is crucial for addressing customer status inquiries and for facilitating proactive alerts between agents in real-time.

- *Information Collection*: The process of information collection in SCRM plays a crucial role in ensuring that all relevant data is gathered, analyzed and interpreted in a systematic manner. This helps in providing actionable insights that can support decision making and risk management activities. The information collected can come from both internal and external sources, which could include customer data, supplier data, market trends, and other relevant sources. The process of information collection is a step-by-step procedure that involves searching, selecting and interpreting the data in a meaningful way. The resulting information can provide a foundation for effective risk management and decision-making processes.

- *Risk assessment and decision-making module*: The Risk Assessment and Decision-Making Module encompasses the strategy for making informed choices regarding potential hazards facing the organization. The initial step involves the formation of a comprehensive risk hierarchy that takes into account all potential dangers to the organization. This involves a thorough examination of the processes involved and identification of any potential weaknesses. The risks are then grouped based on criteria such as severity, frequency, and detectability. Subsequently, the SCR is evaluated using the Neutrosophic Data Analytical Hierarchy Process (NDAHP), as outlined in chapter 3 of the thesis. This process provides a systematic approach to risk assessment and decision-making, ensuring that the organization is equipped with the necessary information to make informed choices.

- *Alert management module*: The alert management module plays a crucial role in ensuring the effective functioning of the system. Based on the results of evaluations performed by other agents, the alert management module generates alerts and distributes them to the relevant internal and external stakeholders. These alerts are crucial in proactively identifying and mitigating potential risks that may impact the organization. The timely dissemination of alerts also helps to foster collaboration and communication among all stakeholders involved in the supply chain risk management process.

- *Communication module*: The Communication module acts as an intermediary between the different agents within the system, enabling them to exchange information and alerts efficiently and effectively. This module plays a key role in ensuring real-time coordination between the agents, allowing for a prompt response to potential risks or adverse events. It facilitates communication between agents using various protocols, including the FIPA ACL message format, ensuring secure and seamless interactions. The real-time nature of this module ensures that the agents can collaborate effectively to assess and manage risks, ultimately reducing the impact on the organization and its external supply network partners. An illustration of the Communication module's function can be seen when an alert is received from an external "RiskAppAgentExternal" belonging to another company. This alert, in the form of a FIPA ACL message, can be transmitted by the Communication module to the internal manufacturing agent "RiskFabAgent".

- *Knowledge Base*: The Knowledge Base is a vital information store used by system agents to make knowledgeable decisions. It encompasses a range of criteria that outlines the terms for each service and criteria concerning customer offers. The Knowledge Base also establishes the threshold for alerts by defining the level of risk that the system can tolerate before taking action. This threshold is based on the company's risk appetite, which considers factors such as the company's financial capacity and strategic objectives. The Knowledge Base specifies action plans for managing risks based on the most suitable treatment strategy, such as avoiding, accepting, or transferring the risk, and ensures that the agents operate within the predefined risk limits. Additionally, the Knowledge Base is designed to store key risk indicators and other types of relevant knowledge that are specific to each type of agent. This information is used by the agents to identify and assess potential risks and to make informed decisions about the best course of action.

- *Database*: The Database component of the system also contains information about key risk indicators (KRIs) that provide insight into potential risks and help to prioritize the need for risk mitigation actions. The data stored in the database is constantly updated and used by the various agents to make informed decisions and respond to risk events in real-time. Additionally, the database supports data analysis and reporting capabilities, providing a historical record of risks, events, and responses. This information can be used to identify trends, patterns, and areas for improvement to further enhance the organization's overall risk management strategy.

- *Reasoning engine*: The Reasoning Engine serves as the central control mechanism of the system, managing the execution of various actions taken by the agents. It is responsible for interpreting the data from the Database and the Knowledge Base, making decisions based on the algorithms and models defined in the system, and coordinating the communication between agents. The Reasoning Engine also plays a critical role in ensuring the efficient and effective operation of the system, ensuring that the right decisions are made in response to risks and adverse events, and minimizing their impact on the organization and its supply network partners.

4.5.4.1 Structure of the RiskDistAgent agent

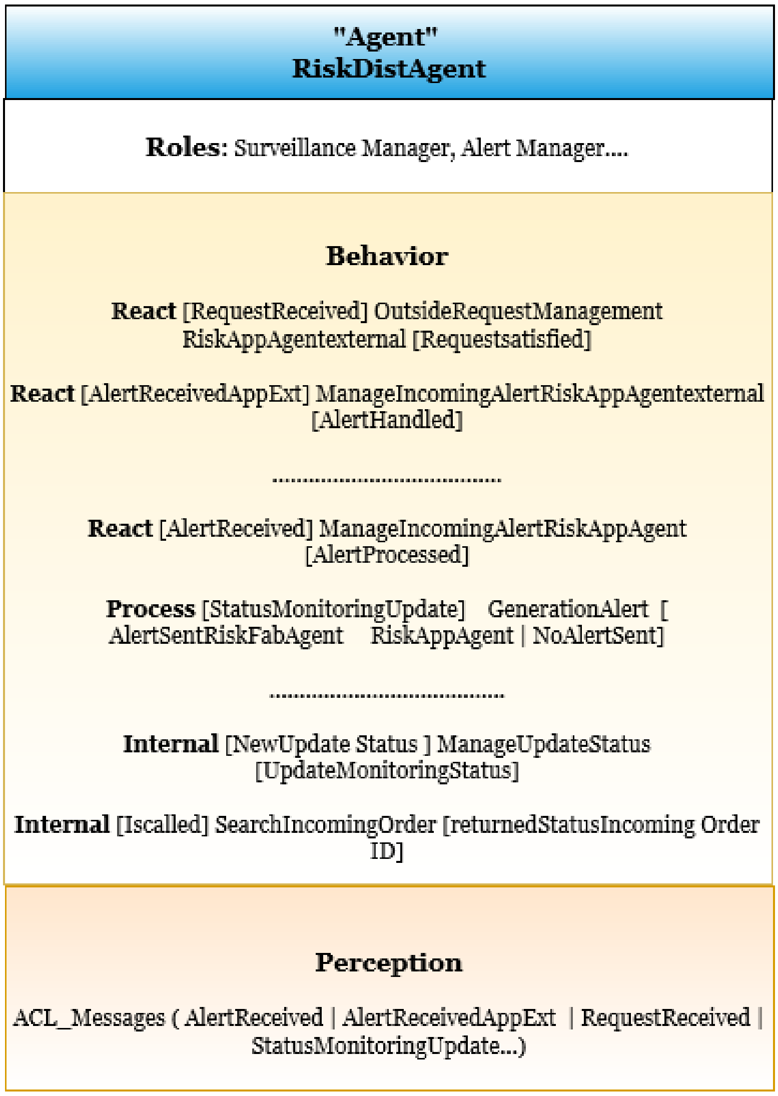


Figure 4.12: AUML class diagram of a Distribution agent

The AUML class diagram provides a visual representation of the structural characteristics of a distribution agent as presented in Figure 4.12. The diagram depicts the distribution agent as a class with the following roles: ***Surveillance Manager*** and ***Alert Manager***. The main resources of the distribution agent, which encompass several knowledge assets for proactive decision making and order tracking, are also depicted in the diagram.

An AUML class diagram is a diagram that illustrates the structural organization of classes in a software system, helping to model its object-oriented architecture. It provides a visual representation of the relationships between classes, including their attributes and methods. Classes are represented by boxes with sections: the top section displays the name of the agent class, the middle section shows the behavior of the agent, and the bottom section represents the perception of the agent.

In the subsequent section, an examination is made of the actions carried out by a distribution agent to carry out its duties, and these behaviors are concisely itemized in figure 4.13. To collect information about its surroundings, a distribution agent relies on a range of sensors. It receives different sorts of messages, such as customer status requests (***RequestReceived***), alerts from outside clients (***AlertReceivedAppExt***). Furthermore, the agent gets two types of messages internally: alerts from the company's production and procurement agents (***AlertReceived***). More information about the circumstances under which these messages are received will be explained in the following sections.

The main advantage of using an AUML class diagram is that it clarifies the design of a software system, making it easier to understand and maintain. It is particularly useful for identifying class hierarchies and relationships, and for capturing the structure of the system at a high level of abstraction.

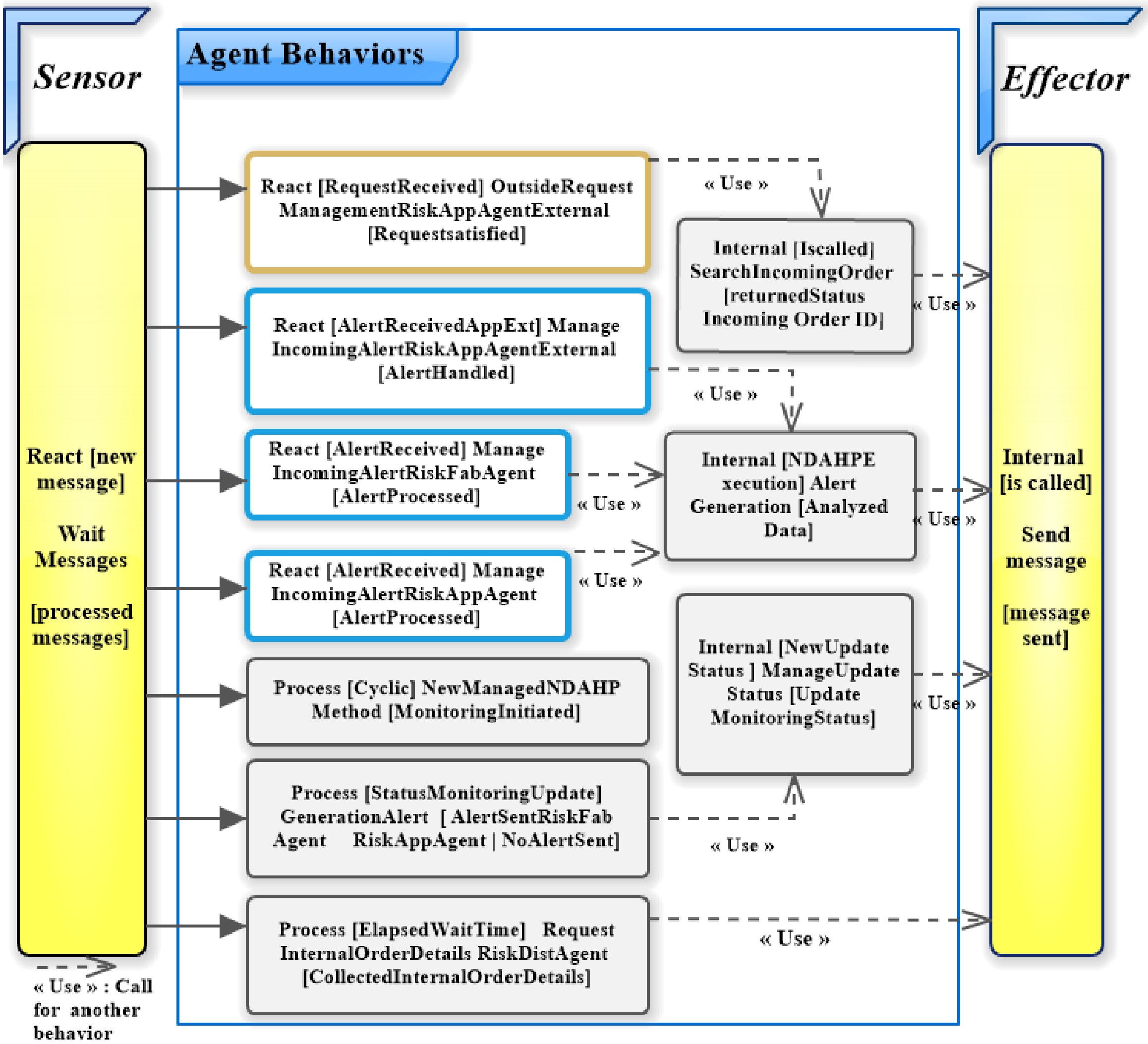


Figure 4.13: Agent Distribution Behaviors

4.5.4.2 Behaviors of the RiskDistAgent agent

The statement implies that since the three agents have similar behavior, only the distribution agents will be analyzed in detail. The distribution agents are in charge of transmitting alerts between client companies and internal agents (***RiskFabAgent*** and ***RiskAppAgent***), which relate to supply chain data, specifically tracking information for production orders.

preview of the behaviors associated with Distribution Agent roles and the interdependencies between these behaviors is presented in Figure 4.13. Two basic behaviors perform the functions of the sensors and actuators of a Distribution Agent:

- The reactive behavior ***Wait*** for Messages acts on newly received Agent messages, extracts their content, and makes it available to other Agents.
- An internal behavior ***Send*** Message is an internal process that is initiated by other behaviors within the system. As an internal behavior, it is not directly triggered by external events, but rather by other processes within the system.

In the role of a Distribution Agent as a Surveillance Manager, foure behaviors are initiated reactively or proactively: The behaviors Manage Demand from Outside RiskAppAgent and Handle incoming Alert RiskAppAgent external *ManageIncomingAlertRiskAppAgentExternal* or Handle incoming Alert RiskFabAgent internal *ManageIncomingAlertRiskFabAgentInternal* and RiskAppAgent internal *ManageIncomingAlertRiskAppAgentInternal* react to messages perceived by the agent, namely the types of perception Received Alert *AlertReceived* or Received Demand *RequestReceived*, as indicated in the prerequisites of these behaviors.

When an entity outside the company alerts the distribution agent about the occurrence or potential occurrence of a disruption in the execution of an order, it creates a new type of perception for the distribution agent. This alert is received in the form of a message, which includes an ***OrderID***. The distribution agent then forwards this OrderID to the relevant internal agent as a request message, through a process known as ***OrderID*** lookup.

The ***ManageIncomingAlertRiskAppAgentExternal*** behavior is responsible for processing this incoming alert and updating the risk database with the information collected from internal sources and the received ACL messages. The ***GenerationAlert*** behavior is then executed, where the Neutrosophic DAHP (Decision Making based on Analytic Hierarchy Process) method is applied. The Neutrosophic DAHP method used in the GenerationAlert behavior focuses on utilizing current data from updated sources to create a single-valued neutrosophic number (SVNN), also known as cross-data. The SVNN is a numerical representation of the uncertainty, indeterminacy, and incompleteness of the data.

This conversion of data into a single numerical value enables decision-makers to efficiently assess the risk associated with a particular event or order, as it provides a concise and objective evaluation of the information. The SVNN takes into account the inherent limitations and ambiguities of the data, making it a more reliable and accurate representation of the information compared to traditional methods that only consider definite values.

In addition, the New Method ***NDAHPExecution*** is cyclically launched by the Distribution Agent or in the case of new risks or critical events. It is therefore a proactive behavior whose initiation is controlled internally by the agent. After the SVNN is calculated, the GenerationAlert behavior produces the overall risk ranking, which can be used by decision-makers to make informed decisions about potential risks and disruptions in the supply chain. The use of the neutrosophic DAHP method and the SVNN provides a robust and comprehensive approach to risk management, improving the efficiency of decision-making in real-time reactions. So, The final step is for decision-makers to review the risk ranking and, if necessary, create a treatment plan and send a message to the agents if an alert is generated. The execution details of this behavior can be found in Figure 4.15.

In the context of the Alert Manager role, a Distribution Agent makes status updates based on the results of surveillance. As soon as the status of an order is updated, the behavior ***StatusMonitoringUpdate*** reacts by updating the corresponding knowledge resources, the behavior Alert Manager acts on the new state data and decides on the generation of alerts.

With the real-time reaction capability of this behavior diagram, the Distribution Agent can respond promptly to incoming messages and quickly process them, making the necessary updates to knowledge resources in response to received alerts. This allows the agent to provide an efficient and effective decision support system for handling surveillance and alert management. The proactive behavior New Method NDAHPGerée enables the agent to continuously monitor the environment and detect any new risks or critical events, allowing it to proactively initiate the necessary responses to maintain a safe and secure system.

A. ***The alert management behaviors***

In the realm of SCRM, it is essential to constantly monitor and assess risks that could potentially impact the supply chain. In order to achieve the desired outcome, the behavior ***GenerationAlert*** outlined in figure 4.14 must be properly executed. This figure serves as a visual representation of the steps that need to be taken in order to achieve the desired result, several steps should be taken to ensure that all relevant information is considered and acted upon. The first step involves the identification of any new status updates that may impact the supply chain. This information can then be utilized to update the SCRM data, thereby providing a more comprehensive understanding of the current situation.

The calculation of Key Risk Indicators (KRIs) is a critical component of SCRM. KRIs are quantifiable measures that provide a concise representation of the level of risk associated with a particular risk factor. The calculation of KRIs involves collecting and analyzing data, and converting this information into metrics that can be used to monitor and assess risk.

For instance, One KRI for a supply chain could be the "Inventory Days of Supply" metric. This KRI measures the number of days that inventory can cover the demand for a particular product or group of products. The KRI can be used to identify potential supply chain risks such as stockouts or overstocking of inventory.

Another KRI for a supply chain could be the "Supplier Performance Scorecard". This KRI measures the performance of a supplier based on factors such as on-time delivery, quality of goods, and responsiveness to issues. The KRI can be used to identify potential risks associated with supplier performance, such as delays in delivery or poor product quality.

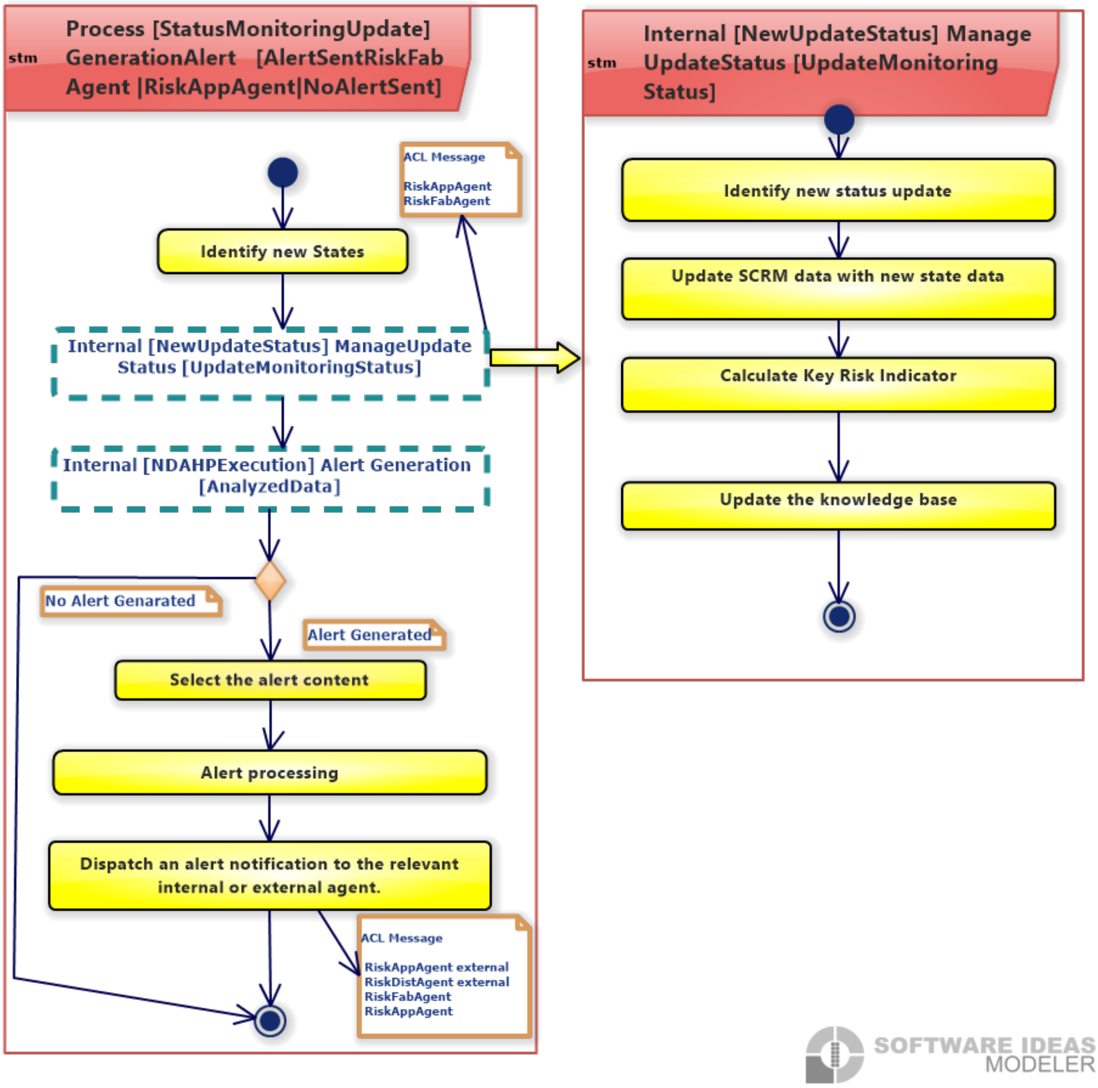


Figure 4.14: Alert Management Role of Distribution Agent

A third KRI for a supply chain could be the "Freight Cost per Unit". This KRI measures the cost of freight for each unit of product shipped. The KRI can be used to identify potential risks associated with rising transportation costs, which can impact the overall cost of goods sold and ultimately, the profitability of the supply chain.

By continuously monitoring and tracking KRIs, organizations can quickly identify the potential impact of a risk event and take necessary actions to mitigate or manage the risk.

In addition to updating SCRM data and calculating KRIs, it is also important to keep the knowledge base up-to-date. The knowledge base is a repository of information related to SCRM and other relevant fields and serves as a valuable resource for those involved in risk management. Regular updates to the knowledge base help to ensure that it remains relevant and useful for decision-making and risk management activities. To update the knowledge base, it is necessary to collect and analyze the latest information on SCRM, including information on KRIs, and integrate this information into the existing knowledge base.

In conclusion, the steps of identifying new status updates, updating SCRM data with new state data, calculating KRIs, and updating the knowledge base form an integral part of a comprehensive SCRM strategy. By following these steps, organizations can continuously monitor and assess risks and take necessary actions to manage and mitigate their impact on the supply chain.

After these steps have been completed, the behavior of the NDAHP can be activated. Based on the information analyzed, the agent will decide if there is an alert that needs to be generated or if the system is in a safe situation without any threats. In the event of an alert, necessary actions can be taken to mitigate or manage the risk. Ultimately, the combination of continuous monitoring and assessment, data analysis, and the activation of the NDAHP ensures that organizations have a comprehensive understanding of the potential risks to their supply chain and are able to take proactive measures to protect their operations. If the system encounters a risk, a real-time reaction must be taken. With the ontology of the communication between the agents, the Agent Communication Language (ACL) alert message will be disseminated to the agents in the system.

B. ***Monitoring management behaviors:***

The purpose of the Monitoring management behavior is to identify and mitigate risks and threats in the SC. By monitoring various elements within the supply chain, such as the status of tasks, resources, and other components, the Surveillance Manager role can identify potential issues and take the necessary actions to prevent or mitigate those risks. This helps to ensure the proper functioning of the SC and minimize any negative impact on the overall performance of the system.

For example, if a component in the supply chain is not functioning as expected, the Monitoring management behavior can detect this and trigger the appropriate response, such as triggering an alert, reassigning tasks, or diverting resources to a different component. This allows the supply chain to continue to operate smoothly and meet its performance goals, despite any challenges that may arise.

To represent these behaviors, detailed activity diagrams using AUML was created. In these diagrams, the different steps and processes involved in monitoring management behaviors are depicted and analyzed.

For example, in the case where a new state request from a client is received, the ***OutsideRequestManagementRiskAppAgentExternal*** behavior becomes active (See figure 4.17). This behavior is responsible for managing the request and determining the appropriate response. The response is then handled separately by the Recherche ***RequestReceived*** role, which is responsible for searching for the requested information and returning it to the client. The distribution agent searches for the orderID state extracted from the ACL message by sending an ACL message to the internal ***RiskFabAgent***, ***RiskDistAgent*** and from the internal database of the agent itself.

As a second example (See figure 4.16), one can discuss the behavior of ***ManageIncomingAlertRiskFabAgent***. The ***RiskDistAgent*** distribution agent, as soon as it identifies a new verification request from the internal ***RiskFabAgent*** manufacturing agent, collects information using key risk indicators (KRI) and identifies new risks. KRI are performance metrics that provide a quantitative measure of an organization's risk exposure. Then, the agent updates the risk database. Afterward, it will either execute the ***Alert-***

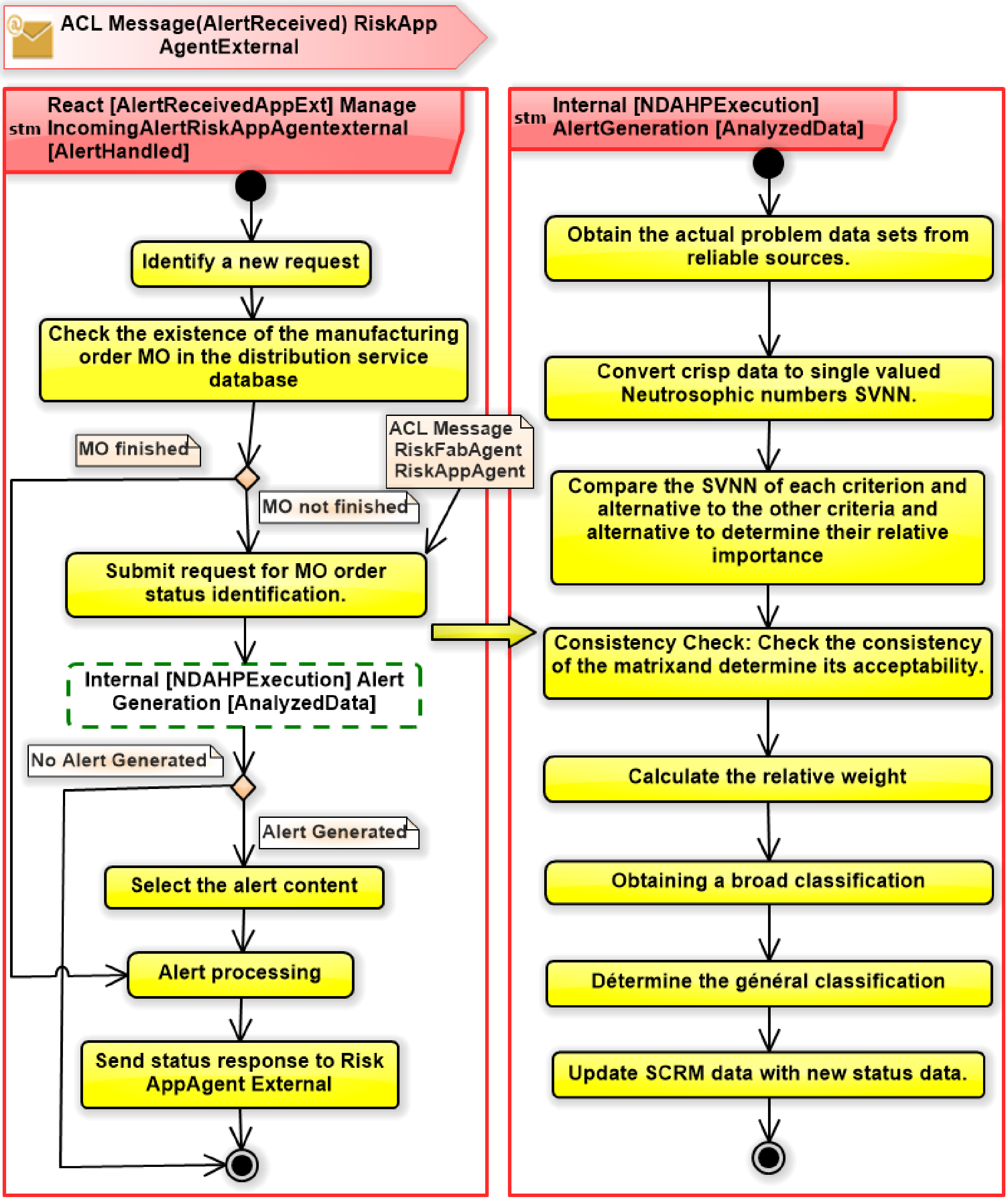


Figure 4.15: Execution Details of ManageIncomingAlertRiskAppAgentExternal Behavior

Generation behavior or apply the neutrosophic Data AHP method (as represented in Chapter 3 and detailed in the work by Meziani et al. [276]) to classify the risks.

Once the risks have been identified and classified, the agent moves on to the application of the treatment step in the risk management process. This step involves implementing strategies and actions to mitigate or manage the risks. For example, if an alert is generated, the agent will initiate an alert handling process which may involve implementing risk mitigation measures and communicating the necessary information to the relevant stakeholders.

It is important to note that the goal of the treatment step is to minimize the impact

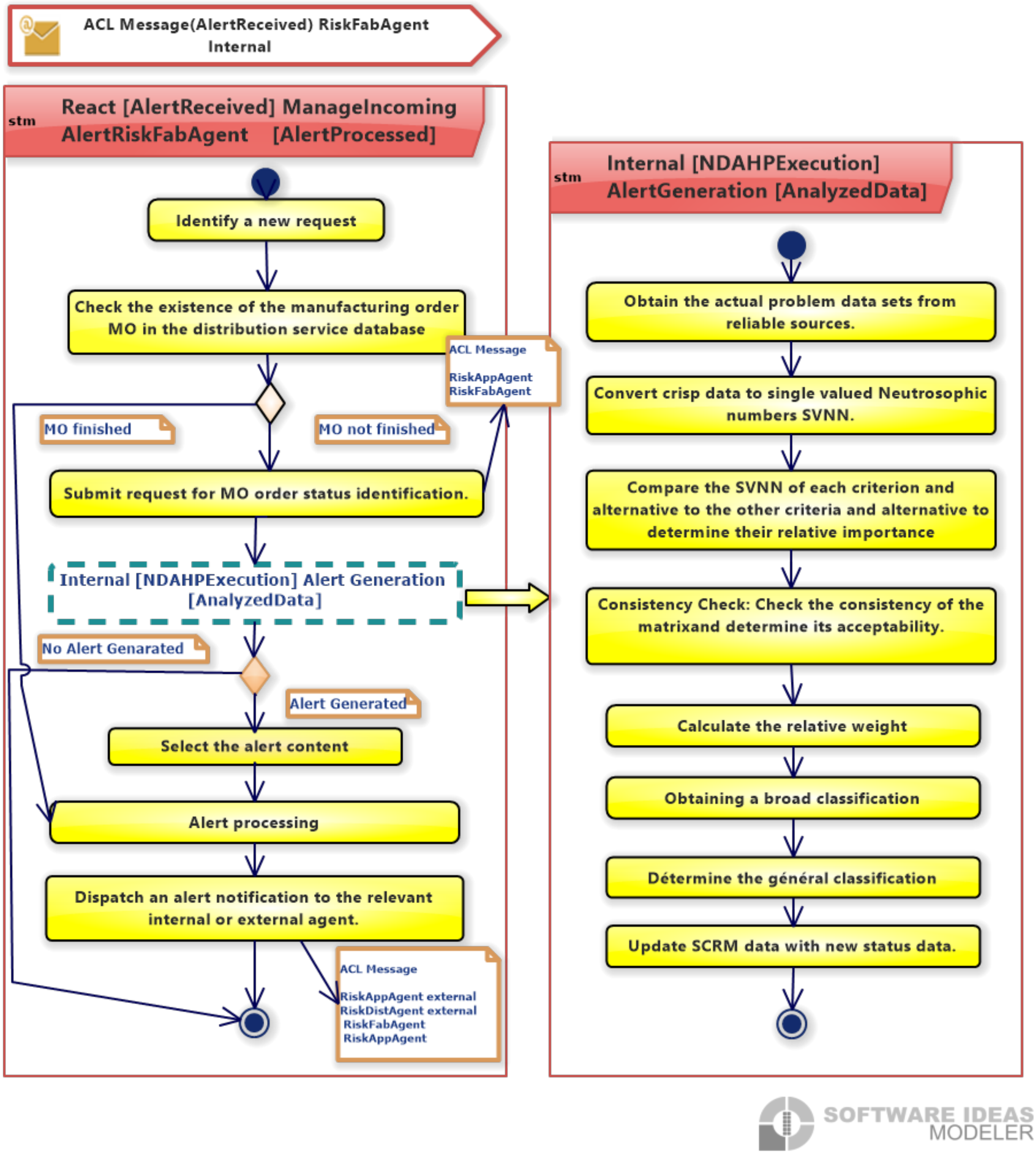


Figure 4.16: Execution Details of the ManagementIncomingAlertRiskFabAgent Behavior

of risks and to ensure that the organization is prepared to respond effectively in the event of a risk materializing. This can include activities such as risk monitoring and review, risk acceptance, risk transfer, or risk reduction through risk mitigation measures. By carrying out these activities, the agent contributes to the overall risk management process of the organization.

In conclusion, the Monitoring management behavior plays a crucial role in maintaining the stability and efficiency of the SC by detecting and mitigating risks and threats in real-time. This helps to ensure that the SC remains reliable and effective, even in the face of changing conditions.

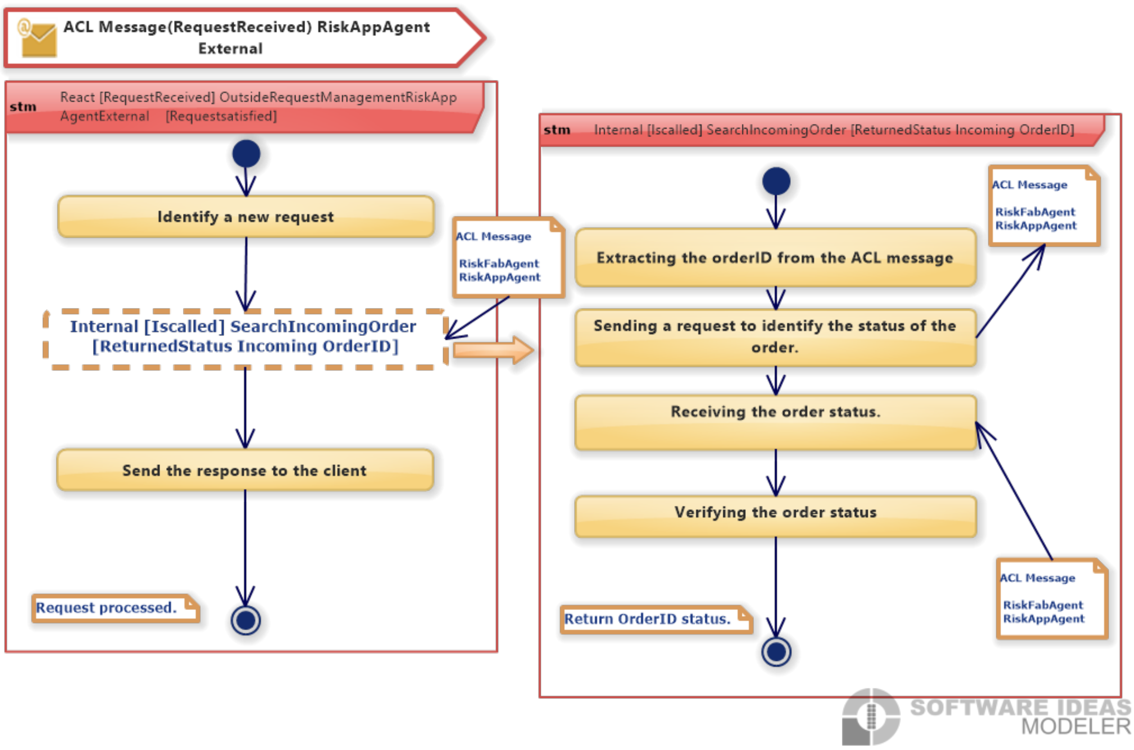


Figure 4.17: Execution Details of the OutsideRequestManagementRiskAppAgentExternal Behavior

4.6 Conclusions

this chapter delved into the topic of multi-agent systems, providing a thorough overview of the defining concepts and development methodologies in the field. The main functions to be performed by a Supply Chain Risk Management solution were outlined, and a technological approach to integration was presented, using software agents as an innovative technology for building autonomous and distributed software solutions.

We also explored the strengths of MASs, highlighting their importance for managing risk in supply chains and their ability to handle cooperation, integration of incomplete expertise, adaptation to reality, modularity, efficiency, reliability, and reusability. The multi-agent approach is based on a set of concepts, including communication, organization, and coordination between more or less intelligent and autonomous entities. This wealth of concepts makes the multi-agent approach a powerful and rich approach to modeling.

In this chapter, we proposed NeutroMAS4SCRM, an enterprise architecture solution consisting of three agents solely dedicated to risk management in the SCRM system. Our proposal was built upon two key choices. The first choice concerned the use of the AUML language during the modeling phase, while the second choice involved the selection of the optimal enterprise architecture for managing risks in the supply chain. Additionally, in the upcoming chapter, we will delve deeper into the proposed ontology, which aims to enhance the collaboration between the system's agents. We will also cover the implementation of our system on the JADE platform and discuss the validation process. Overall, this chapter serves as a significant contribution to the field of MASs and SCRM, offering a thorough understanding of the topic and proposing an effective solution for managing risk in the SC.

Chapter 5

AgentSCRM Ontology and Evaluation.

Chapter 5

AgentSCRM ontology and evaluation.

Contents

5.1 Introduction

Multi-agent systems rely heavily on effective communication among the agents to achieve their goals. Communication ontology plays a crucial role in facilitating this communication by providing a shared understanding and vocabulary for the agents to exchange information and coordinate their actions. The accuracy and consistency of the communication ontology have a direct impact on the performance and success of the MAS system.

In recognition of the importance of communication ontology in MAS, we have proposed a communication ontology for our system. This ontology is designed to provide a standardized and efficient exchange of information among the agents, improving their coordination and decision-making. Our proposed communication ontology has been carefully crafted to meet the requirements of the MAS system and to accurately reflect the intended meaning of the communication among the agents. Through the use of our proposed communication ontology, we aim to enhance the performance and success of the MAS system.

Assessing the concept of SCRM and its associated prototype implementations must take into account the specifics of the supply chain domain, particularly its structural complexity. In what follows, an evaluation approach is selected that allows for consideration of the advantages and limitations of agent-based SCRM from various perspectives. Given the proposal of a comprehensive risk management framework to address the complexity of the logistics chain, the evaluation method is chosen.

In this chapter, The validation process involves verifying the compliance of the proposed ontology with the requirements of the MAS system, testing its accuracy and consistency through simulation or experimentation, and ensuring its effectiveness in facilitating communication among the agents. This chapter provides a comprehensive overview of the proposed ontology and the validation method, allowing for a thorough evaluation of the SCRM concept and its associated prototype implementations.

5.2 AgentSCRM ontology

The history of ontologies in the field of computer science traces back to the 1970s when the first artificial intelligence systems and knowledge representation techniques were developed. During that time, ontologies were primarily used for modeling specific domains and facilitating the resolution of complex problems.

In the 1990s, with the emergence of the World Wide Web, the use of ontologies expanded to knowledge management and information retrieval on the internet. Knowledge representation languages such as Resource Description Framework (RDF) and Web Ontology Language (OWL) were developed to enable the creation and sharing of ontologies on the web.

The utility of ontologies in the field of computer science is manifold. Firstly, they provide a formal and coherent structure for organizing and structuring the knowledge within a specific domain. This facilitates searching, navigating, and integrating information by establishing a common framework for mutual understanding between computer systems and users.

Additionally, ontologies promote interoperability among different computer systems by providing a shared vocabulary and semantics. They address the challenge of data heterogeneity by ensuring a shared understanding of concepts and relationships.

Furthermore, ontologies are employed in applications such as knowledge extraction, content recommendation, information management, and machine learning. They offer a formal framework for logical reasoning, inference, and deduction, enabling systems to reason about the knowledge represented within the ontology.

5.2.1 Languages for Inter-Agent Communication

The coordination of diverse autonomous agents is critical for a multi-agent system to effectively carry out its tasks. To achieve this, all agents must be able to understand a common language that they can use to communicate with one another. This requires a shared vocabulary with a clear syntax for structuring symbols, a shared understanding of pragmatics for interpreting symbols, and a shared ontology to ensure the use of common terms.

Comparing KQML and FIPA-ACL: Key Differences in Agent Communication Languages. KQML (Knowledge Query and Manipulation Language) and FIPA-ACL (Foundation for Intelligent Physical Agents - Agent Communication Language) are two of the most prominent languages for communication between agents. They share similar basic concepts and principles, but differ mainly in the details of their semantic frameworks. This difference can be substantial, as it is not possible to systematically translate between KQML performatives and their equivalent in FIPA, or vice versa. However, for programmers of intelligent agents, these differences may be inconsequential if their agents are not true BDI (Belief-Desire-Intention) agents.

Each KQML or FIPA-ACL message comprises several elements, including:

- ***Performative:*** The performative is a crucial element in KQML and FIPA-ACL messages, as it defines the type of communicative act being performed by the sender. This act can take on different forms, such as informing, requesting information, making a proposal, accepting or rejecting a proposal, and so on. The performative determines how the receiver should interpret the message and how they should respond to it, based on the expected norms and conventions of the system.

  For example, if the performative is "inform", the receiver of the message would be expected to simply acknowledge the information provided, without necessarily taking any further action. On the other hand, if the performative is "request", the receiver would be expected to provide the requested information in response to the message. The use of standardized performative types helps to ensure that all agents in the system can communicate effectively and efficiently, and that their messages are properly understood and acted upon.

- ***Sender:*** the sender of the message.
- ***Receiver:*** the recipient of the message.

- ***Content:*** The "content" element of a KQML or FIPA-ACL message refers to the information conveyed by the message. The content can take different forms depending on the specific communicative act being performed by the sender. For example, if the performative is an "inform" type, the content might be a statement or a piece of information that the sender wants to convey to the receiver. On the other hand, if the performative is a "request" type, the content might be a question or a request for information that the sender is asking the receiver to provide.

  The content of a message is crucial for successful communication between agents in a multi-agent system. It needs to be carefully structured and unambiguous to ensure that the receiver can understand the intended meaning of the message. In addition, the content needs to be relevant and informative, so that the receiver can use the information to make appropriate decisions and take actions in response to the message. Therefore, designing effective content for messages is an important aspect of developing a communication ontology for a multi-agent system.

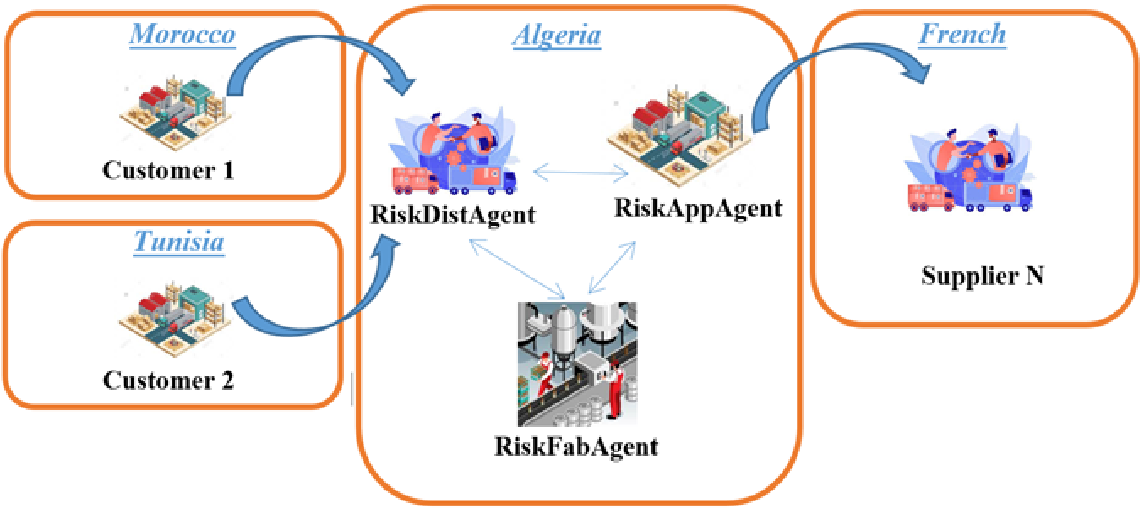


Figure 5.1: Communication Among SCRM Agents

In the context of describing the structure of a conversation between agents, neither language imposes a specific format for the content. Instead, various coding languages can be employed. Examples of such languages include KIF (Knowledge Interchange Format) or an ontology. KIF is a standardized computer language that facilitates the representation and exchange of knowledge, while an ontology provides a formal description of the concepts and relationships within a domain. By using KIF or an ontology, the structure of the conversation can be defined, enabling agents to communicate and exchange information in a well-defined and mutually understandable manner.

The use of ontology plays a crucial role in enabling agents working in a cooperative system to communicate with each other during the process of information search and analysis. An ontology provides a shared vocabulary, which is essential for communication between agents.

By agreeing on a common ontology, different agents within a system can achieve a mutual understanding. This way, they are able to exchange knowledge, make statements, and ask questions about a particular domain. The use of ontology enables the agents to communicate with each other, share information, and collaborate effectively by coordinating their actions.

It's important to note that ontologies can be expressed in various forms, such as:

- ***Taxonomies:*** A taxonomy is a hierarchical classification of concepts, with each concept being a subcategory of a broader category. It typically represents a domain of knowledge in a tree-like structure, where each node represents a concept and the edges represent the relationships between the concepts. For example, in a taxonomy of animals, the category "mammals" would be a parent node of the category "dogs," "cats," and "humans."

- ***Concept maps:*** Concept maps are graphical representations of the relationships between concepts. They typically consist of nodes representing concepts and lines connecting them to show relationships between the concepts. These relationships can be of different types, such as hierarchical, associative, or causal. Concept maps can be useful for visualizing complex concepts and relationships, and for communicating them to others.

- ***Frame-based systems:*** A frame-based system represents knowledge in terms of frames, which are structured objects that represent a concept or entity in the domain of interest. Each frame has a set of attributes that describe the properties of the concept or entity, as well as a set of slots that define the relationships between the frame and other frames. For example, a frame-based system for representing cars might have frames for different types of cars, each with attributes such as make, model, and year, and slots for related frames such as engines and transmissions.

All of these methods can be used to express an ontology, which is a formal representation of knowledge that specifies the concepts and relationships within a specific domain. Ontologies are used in multi-agent systems to enable effective communication and coordination between agents, by providing a shared understanding of the domain-specific vocabulary and semantics.

In the example depicted in Figure 5.1, the clients are represented by factories in Morocco and Tunisia, while the suppliers are represented by a French factory. The focal factory, responsible for coordinating the SCRM activities, is located in Algeria. The agent ***RiskDistAgent*** plays a pivotal role in this scenario, as it is responsible for communicating and assigning tasks to different SCRM agents.

The RiskDistAgent interacts with other agents by receiving alert ACL messages and sending requests to the ***RiskAppAgent*** and ***RiskFabAgent***. These agents are responsible for assessing risks and managing the supply chain within the focal factory. Once the ***RiskDistAgent*** retrieves the necessary information, it communicates the results with external agents representing the company's clients and suppliers.

This type of communication is crucial as it allows for seamless coordination and collaboration among agents. The agents are designed to work together and share information effectively to ensure smooth operations within the supply chain. By facilitating communication between the different stakeholders, the SCRM agents contribute to the efficient management of risks and the overall success of the supply chain.

5.2.2 Advantages of ontology for smart MAS

As ontology-based systems and agents deal with different and complementary aspects of the same problem, we believe that the integration of these two approaches would result in a highly effective and efficient system. We will discuss the various forms of benefits that arise from integrating ontology, including communication among different agents, information retrieval and localization, as well as analysis and manipulation of information.

Advantages of Integrating Ontology into Intelligent Multi-Agent Systems:

- ***Improved Communication:*** Ontology provides a shared vocabulary and common understanding between agents, enabling effective and efficient communication. This helps in eliminating ambiguity and misunderstandings between agents.

- ***Enhanced Information Retrieval:*** The use of ontology facilitates the integration of knowledge from multiple sources and enables a unified representation of information, which can aid in the discovery and retrieval of information.

  The ontology being constructed must be designed to represent knowledge about SCRM risks and allow reasoning about this knowledge. It must contain information about disruptive events and the agents must communicate and share the SCRM system data and make updates, then make a decision on whether to send a risk alert message to other agents or not.

  The ontology is used to structure the information and give an overview of the knowledge in the domain, and presents the information in a meaningful way. In addition, the hierarchical organization of ontologies adds a taxonomic context to this information and allows easier identification of conceptual relationships in the data.

- ***Improved Knowledge Representation:*** Ontology provides a structured representation of knowledge that can be used to reason about and manipulate information. This can help in improving the accuracy and consistency of information.

- ***Facilitation of Cooperation and Coordination:*** Ontology enables agents to share their knowledge and understand each other's goals, allowing them to cooperate and coordinate their actions effectively.

  In our example of information retrieval on risk and risk trigger events in the logistics chain, all agents in the system must share and use the common ontology when communicating with each other. Concepts such as "Risk," "Risk Consequence," and "Treatment Strategy" must be precisely defined by this ontology and these concepts must be interpreted in the same manner by different agents in the system. This will facilitate effective task sharing and results from the Intelligent Multi-Agent System.

- ***Supports Reusability:*** Ontology provides a reusable and transferable representation of knowledge that can be leveraged across multiple applications and domains.

- ***Facilitation of Reasoning:*** Ontology provides a formal framework for reasoning about and inferring new knowledge, which can help in improving the decision-making process of intelligent agents.

- ***Improved Scalability:*** Ontology enables the modularization and abstraction of knowledge, which can help in managing complexity and improve scalability of intelligent multi-agent systems.

5.2.3 Ontologies in the field of SCRM

SCRM is an important aspect of business operations that aims to mitigate the impact of uncertainties on supply chain performance. In recent years, researchers have proposed several ontologies for SCRM, which provide a structured and formal representation of knowledge about SCRs. These ontologies differ in their focus, and each brings its own set of benefits to the risk management process.

[277] developed a prototype that allows the amalgamation of information from various data sources and different data types. Nevertheless, their work did not specify how decision-making can be facilitated after the detection of threats. Moreover, their study mostly concentrated on local supply chains as a research subject. On the other hand, [278] proposed an ontology that facilitates risk evaluation for manufacturing service systems in the global manufacturing network domain. Additionally, [279] introduced an approach to construct a multi-view risk ontology for enhancing visibility and communication of supply chain risks.

Each of these ontologies has unique advantages to the SCRM process and helps to address specific challenges in the management of SCRs, as summarized in Table 5.1.

Table 5.1: Comparison of Supply Chain Risk Ontologies.

	[277]	[278]	[279]
Purpose			
Assessment of supply chain risks using semantic technologies	X	-	-
Configuration of supply networks	-	X	-
Improved visibility and communication of supply chain risks	-	-	X
Benefits			
Improved accuracy of risk assessments	X	-	-
Intelligent configuration of supply networks	-	X	-
Better visibility and communication of supply chain risks	-	-	X
Standardized and systematic risk assessment process	X	-	-
Integration of multiple perspectives in risk assessment	-	X	X
Better understanding of the interplay between different risks	X	-	-

5.2.4 AgentSCRM ontology proposal

JADE is a software framework for developing multi-agent systems. It provides a platform for developing and deploying applications based on agents.

The proposed NeutroMAS4SCRM system leverages an ontology for intelligent and dynamic information retrieval. For JADE to conduct appropriate semantic checks on a given content expression, it is essential to categorize all potential elements within the discourse domain. These elements encompass those that may appear in a valid sentence transmitted by an agent as the content of an ACL message, and are classified based on their generic semantic characteristics. This classification is informed by the ACL language delineated in FIPA, which mandates that the content of each ACLMessage possesses suitable semantics corresponding to the performative of the ACLMessage. At the initial level, we distinguish between predicates, terms, and agent actions. In simpler terms, the multi-agent system uses an ontology to categorize elements in the discourse domain based on their semantic characteristics. This categorization allows JADE to perform semantic checks on the content of an ACL message to ensure that it is appropriate. The system differentiates between predicates, terms, and agent actions as part of this categorization process.

In more detail, at the first level, we distinguish between predicates, terms, and agent actions.

Predicates (or facts) are expressions that state something about the world and can be true or false. Predicates can be used meaningfully, for example as content of an ***INFORM*** or ***QUERY-IF*** message, while they would have no sense if used as content of a ***REQUEST*** message.

Concepts describe common characteristics of a set of individuals/objects. Concepts are general, abstract or concrete notions in a domain of discourse. They are similar to classes in the object-oriented modeling paradigm. From a logical point of view, each concept is associated with a term, generally a natural language description, expressing its name and a set of properties that characterize it. Concepts generally have no sense if used directly as content of an ACL message. They are generally referenced in predicates and other concepts.

Agent actions are special concepts that indicate actions that can be performed by some agents, for example, (HaveRisk (RiskType :Description "Machine failure") (OF :Type Distribution)). It is useful to treat agent actions separately because, unlike "normal" concepts, they are significant contents of certain types of ACLMessage such as REQUEST. Communication acts (i.e., ACL messages) themselves are agent actions.

Our ontology was realized using the Protégé software which is an open-source tool based on a graphical ontology development environment. It has evolved since its first version (Protégé-2000 [280]) to integrate semantic web standards including OWL (Web Ontology Language) from 2003 onwards. This tool has many optional components such as graphical interfaces, the structure schemas of agent actions, predicates, and concepts are well illustrated by this software. Many plugins are available and can be added by users.

To enable JADE to conduct the necessary semantic checks on a provided content expression, it is imperative to categorize all potential elements within the discourse domain. These elements encompass those that may appear in a valid sentence transmitted by an agent as the content of an ACL message, and are classified based on their inherent semantic attributes. This classification is informed by the ACL language stipulated in FIPA, which mandates that the content of each ACLMessage possesses suitable semantics commensurate with the performative of the ACLMessage.

Our proposed ontology, AgentSCRM, aims to capture the essential concepts and their interrelationships in risk management. In this field, there are several fundamental concepts and their relationships that are critical to comprehend. One such concept is the identification of potential risks that may arise in a supply chain environment. Another important concept is the assessment of the severity and probability of these risks occurring. Additionally, there is the need to establish strategies to manage and mitigate the identified risks. These concepts, along with others, have been incorporated into the AgentSCRM ontology, which are exposed in figure 5.2.

- ***OF:*** which stands for the manufacturing order that is executed within a company. The properties of this order include the legal entity it belongs to and the scheduled start and finish dates of manufacturing. It is important to link all the activities together to create the OF and calculate the cost of sales.

- ***RiskType:*** represents the type of risk that can potentially harm a production order. Risk is an unpredictable variable that can steer the company away from its expected outcome and affect its overall performance. This is why risk management is a crucial area of research in the field of supply chains. The concept of risk triggering event refers to a specific occurrence or event that activates or initiates a risk. On the other hand, the occurrence end impact of risk refers to the eventual impact or outcome that results from the activation of the risk, which can be negative or positive. Effective risk management requires a thorough understanding of the potential risks that a company may face, as well as the ability to accurately identify and respond to risk triggering events and minimize their occurrence end impact.

- ***DisruptiveEvType:*** A risk-triggering event refers to an occurrence or situation that has the potential to trigger a risk. This can be a positive or negative event, but it is typically considered to be a negative event that could cause harm, damage, or loss to a production order. This event is a crucial aspect to consider during the risk identification step in the risk management process, as it is the first step in the process of identifying and assessing risks that may affect the production order.

  Risk-triggering events can take many forms, including but not limited to: changes in market conditions, changes in technology, natural disasters, unexpected equipment failures, and changes in the regulatory environment. Understanding these events and the impact they can have on the production order is crucial for developing an effective risk management plan.

  For example, a natural disaster, such as a hurricane or earthquake, could trigger a risk in the production order if the facility or equipment is damaged. Similarly, an unexpected equipment failure could trigger a risk if it causes a delay in the production process.

  It's important to note that not all risk-triggering events are immediately apparent or easily recognizable, which is why it's crucial to consider all potential events during the risk identification step. The risk management process should involve a thorough evaluation of all potential risk-triggering events to ensure that all possible risks are identified and assessed.

  So, the risk-triggering event is a critical aspect of the risk management process for a production order. By identifying and assessing the potential risks, organizations can take proactive steps to minimize their impact and ensure a successful production process.

- ***RiskConsequence:*** Risk Consequence is an important concept in risk management as it helps organizations to understand the potential impact of a negative event on their operations, finances, reputation, and other assets. By understanding the potential consequences of a risk, organizations can take proactive measures to mitigate or prevent the risk from occurring, or develop contingency plans to respond to the risk if it does occur.

The severity of a risk consequence is typically measured in terms of financial losses, physical damage, or harm to individuals or the environment. For example, the consequences of a cyber attack on a company's IT systems could include the loss of sensitive data, downtime, loss of revenue, and damage to the company's reputation. The severity of these consequences would be assessed based on the amount of data lost, the duration of the downtime, the potential financial losses, and the impact on the company's reputation.

It is important to note that risk consequences can be both direct and indirect. Direct consequences are those that are immediate and directly caused by the risk event, such as financial losses or physical damage. Indirect consequences are those that are more indirect, such as the loss of reputation or reduced customer confidence.

In order to effectively assess the risk consequence of a particular event, it is necessary to consider a variety of factors, including the likelihood of the event occurring, the severity of the consequences, and the potential impact on key stakeholders, such as employees, customers, shareholders, and the environment.

In conclusion, understanding the potential consequences of a risk is crucial for organizations to effectively manage risk and minimize the impact of negative events on their operations and stakeholders. By taking a comprehensive approach to risk management, organizations can better protect their assets and ensure long-term success.

- ***RiskPlanTreatment:*** RiskPlanTreatment is an integral part of a comprehensive risk management process. The risk treatment strategies may include mitigation, avoidance, transfer, or acceptance. Mitigation involves reducing the impact of the risk, while avoidance involves avoiding the risk altogether. Transferring the risk involves transferring the risk to another party, such as an insurance company, while acceptance involves accepting the risk and making contingency plans for dealing with it.

  It is important to note that the risk treatment strategies should be documented in the RiskPlanTreatment and regularly reviewed and updated. This helps ensure that the risk management process remains effective over time and that the production order is completed successfully.

  In conclusion, RiskPlanTreatment is an essential component of the risk management process, and it plays a critical role in ensuring the successful completion of production orders. It helps organizations to effectively manage risks and minimize their impact, ensuring that the production order is completed on time, within budget, and with minimal disruption.

- ***RiskSeverity:*** RiskSeverity is a crucial aspect of risk management and refers to the potential impact of a risk. It measures the extent of harm or loss that could occur if a risk materializes. The severity of a risk can be evaluated in terms of various factors, such as financial loss, injury to people, damage to property, or harm to the environment.

  The determination of risk severity is an important step in the risk assessment process as it helps to prioritize the risks that need to be addressed. Risks with a high severity rating are considered to be more significant and require more attention and resources to manage. On the other hand, risks with a low severity rating are considered to be less critical and may require a more limited response.

It is essential to understand that risk severity is not the same as the likelihood of a risk occurring. While a risk with a high likelihood of occurrence may not necessarily have a high severity, a risk with a high severity has a greater impact and requires more attention and resources to manage, regardless of its likelihood of occurring.

In summary, RiskSeverity is a critical concept in risk management that represents the potential impact of a risk. It is used to determine the extent of harm or loss that could result from an incident and to prioritize the risks that need to be addressed. Understanding and assessing risk severity is an essential step in the risk management process and helps organizations to effectively manage risks and minimize their impact.

- ***OF-Comprise-Risk:*** an object property that links the OF and RiskType classes. It is the property that shows that a production order can be threatened by several risks.

- ***Risque-Comprise-Severity:*** A property of an object describing the relationship between the RiskType class and the RiskSeverity class. It is characterized by a specific level of impact.

- ***Risk-Comprise-StrategyTreatmet:*** A property of an object that outlines the connection between the RiskType class and the StrategyTreatmetRisk class. This relationship is significant because it highlights that different risks can be addressed using different treatment strategies.

- ***Risque-Comprise-DE:*** An object property that describes the relationship between the RiskType and DisruptiveEvType classes. It's possible that the risk could be caused by a variety of incidents.

- ***StrategyTreatmetRisk:*** The process of risk management involves evaluating potential risks in relation to a company's goals and tolerance levels. The Agents team must come up with an appropriate response plan for each risk, using one of the four basic approaches: avoiding, reducing, transferring, or accepting the risk. In the case of accepting risk, it is important to consider the total cost of the risk, including both expected and unexpected losses, such as the cost of economic capital, administrative expenses, and the cost of transferring the risk. This cost should then be reflected in the product price and/or performance evaluation system.

5.3 Formal specification of the problem

The results of the previous sections are summarized in a formalized model of the Supply Chain Risk Management problem. This model serves as the foundation for evaluating the effectiveness of our risk prediction solution in logistics chains, part of this proposal is inspired from Zimmermann et al. [245].

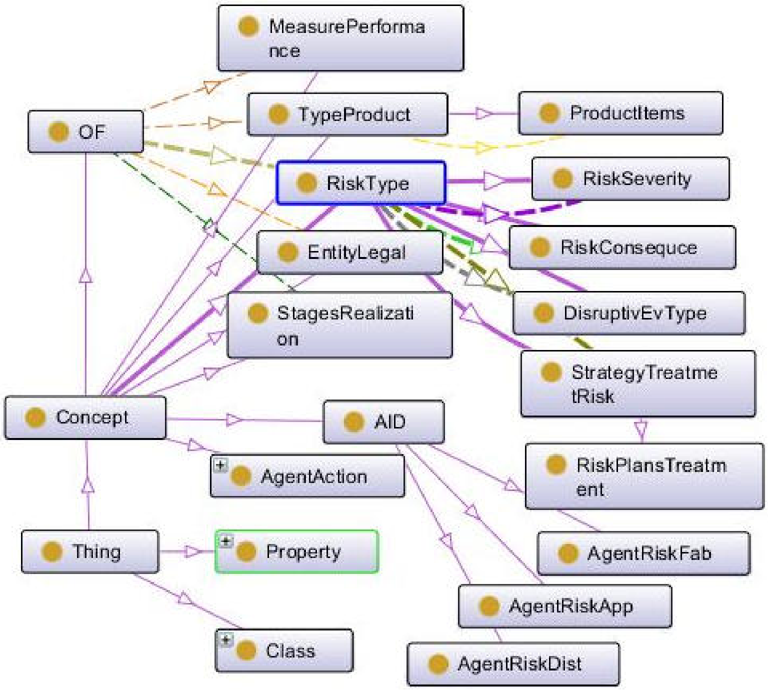


Figure 5.2: Presentation of the Main Classes of AgentSCRM Ontology Edited Using the PROTÉGÉ Tool.

5.3.1 Definitions

- ***Legal Entity:*** A legal entity with LE_K, with $K \in N$is an entity that can conclude a legal contract. It is either an individual or a company that can be a customer or a supplier.
- ***Risk:*** A Risk R_h, with $h \in N$ is the term for any type of disturbance. R_h represents the possibility of an event occurring that would result in (positive or negative) consequences on the performance of the system. A R_h originates from a specific legal entity LE_K and occurs at a timeT_t and is written: $R_h(LE_K, T_t)$.
- ***Manufacturing Order:*** A Manufacturing Order MO_i, with $i \in N$ is a legally binding contract regarding a transaction between two or more legal entities LE_K. It is issued by one LE_K and received by another and is written $MO_i(LE_K, LE_{K-x}) For x \in N$.
- ***Sub Manufacturing Order:*** Work division leads to sub orders that must be executed before a super order can be executed. A Command relationship SMO_{ji} between a super order MO_j and a sub order MO_i is defined as: $SMO_{ji}(MO_j, MO_i)$.
- ***Order Attribute:*** A Manufacturing Order MO_i has one or more characteristics or attributes AMO_i, with $i \in N$. Some of them have a constant value while others can change during the execution of the MO_i. Therefore, $AMO_n(T_t)$ is the value of an attribute AMO_n at a certain time T_t. The value of a manufacturing order attribute is characterized by the order parameters MO_i and time T_t : $AMO_n(MO_i, T_t)$.
- ***Order State:*** The situation that describes all the attributes of an order at a given time T_t is defined as: $SOMO_i(T_t) = AMO_n(MO_i, T_t)$ For $n \in N$. In this equation, $SOMO_i(T_t)$ represents the order state of order i at time T_t, and $AMO_n(MO_i, T_t)$ represents the attribute n of the order i at time T_t. The index n ranges over the set of attributes N associated with the order.

This formulation allows for a comprehensive representation of the order state, capturing all relevant attributes at a given point in time. It enables a detailed analysis and evaluation of the order's characteristics and facilitates decision-making processes within the supply chain management context.

- ***Activity:*** An activity A_v is something that is executed over a certain time interval, with "something" referring to physical and/or mental tasks that are carried out by an entity.
- ***Demand:*** A demand D_q is the need of an actor (for example a legal entity) for goods or information.
- ***Message:*** Ms is a written or spoken information item that is sent from one actor to another.
- ***Content:*** Content C_p is defined as the subject contained in information (for example in a Message).
- ***Reaction:*** A reaction, denoted as RE_u, represents an activity that directly arises as a result of a risk event or a disruptive event within the supply chain. When a risk event occurs, it triggers a reaction from the entities involved in the supply chain to mitigate the impact or address the consequences of the event.

  Reactions can take various forms, depending on the nature of the risk and the specific circumstances. They may involve immediate actions, contingency plans, or alternative strategies to minimize disruption, restore operations, or prevent further negative consequences. Examples of reactions can include activating backup suppliers, rerouting shipments, implementing emergency protocols, or adjusting production schedules.

  By recognizing and planning for potential reactions to risks, supply chain managers can enhance their ability to respond effectively to disruptions and maintain continuity. Developing proactive response strategies and incorporating them into risk management frameworks can help minimize the impact of risk events and enable the supply chain to recover quickly and efficiently.
- ***Consequence:*** A consequence, denoted as CSQ_w, refers to the outcome or result that arises from the execution of a specific reaction within the supply chain. When a reaction is implemented in response to a risk event, it leads to various consequences that may impact the overall supply chain performance.

  Consequences can manifest in different ways depending on the nature of the reaction and the context of the risk event. They can include both positive and negative outcomes, such as improved operational efficiency, increased customer satisfaction, financial losses, delays in delivery, reputational damage, or changes in resource allocation.

  Understanding and evaluating the consequences of reactions is essential for assessing the effectiveness of risk mitigation strategies and identifying areas for improvement within the supply chain. By analyzing the consequences, supply chain managers can make informed decisions, adjust their response strategies, and take proactive measures to minimize negative outcomes and maximize positive impacts in the face of risk events.

The data used by a SCRM solution must reflect both the static structure of the supply networks and the dynamic behaviors that the networks exhibit over time. As a result, different order relationships must be represented in a data model along with order attributes that characterize an order (such as quantities, delivery dates, quality measures, prices, costs). To assess the status of an order, data on the planned execution of processes (such as a scheduled delivery date) is also required. Some order attributes change in value during the execution processes, both due to progress in execution and trigger events that pose risks.

5.3.2 Statements

The following statements are based on the concepts defined above and characterize the risk problem that threatens the supply chain.

Let $R_h(LE_{k-x}, T_1)$ denote a risk occurring at time T_1 and originating from entity EL_{k-x}. This risk will affect one or multiple orders MO_i, leading to changes in order attribute values represented as $\Delta AMO_n(MO_i, T_1)$ and changes in order state $SOMO_i$ represented as $\Delta SOMO_i(T_1)$.

$$R_h(LE_{k-x}, T_1) \rightarrow \Delta AMO_n(MO_i, T_1) \qquad \rightarrow \Delta SOMO_i(T_1) \text{ with } n \in \mathbb{N} \tag{5.1}$$

The information regarding the relationship between the Risk R_h and the modified order state $\Delta SOMO_i(T_1)$ is defined as the potential content C_p of a message.

$$C_p(R_h, \Delta \text{SOMO}_i) \tag{5.2}$$

Regarding the interdependencies between commands and their sub-commands, a change in the attributes of the command $\Delta AMO_n(MO_j, T_1)$ and the respective change in the state of the command $\Delta SOMO_i(T_1)$ will impact a related super-order MO_j of the legal entity LE_k at a future time T_f.

$$\begin{aligned}\Big((\text{SMO}_{ji} = (\text{MO}_j, \text{MO}_i)) \bigwedge (\Delta\text{SOMO}_i(T_1) \neq 0)\Big) &\rightarrow \Delta\text{AMO}_n(\text{MO}_j, T_f) \\ &\text{with } n \in \mathbb{N} \text{ and } T_f > T_1\end{aligned} \tag{5.3}$$

With the deviation of $\Delta SOMO_i(T_1)$, an implicit information demand D_q arises at time T_1 on the supply network partner who may be impacted by the future Risk R_h as described in (5.1). This demand cannot be articulated as it is unknown to the partners at the time of occurrence of Risk R_h. The content C_p defined in formula (5.2) is required at time T1 (as soon as the risk occurs), and it is necessary for the recipient LE_k.

$$\begin{aligned}\Big((\text{SMO}_{ji} = (\text{MO}_j, \text{MO}_i)) \bigwedge (\Delta\text{SOMO}_i(T_1) \neq 0)\Big) &\rightarrow D_q\left(\text{LE}_k, C_p, T_1\right) \\ &\text{with } \text{MO}_i\left(\text{LE}_k, \text{LE}_{k-x}\right).\end{aligned} \tag{5.4}$$

Ideally, demand D_q is satisfied by a message M_s that is communicated from the legal entity LE_{k-x}, where the event took place, to the potentially affected legal entity LE_k. This content C_p is transmitted at time T_2 from the sender LE_{k-x} to the recipient LE_k.

$$D_q\left(\mathrm{LE}_k, C_p, T_1\right) \rightarrow M_s\left(C_p, T_2, \mathrm{LE}_{k-x}, \mathrm{LE}_k\right) \quad \text{With} \quad T_2 > T_1 \tag{5.5}$$

Based on the content C_p communicated in the message M_s, the recipient LE_k is capable of reacting to the arisen problem in order to reduce the potential negative effects. The reaction RE_u is characterized by parameters describing the actor LE_k, an activity A_v, the target MO_j of the activity, and also the time T_3.

$$M_s(C_p, T_2, LE_{k-x}, LE_k) \rightarrow RE_u(LE_k, A_u, MO_j, T_3) \text{ avec } T_3 > T_2 > T_1 \tag{5.6}$$

Any RE_u reaction, as defined in equation (5.6), will have a CSQ_r consequence on the state of the $SOMO_j(T_t)$ command of the manufacturing order MO_j. The consequence is described by the negative effect $\Delta SOMO_j(T_f)$ of the remaining states at time T_f of the R_h risk on the super order MO_j. The chosen RE reaction must minimize or eliminate the negative effect of the risk.

$$\begin{aligned} \mathrm{RE}_u(\mathrm{LE}_k, A_v, \mathrm{MO}_j, T_3) &\rightarrow \mathrm{CSQ}_w = \Delta\mathrm{SOMO}j(T_f) \\ &\rightarrow \mathrm{Min}(\mathrm{CSQ}r) \quad \text{With} \quad Tf > T_3 > T_2 > T_1 \end{aligned} \tag{5.7}$$

The formula can be used to monitor and analyze the supply chain in real time, allowing for quick reactions to risks and minimizing their impact. By tracking changes in the order attributes and state, the system can identify potential disruptions and take corrective actions to mitigate their effects. This can help to ensure that the supply chain operates efficiently and effectively, even in the face of risks and uncertainties.

5.3.3 Implications

The objective of minimizing the negative effects of risks and their trigger events on supply networks, by using data communication between supply network entities to allow for precautionary actions, is defined in formula (5.7) with the term $Min(CSQ_r)$.

The analysis of previous formulas regarding potential problems highlights a critical evident fact, the demand $D_q(LE_k, C_p, T_1)$ experienced by a legal entity LE_k in a risky state has no information about the risk trigger event that occurred at time T_1 at LE_{k-x}, even though this information is already available as content $C_p(R_h, \Delta SOMO_i(T_1))$ on LE_{k-x}. A deficit of information is the result. Therefore, the relatively vague need for proactive information management in a supply network, which has become visible in statement (5.4), is refined in formula (5.5) by defining the message $M_s(C_p, T_2, LE_{k-x}, LE_k)$ necessary to satisfy the implicit demand D_q.

The formalized model presented above considers the autonomy of supply network partners, which is reflected in the notion of different legal entities LE_k that voluntarily enter into contracts through orders. Implicitly, the model also considers the heterogeneity of participants and their different information needs, since the demand D_q is defined without any data restrictions. Given that the restrictions of heterogeneity and autonomy are reflected in our formal model of the SCRM problem, the model is used as a basis for risk management in the supply chain.

5.4 Potential benefits

In supply chain risk management, the detection and processing of trigger events must be done in advance and provided by the SCRM system to enable decision-makers to react in real-time with a greater range of possible solutions before the consequences of the risks accumulate and worsen. Our solution illustrates this through the result of a reaction $RE_u(LE_k, A_u, MO_j, T_3)$, where a significant amount of risk-related information is needed for rational decision-making, such as the type, severity, and date of occurrence, to determine the necessary activities A_u during an RE_u reaction. The SCRM data model must explicitly characterize trigger events with data types that allow for understanding and evaluating the type and quality of a risk.

Real-time risk reaction provides many benefits, including reducing the negative consequences associated with the risk for all parties involved. The advantages of risk management in supply networks are achieved at various levels, as multiple companies are affected by the spread of trigger events. To quantify the reductions in negative consequences, an evaluation of the benefits for individual companies is performed, followed by a cumulative evaluation of these benefits at the network level. All benefit quantifications are based on a cost model that is presented in the following sections.

5.4.1 Benefits for individual companies

In a simple scenario, a machine failure occurs that has a serious impact on a production order. If the trigger event of the risk is not detected, then production and shipping delays will result. Only a few alternatives are left for reaction, and the company will have to pay high costs to solve the problem. However, if the risk is detected earlier using an NeutroMAS4SCRM solution, a greater number of reaction alternatives would have been available and lower costs associated with the risk would have been incurred. A longer reaction time flexibility would have been gained.

An early discovery of the situation would have allowed for re-planning, as more reaction alternatives would have been available and the situation could be modified, which can lead to lower costs, increased flexibility, and improved performance. Additionally, it can help them maintain a competitive edge in the market and enhance their reputation by ensuring high-quality products and services are delivered on time.

Figure 5.3 offers a scenario on the potential benefits of an NeutroMAS4SCRM system for a single company. Figure 5.3 indicates the ability of a company to react to a problem caused by a trigger event of risk that occurs during an execution process. The ability degrades as time advances, and some reaction options become impractical. In contrast, costs related to risk increase with time compared to a planned execution.

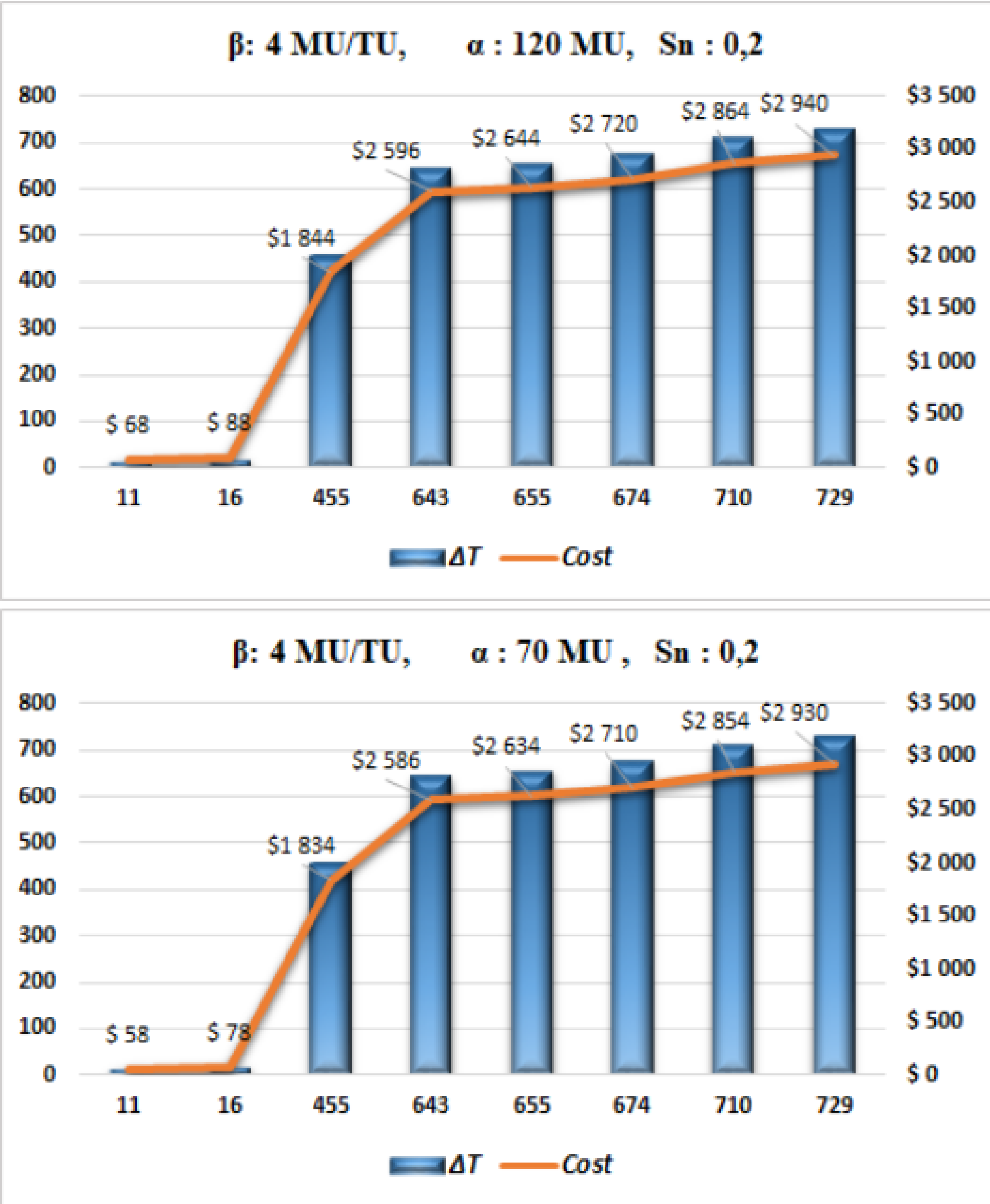


Figure 5.3: The cost per cost function for a single risk

The main parameter influenced by risk management is the time interval between the occurrence of a risky situation and its identification, referred to as $\Delta T = T_{\text{identifRisk}} - T_{\text{OccurrencRisk}}$.

Our agent-based NeutroMAS4SCRM system updates the system and database information based on new input data, which also allows for the update of Key Risk Indicators (KRI) indicators, upon which alerts are generated as necessary. The time interval between the occurrence and identification of a trigger event of $risk = \Delta T$ is determined by the number of update cycles per period. The higher the number, the more quickly any risk will be discovered and the lower it will be.

If no explicit risk management mechanism is in place, risky states are identified at a certain point after the planned date of order execution, namely when a human actor realizes that an order has not yet arrived due to a delay or some problem (e.g., product failure, incomplete delivery, etc.). In such cases, a manual risk management process is initiated and data will be collected by human actors to identify the reason for the problem and react accordingly. Therefore, a single SCRM cycle is assumed to be sufficient for identifying any risk before the planned date of order completion.

In a supply chain, a production cycle refers to the time it takes to produce and deliver a product or service to the end customer. It involves all the processes from the procurement of raw materials to the delivery of the finished product. The duration of a production cycle varies depending on the complexity of the product, the number of steps involved, and the efficiency of the production process.

A typical production cycle starts with the procurement of raw materials, which are then processed into intermediate products. The intermediate products are then assembled into finished products, which are then tested, packaged, and shipped to the end customer. Each of these steps takes a certain amount of time, and the total time it takes to complete all the steps is the production cycle time.

The production cycle time is a critical metric in supply chain management, as it determines the lead time for the delivery of products to the end customer. A shorter production cycle time means faster delivery times, which can help a company to meet customer demands and gain a competitive advantage. However, reducing the production cycle time can also increase costs, as it may require investments in new equipment, process improvements, or additional labor.

To optimize the production cycle time, companies may use various strategies such as just-in-time (JIT) manufacturing, lean manufacturing, or agile manufacturing. JIT manufacturing involves producing goods only when they are needed, while lean manufacturing focuses on reducing waste and improving efficiency. Agile manufacturing is a flexible approach that allows companies to adapt quickly to changes in demand or production requirements.

Overall, the production cycle is a critical aspect of the supply chain, and managing it effectively can help companies to improve their performance and competitiveness.

5.4.1.1 Reduction of costs related to risk

Any acceptance of risk must be followed by discussions on how to integrate the total cost of risk into product pricing or performance measurement systems. All costs associated with a risk can be divided into two parts: costs associated with direct problem resolution (e.g. management costs) and follow-up costs (e.g. lost sales or higher inventory levels).

The detailed analysis of the described benefits is based on a cost function as described in [245]. Let CR be a cost function of the form $CR(S, \Delta T)$, where S is the measurable severity of a risk and ΔT is the positive difference between the time of identification of a risk trigger event and the time of occurrence of the risk. The cost function (5.8) is based on an additive model with two cost parameters α and β.

$$CR(S, \Delta T) = \alpha S + \beta \Delta T, \quad \Delta T > 0 \text{ and } \alpha, \beta > 0 \tag{5.8}$$

The costs associated with a risk tend to increase as the severity of the disruptive event increases, as it affects more orders and results in longer delays. Additionally, ΔT cannot be zero because it always takes at least a very short period of time for an event to be identified and communicated. The two cost parameters, α and β, are positive because the occurrence of a disruptive event and the time it takes to respond cannot reduce costs compared to a situation without a disruptive event. However, cases with $S_n = 0$ are not relevant as no problem occurs, and no additional specific cost can be associated with this situation.

The cost parameter α reflects the impact of the severity of a risk trigger event, and determines the costs associated with the risk that cannot be reduced by operational reactions. This impact is determined by the organizational structures and processes of a company that are affected by this risk, but can be reduced as a result of organizational optimization efforts. The second term consists of the cost parameter β, which varies for different types of risks and depends on the time of occurrence of the risk trigger event.

In Figure 5.3, data is used to simulate an alert scenario between the company's agents. The production agent sends a request message to the enterprise agents when it detects an alert after the cyclic risk assessment at the manufacturing service level using the NDAHP method. The severity level, represented by the cost parameter α, is set to 120 monetary units [MU] on the top and 70 monetary units [MU] on the down, multiplied by the random value $S_n = 0.2$. The time between risk occurrence and identification is calculated using the value $\beta = 4$ MU per time unit (TU) in the cost-benefit model. Time is measured in seconds in the agent runtime simulation. The simulation, conducted using the Jade platform, demonstrates that the delay between the alert detection time and the risk occurrence time impacts the company's costs.

One unit of time is an abstract measure of time in the cost benefit model, and in execution processes, time is mainly measured in hours.

5.4.1.2 The automation of event management

The proactive collection of data in inter-organizational environments is one of the main features required for automated risk management. Several companies are simulated, as shown in the generic prototype (See chapter 4). Each of the three distributed agents that make up the E_n company, if they encounter an alert state during their updates, will react instantly by sending the alert message to either the E_{n-1} client company or the E_{n+1} supplier company. The overall response time between the initial request of the agent that detected the risk and the final response received by the agent is measured.

Calculation times are necessary for each company, as the complex data retrieval mechanisms may take additional time in reality. After analyzing the data collected in the supply chain, the step of activating the Neutrosophic logic module with the AHP method integrated in each agent is taken to decide whether or not to generate alerts.

5.4.1.3 Propagation of risk effects throughout the supply chain network

In order to show how risk affects other companies within the supply chain network, it is necessary to track how negative risk effects spread. These effects determine how serious risky events are at different levels of related companies' supply chain networks.

When there is a risk that affects a particular Order Fulfillment (MO), the consequences of that risk will spread to the end customer along the path determined by the order relationships. This spreading effect starts at level n and goes to level $n+1$, and then to levels $n+2$ and $n+3$, as shown in Figure 5.4.

The effect of a trigger event of a risk that happens at level n of the distribution network and affects the next level, n+1, is calculated using $E_n(S_n, \Delta T_n)$. This is a measure of the severity of the risk tracking at level $n+1$.

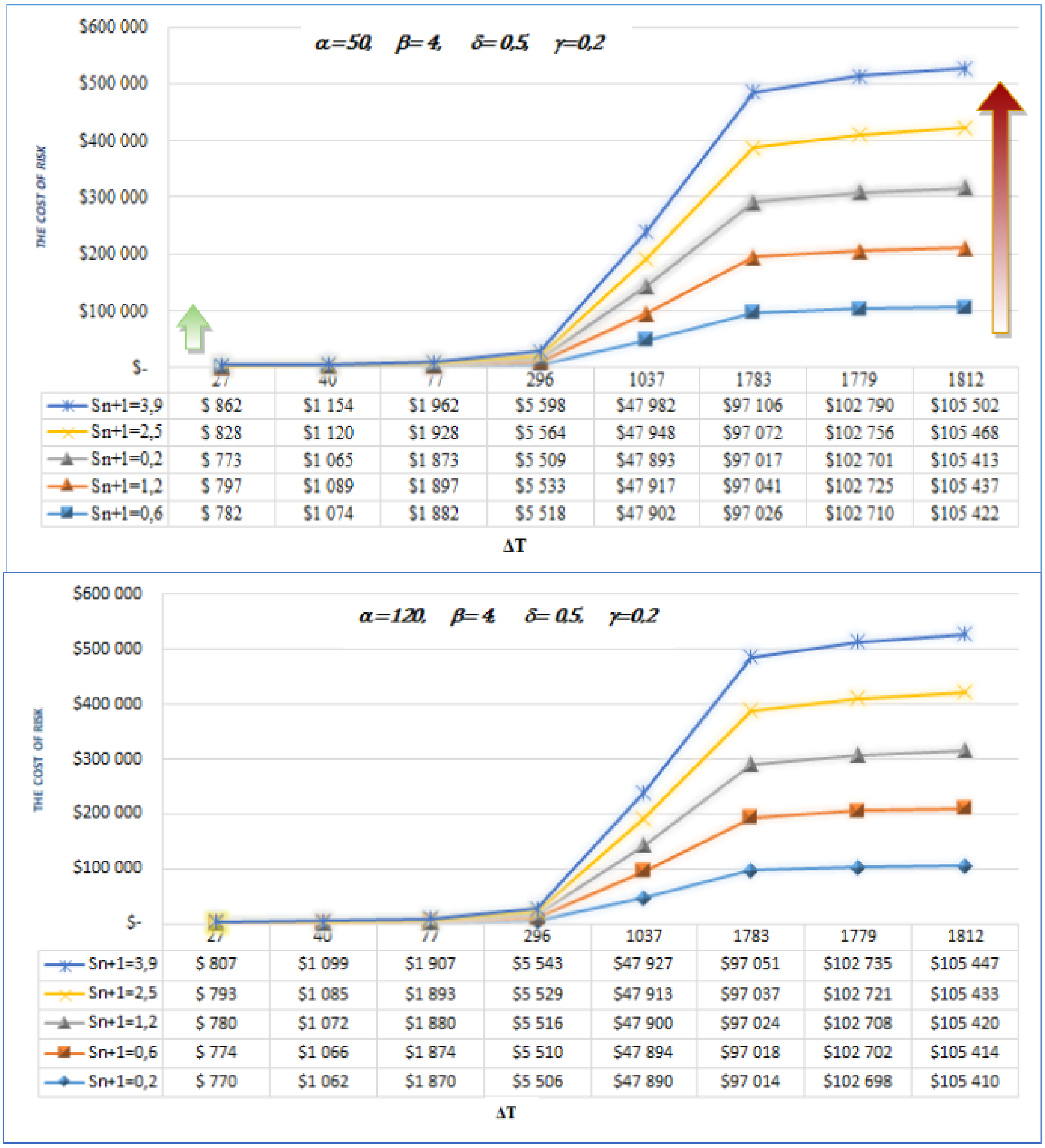
$$S_{n+1} = E_n = \gamma S_n + \delta \Delta T_n \text{ With } S_n, \Delta T_n > 0 \text{ And } \gamma, \delta > 0 \tag{5.9}$$

Figure 5.4: Propagation of risk effects throughout the SC.

The severity of a risk, represented by S_n, has an impact on the effect, represented by E, that other partners in the supply network will experience. The magnitude of this impact is determined by the company's structural processes, which can vary in their sensitivity to different risk-triggering events.

A high value for the parameter δ indicates that a company is less equipped to handle disruptions, while a low value indicates advanced risk management abilities that can help to minimize harmful impacts. The parameters γ and δ are unique to each supply network member and not necessarily specific to a given type of risk-triggering event.

In Figure 5.5, the impact of different ΔT_n values on risk severity at level S_{n+1} is shown. An increase in ΔT_n suggests the occurrence of a risk-triggering event at supply chain range n, and its adverse effects propagate to the next partner in the supply network at sequence $n+1$. It's assumed that ΔT_n does not directly influence the factor γS_n, which leads to an advancement of γS_{n+1}.



	27	40	77	296	1037	1783	1779	1812
Sn+1=3,9	$ 862	$1 154	$1 962	$5 598	$47 982	$97 106	$102 790	$105 502
Sn+1=2,5	$ 828	$1 120	$1 928	$5 564	$47 948	$97 072	$102 756	$105 468
Sn+1=0,2	$ 773	$1 065	$1 873	$5 509	$47 893	$97 017	$102 701	$105 413
Sn+1=1,2	$ 797	$1 089	$1 897	$5 533	$47 917	$97 041	$102 725	$105 437
Sn+1=0,6	$ 782	$1 074	$1 882	$5 518	$47 902	$97 026	$102 710	$105 422

	27	40	77	296	1037	1783	1779	1812
Sn+1=3,9	$ 807	$1 099	$1 907	$5 543	$47 927	$97 051	$102 735	$105 447
Sn+1=2,5	$ 793	$1 085	$1 893	$5 529	$47 913	$97 037	$102 721	$105 433
Sn+1=1,2	$ 780	$1 072	$1 880	$5 516	$47 900	$97 024	$102 708	$105 420
Sn+1=0,6	$ 774	$1 066	$1 874	$5 510	$47 894	$97 018	$102 702	$105 414
Sn+1=0,2	$ 770	$1 062	$1 870	$5 506	$47 890	$97 014	$102 698	$105 410

Figure 5.5: Variations in risk severity at the level of the client company n+1.

5.4.2 Benefits for supply chain networks

5.4.2.1 Reducing costs in the supply chain

Using the E supply network as a basis, it is possible to calculate the effects of the network on costs and evaluate the cumulative impact of cost reduction on potential supply network benefits. By analyzing the costs associated with the E network, it becomes possible to identify areas where cost reductions can be made without compromising the effectiveness of the network. This analysis can provide valuable insights for supply chain management, allowing for the implementation of targeted cost reduction strategies that can yield substantial benefits.

Furthermore, by assessing the cumulative effects of cost reduction on the network, it is possible to determine the potential benefits that can be achieved through this approach. These benefits may include improved efficiency, increased productivity, and better alignment with customer demands, among others. Overall, the calculation and evaluation of supply network costs and the cumulative impact of cost reduction can help organizations make informed decisions regarding their supply chain strategy and improve their overall operational performance.

The formula used to calculate the cost for a company at level n:

$$\mathrm{CR}_n(S_n, \Delta T_n) = \alpha S_n + \beta \Delta T_n \quad \text{With } \Delta T_n > 0 \text{ And } \alpha, \beta > 0 \tag{5.10}$$

The formula used to calculate the cost for a company at the next level, which is level n+1:

$$\begin{aligned} CR_{n+1}(S_{n+1}, \Delta T_{n+1}) &= \alpha S_{n+1} + \beta \Delta T_{n+1} \\ &= \alpha(\Upsilon S_n + \delta \Delta T_n) + \beta \Delta T_{n+1} \\ &= \alpha \Upsilon Sn + \alpha \delta \Delta T_n + \beta \Delta T_{n+1} \end{aligned} \tag{5.11}$$

The cost formula for level n+2 company:

$$\begin{aligned} CR_{n+2}(S_{n+2}, \Delta T_{n+2}) &= \alpha S_{n+2} + \beta \Delta T_{n+2} \\ &= \alpha \Upsilon S_{n+1} + \alpha \delta \Delta T_{n+1} + \beta \Delta T_{n+2} \end{aligned} \tag{5.12}$$

In this study, a simulation was conducted to investigate the impact of ΔT_n on the severity of risks at level $n+1$ in companies. The simulation results in Figure 5.5 show that the costs associated with a disruptive incident increase with its intensity, such as more orders being affected by a prolonged machine outage, resulting in lengthier delays. The values of α and β, however, do not affect the severity of risks since they remain constant during the simulation run with different ΔT_n values.

To further understand the behavior of the system, a simulation was conducted with a single risky event but with varying severity and ΔT_n values to show the influence of these factors on the costs associated with the cumulative effects of risk propagation to level $n+1$ companies.

Figure 5.5 presents two possible scenarios, where the first scenario, depicted by a green arrow, represents the proposed NeutroMAS4SCRM system, where agents representing relevant companies proactively communicate risk-triggering event information, leading to a reduction in ΔT in subsequent stages, resulting in lower costs. The second scenario, depicted by a red arrow, represents a supply chain without a risk management system and real-time communication, resulting in greater ΔT and higher loss costs.

It is worth noting that, in addition to multi-agent systems and their advantages in distributed systems, the proposed system also utilizes the NDAHP and AgentSCRM ontology to facilitate the collection and extraction of real-time event evaluation knowledge.

In general, the costs for each level $n + x$ tend to increase due to larger cost parameters. However, with the proposed real-time risk detection system and the decision to alert other companies, there is an expected decrease in costs for all levels of the distribution network. This highlights the important role of the system in reducing SC costs.

5.5 Implementation of the proposed approach

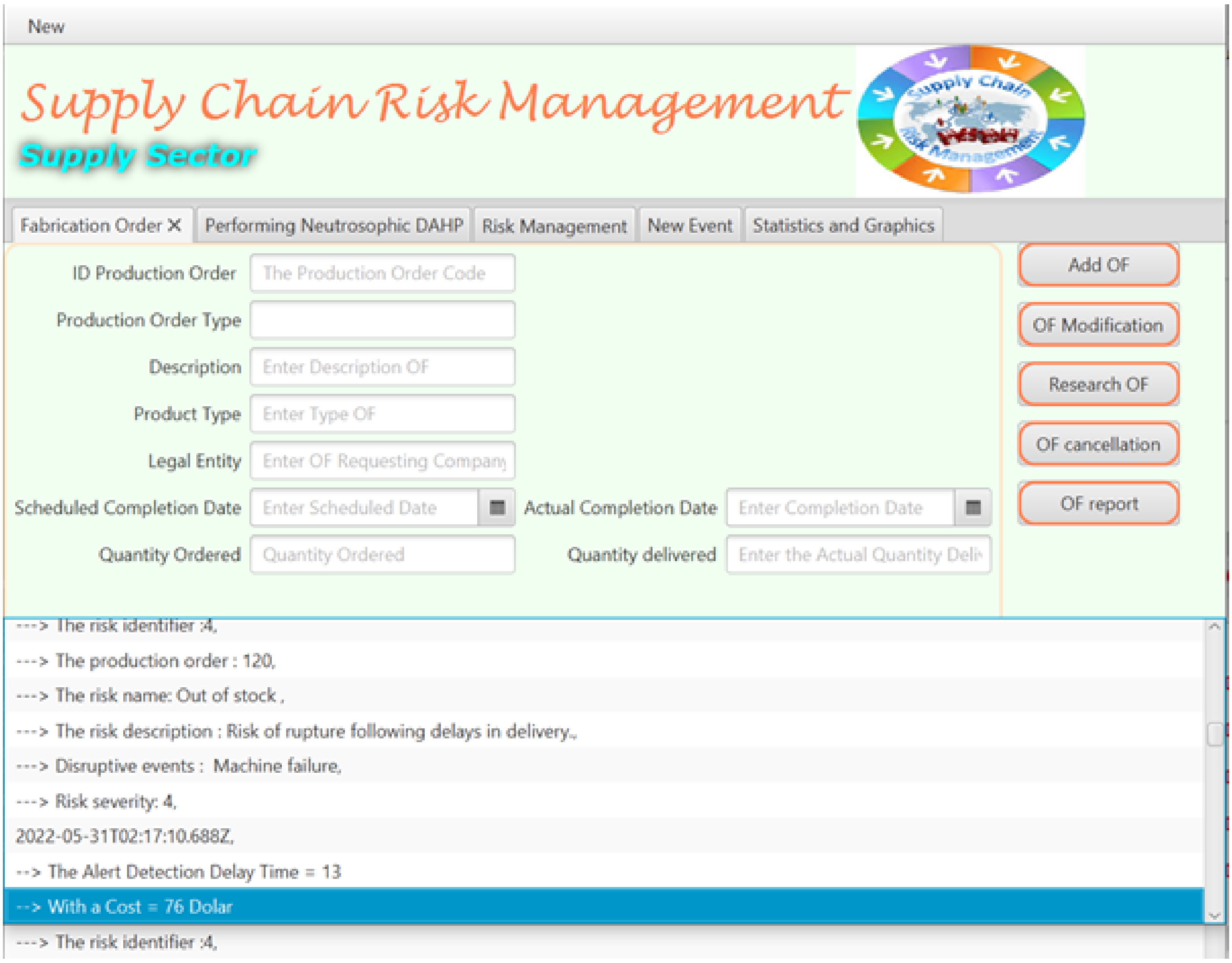


Figure 5.6: A visual representation of risk assessment and monitoring in the supply sector.

```
public static final String NAME = "AgentSCRM-ontology";

//
private static Ontology theInstance = new AgentSCRMontology();
//
public static Ontology getInstance() {
return theInstance;
}

// Private constructor
private AgentSCRMontology() {
//
super(NAME, BasicOntology.getInstance());
try {
    ConceptSchema cs = new ConceptSchema(Risk);
    add(cs,AgentSCRM.OntologySCRM.Risk.class);

    //cs = (ConceptSchema) getSchema(Risk);
    cs.addSuperSchema((ConceptSchema) getSchema(Risk));
    cs.add(Risk_NAME, (PrimitiveSchema) getSchema(BasicOntology.STRING));
    cs.add(Risk_Desc, (PrimitiveSchema) getSchema(BasicOntology.STRING),ObjectSchema.OPTIONAL); //

    ConceptSchema cs1 = new ConceptSchema(OF);
    add(cs,AgentSCRM.OntologySCRM.OF.class);

    cs1.addSuperSchema((ConceptSchema) getSchema(OF));
    cs1.add(OF_TITLE, (PrimitiveSchema) getSchema(BasicOntology.STRING));
    cs1.add(OF_Descriptio, (PrimitiveSchema) getSchema(BasicOntology.STRING),ObjectSchema.OPTIONAL);
    // Structure of the schema for the HaveRisque predicate
    PredicateSchema ps= new PredicateSchema(HR);
    add(ps,AgentSCRM.OntologySCRM.HaveRisk.class);

    ps.add(Risk1_Desc, (ConceptSchema) getSchema(Risk));
```

Figure 5.7: Communication between Agents.

In this study, we conducted a simulation to investigate the influence of different parameters on the performance of a multi-agent system. The simulation was realized using JADE, a popular platform for developing and deploying multi-agent systems.

JADE (Java Agent Development Framework) is an open-source platform for developing multi-agent applications in Java. As defined by Bellifemine [281], JADE is a "middleware" that provides developers with a set of libraries and tools to create and manage autonomous agents that communicate and collaborate with each other.

The platform is built on top of the FIPA (Foundation for Intelligent Physical Agents) specifications, which define a standard communication protocol and ontology for multi-agent systems. According to Zambonelli [282], FIPA is "the most significant and widely used standard for the development of multi-agent systems."

JADE consists of several components:

- *Agent Container:* The Agent Container is a platform for hosting agents. It is responsible for creating, starting, stopping, and managing agents, and provides the infrastructure for inter-agent communication.
- *Agent Management System (AMS):* The AMS is a special agent that is responsible for managing the Agent Container. It provides services such as agent creation, deletion, and monitoring, and allows agents to discover and communicate with other agents.

- ***Directory Facilitator* (*DF*)*:*** The DF is a special agent that provides a yellow pages service for agents. It allows agents to register their services and capabilities, and provides a directory of agents that can be queried by other agents.

- ***Message Transport Service* (*MTS*)*:*** The MTS is responsible for delivering messages between agents. It provides support for different communication protocols such as TCP, UDP, and RMI, and allows agents to communicate across different machines.

- ***Agent Development Environment* (*ADE*)*:*** The ADE is a set of tools and libraries that support the development of JADE-based agents. It includes an agent development kit, a graphical user interface for monitoring and controlling agents, and various application programming interfaces (APIs) for building agents.

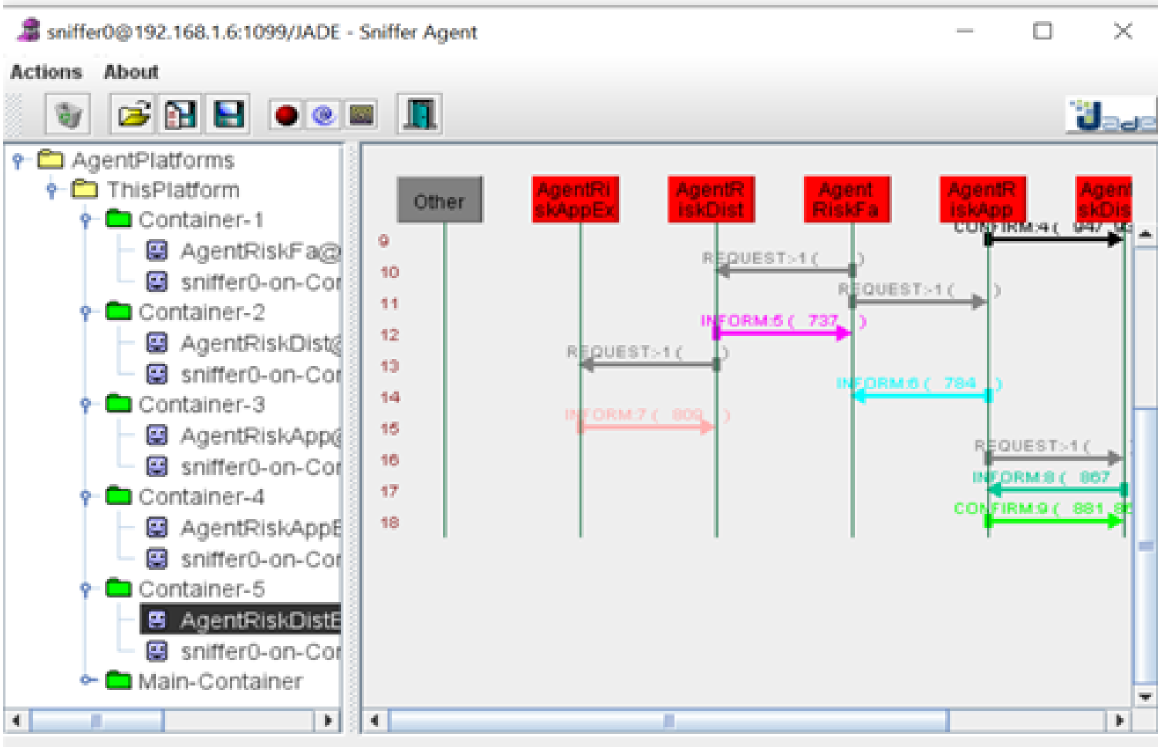


Figure 5.8: A Visual Representation of the interface of Agent RiskAppAgent.

Overall, JADE provides a flexible and robust platform for building and deploying multi-agent systems. As stated by Bellifemine [281], "the combination of JADE and FIPA provides a powerful and flexible tool for the development of multi-agent systems."

The interfaces implemented using the JADE platform and Java language (as presented in Figure 5.6) are designed to capture and convey the state of alerts signaled by the agents to the companies in the supply chain. These alerts are generated based on real-time risk detection and evaluation of disruptive events in the supply chain. As illustrated in Figures 5.9 and 5.8, the JADE platform facilitates efficient communication and coordination among agents from diverse companies. This capability enables timely and accurate information sharing in response to risk-triggering events. Furthermore, the use of the Java language provides a robust and flexible programming framework for the development of the interfaces, which can be easily customized to suit the specific needs and requirements of the supply chain partners.

This integration of JADE platform and Java language thus enables efficient risk management in the supply chain and helps to minimize the negative impacts of disruptive events.

The ontology of communication between agents that appears in the interface in Figure 5.7 plays a crucial role in facilitating effective communication and ensuring a common understanding of risk-related information between supply chain partners. By using a common ontology, our proposed approach can improve the accuracy and efficiency of risk detection and response in the supply chain, ultimately leading to reduced costs and improved performance.

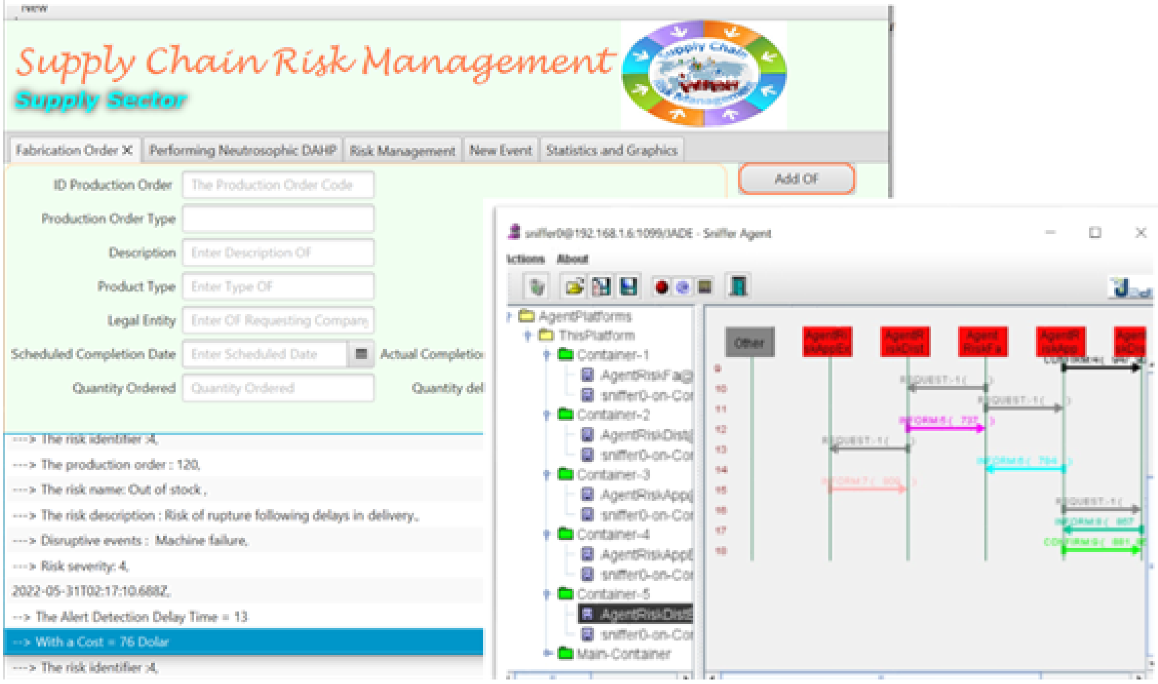


Figure 5.9: JADE Interface for Communication among Agents.

5.6 Conclusions

This chapter has introduced the proposed scenarios for the detailed validation of our agent-based system for risk management in a distributed supply chain environment. As previously mentioned in the preceding sections, the agents in our system communicate and collaborate with one another to effectively share tasks and information. In this section, we have discussed the advantages of using an ontology to facilitate communication in multi-agent systems. Specifically, we presented our ontology AgentSCRM which helps to formalize the vocabulary and relationships between the concepts used in our system.

The proposed JADE platform offers several benefits for supply chain networks, particularly in terms of reducing costs. By analyzing the costs associated with the supply network and identifying areas for cost reduction without compromising network effectiveness, organizations can implement targeted strategies that lead to significant benefits. The calculation and evaluation of supply network costs, along with the cumulative impact of cost reduction, enable informed decision-making and improved operational performance. The cost formulas presented in this study provide a framework for assessing costs at different levels within the supply chain. Simulation results demonstrate that the severity of risks and the time delay (ΔT_n) have a direct impact on costs associated with disruptive incidents. The proposed NeutroMAS4SCRM system, with proactive communication and real-time risk management, shows a reduction in ΔT and subsequent cost savings compared to scenarios without such a system.

Furthermore, the utilization of multi-agent systems, NDAHP, and AgentSCRM ontology enhances the system's ability to collect and extract real-time event evaluation knowledge. This integration facilitates effective risk detection and communication, leading to cost reduction at all levels of the distribution network.

In summary, the JADE platform offers significant benefits for supply chain networks by enabling effective communication, coordination, and timely information sharing in response to risk-triggering events. This approach leads to cost reduction, improved efficiency, increased productivity, and better alignment with customer demands. By implementing the proposed system, organizations can make informed decisions, enhance their supply chain strategy, and ultimately improve their overall operational performance.

In addition to the aforementioned points, it is important to note that this chapter primarily focuses on the implementation phase of the system. However, it is worth mentioning that, as of now, there is no available Java library specifically designed for neutrosophic logic. Neutrosophic logic, with its ability to handle uncertain and indeterminate information, has potential applications in various domains, including risk management in supply chain environments. While neutrosophic logic is a promising framework, further research and development are required to create a dedicated Java library that fully supports neutrosophic logic operations and reasoning.

Through our work, we have proposed a method for performing calculations using neutrosophic logic within a Java environment. This method, developed as part of our research, aims to provide a computational framework that incorporates neutrosophic logic operations and reasoning.

Chapter 6

Conclusions And Future Work

Chapter 6

Conclusions And Future Work

6.1 Conclusions

Throughout the course of our thesis, we have delved into several key areas of interest. We have discussed a range of pertinent issues and topics that are central to our research, providing in-depth analysis and critical evaluation along the way. Furthermore, as we have continued to develop our ideas and arguments, we have explored a variety of related aspects that we believe are important for fully understanding and addressing our research questions. In this regard, we have sought to build a comprehensive and nuanced picture of the issues at hand, drawing on a range of theoretical and empirical sources to support our claims and assertions.

6.1.1 Review of the realized study

Disruptions in the supply chain can lead to significant losses for companies, affecting not only their financial performance but also their reputation and relationships with customers and trading partners. The COVID-19 pandemic has highlighted the vulnerability of global supply chains, making it clear that businesses must be prepared to mitigate risks and respond quickly to changing conditions. While SC managers have developed strategies for risk identification, assessment, treatment, and monitoring, there are still significant gaps in knowledge and many companies have not implemented proactive or flexible processes for dealing with adverse events. The use of real-time information and intelligent tools offers new opportunities for managers to react and manage risks in a shorter time frame, but more research is needed in this area. Overall, the complexity of SCRM issues requires an integrative and collaborative approach, using all available technologies and strategies to encourage informed decision-making and minimize the impact of disruptions on businesses and the wider economy.

This section provides a summary of the main research findings on Supply Chain Risk Management, as well as new approaches and recommendations for future research. Researchers have studied SCRM extensively, focusing on measures such as resilience, robustness, stability, and flexibility to assess SC performance under disruptions. However, there is still a gap between practical needs and research outcomes. Globalization has brought benefits such as new markets, reduced costs, internet opportunities, and commercial treaties, but also challenges such as political instabilities, cultural diversity, extended distances, and normalization difficulties, which make SC more vulnerable to risks. Although the literature on SCRM mainly focuses on a single company and its direct business partners, some studies have extended the analysis to multi-level supply chains. The authors call for more empirical research to bridge the gap between theory and practice, linking conceptual and empirical studies, and developing global frameworks and holistic approaches with Decision Support Systems that cover all stages of SCRM. The speed of recovery is essential in mitigating the impact of disruptions, and investment in SCRM can help avoid many problems related to disruptive events. However, it is not possible to avoid all disturbances, and the emphasis should be on recovery policies. Overall, the SCRM field is evolving, and further quantitative and qualitative studies are necessary to improve the understanding and management of SC risks.

As our thesis has progressed, we have addressed the following points:

Chapter 2 of the thesis provides an overview of supply chain risk management process, scope, and independent techniques that can be used to manage risks in the supply chain. The chapter begins with an introduction to SCRM, which involves identifying, assessing, mitigating, and monitoring risks in the supply chain to minimize the impact of potential disruptions.

The chapter 3 presents various methodological tools that can be used in decision-making processes. The first tool introduced is neutrosophic logic, which includes fuzzy and intuitionistic fuzzy sets. Neutrosophic sets are then defined, along with their complement, containment, union, intersection, and single-valued variations. The classic Analytic Hierarchy Process method is also described, including its strengths and limitations, as well as the steps involved in the decision-making process. Finally, the chapter presents the Neutrosophic Data AHP method, which combines neutrosophic logic and the AHP method to improve the accuracy of decision-making processes.

Chapter 4 of the thesis discusses the use of Multi-Agent Systems for risk management in supply chains. The chapter begins by defining the concept of an agent and its importance in MAS. It then goes on to describe the characteristics of MAS and the communication languages used between agents. A typology of agents is also presented. The chapter then provides an overview of MAS studies in SCRM and introduces the authors' own approach to risk management using MAS. This approach takes a macro and micro perspective and utilizes methodologies for the development of MAS. The agent society for supply chain risk management is described, including the roles and types of agents and the structural design of the agent society. The interactions among agents are then discussed, including the basic interaction protocol, intra-organizational communication, and external triggers. The chapter also highlights the importance of commitment to an ontology. The chapter concludes with a detailed description of the RiskDistAgent, including its structure and behaviors. Overall, the chapter not only presents a theoretical framework for the use of MAS in SCRM, but also provides a practical approach to implementing a multi-agent system for risk management in supply chains.

Chapter 5 of the dissertation discusses the use of ontology in Smart Multi-Agent Systems for Supply Chain Risk Management. The chapter begins by introducing the AgentSCRM ontology proposal, which is designed to facilitate communication and knowledge sharing between different agents in the SMA system. The benefits of ontology for SMA are discussed, including the ability to represent and reason about knowledge in a more formal and structured manner. The chapter then moves on to formally specify the problem of SCRM, defining key terms and outlining the implications of different events and actions. The potential benefits of implementing the proposed approach are discussed, including cost reduction, event management automation, and risk propagation management. The implementation of the proposed approach is then discussed, highlighting the challenges and opportunities for realizing the benefits of the AgentSCRM ontology. Finally, the chapter concludes by emphasizing the importance of using ontology in SMA for SCRM to improve supply chain resilience and risk management.

6.1.2 Limitations and extensions

Limitations:

- The proposed decision support system will rely heavily on accurate and up-to-date data, which may not always be available in real-time. This may limit the effectiveness of the system in certain situations.
- The proposed ontology-based communication mechanism may be limited by the availability of a standardized ontology for SCRM, which may vary across industries and regions.
- The proposed Neutrosophic Data Analytical Hierarchy Process method may require significant computational resources, which may limit its applicability to smaller organizations.

Extensions:

- Further research could explore the use of other decision-making systems in combination with multi-agent systems to improve SCRM, such as fuzzy logic or artificial neural networks.
- The proposed ontology-based communication mechanism could be expanded to incorporate machine learning techniques to automatically categorize and prioritize risk information.
- The proposed Neutrosophic Data Analytical Hierarchy Process method could be further refined and extended to incorporate additional criteria or factors for risk evaluation.
- The validation scenarios proposed for the agent-based system could be extended to incorporate a broader range of supply chain scenarios, including those involving multiple tiers of suppliers and complex logistics networks.

6.2 Future work

Future work involves developing a neutrosophic logic-based multi-agent system to improve risk mitigation in supply chain management. This research will significantly contribute to the current literature on SCRM by presenting an innovative approach that combines neutrosophic logic and multi-agent systems. The findings will offer valuable insights and guidance for practitioners and researchers in creating efficient SCRM strategies in the future. Additionally, the proposed system is expected to enhance the decision-making process for risk mitigation in real-time, thereby improving supply chain operations' efficiency and effectiveness. Ultimately, the results will play a crucial role in advancing the field of SCRM and increasing supply chain performance and resilience.

6.3 Overall Conclusions

In conclusion, this thesis has proposed a novel approach to supply chain risk management through the development of a neutrosophic logic-based multi-agent system called NeutroMAS4SCRM [283]. The system was designed to improve the decision-making process for risk assessment and mitigation in real-time, with the aim of increasing the efficiency and effectiveness of supply chain operations.

The study has contributed to the existing literature on SCRM by highlighting the importance of understanding what SCRM means and which information should be controlled. It has also shown that becoming a sustainable supply chain is not a destination but a journey, and that meeting sustainability and SCRM cooperatively is sensible.

Our research has made significant contributions to understanding and resolving challenges related to risk assessment in the presence of uncertain, incomplete, and imprecise information. The findings of our study have led to the recommendation of using the NeutroMAS4SCRM method for effective risk assessment and management in the supply chain. This holistic approach provides real-time decision support, ensures optimal collaboration among supply chain organizations, and assists decision-makers in making informed decisions in the face of risks. In conclusion, our research has adequately addressed the questions raised in the thesis and provides practical recommendations for enhancing risk management in the supply chain.

Additionally, the study presents detailed validation scenarios to showcase the potential effectiveness of the proposed system. However, it is important to acknowledge that currently, there is a lack of a dedicated Java library specifically designed for neutrosophic logic, despite its wide-ranging applications, including risk management in supply chain contexts. As part of this research, we have introduced a methodology for conducting calculations using neutrosophic logic within a Java environment. This approach offers a computational framework that integrates neutrosophic logic operations and reasoning. Nevertheless, further research and development efforts are necessary to develop a specialized Java library that comprehensively supports these functionalities.

Overall, the findings of this research have significant implications for practitioners and researchers interested in developing effective SCRM strategies. The proposed approach has the potential to enhance the decision-making process for risk mitigation and improve supply chain performance and resilience. Future research could explore the use of other decision-making systems, incorporate machine learning techniques, or extend the proposed risk evaluation method.

In summary, this thesis has made a valuable contribution to the field of SCRM by proposing a novel approach that incorporates neutrosophic logic and multi-agent systems. It is hoped that the findings of this research will serve as a useful guide for practitioners and researchers seeking to improve supply chain resilience in the face of increasing complexity and instability.

Bibliography

Bibliography

[1] Matthew Leitch et al. Iso 31000: 2009-the new international standard on risk management. *Risk analysis*, 30(6):887, 2010. doi:10.1111/j.1539-6924.2010.01397.x. XII, 9, 20, 25

[2] R Lindroth and A Norrman. Supply chain risk management: Purchasers' vs. planners view on sharing capacity investment risks in the telecom industry.'. In *Proceedings of the IPSERA 11th International Conference*, pages 25–27, 2001. XII, 32

[3] Ibrahim M Hezam, Mohamed Abdel-Baset, and Florentin Smarandache. *Taylor series approximation to solve neutrosophic multi-objective programming problem*. Infinite Study, 2015. XII, 74

[4] Mohsen Pirdashti, Arezou Ghadi, Mehrdad Mohammadi, and Gholamreza Shojatalab. Multi-criteria decision-making selection model with application to chemical engineering management decisions. *International Journal of Chemical and Molecular Engineering*, 3(1):1–6, 2009. XII, 78, 79

[5] Thomas L Saaty. The analytic process: planning, priority setting, resources allocation. *McGraw, New York*, 1980. XIV, 85

[6] G Tomas M Hult, Christopher W Craighead, and David J Ketchen, Jr. Risk uncertainty and supply chain decisions: a real options perspective. *Decision Sciences*, 41(3):435–458, 2010. doi:10.1111/j.1540-5915.2010.00276.x. 3

[7] Debby Guha-Sapir, Femke Vos, Regina Below, and Sylvain Ponserre. Annual disaster statistical review 2011: The numbers and trends. Technical report, Centre for Research on the Epidemiology of Disasters (CRED), Brussels, Belgium, 2012. URL: http://www.cred.be/sites/default/files/ADSR_2011.pdf. 3

[8] ManMohan S Sodhi, Byung-Gak Son, and Christopher S Tang. Researchers' perspectives on supply chain risk management. *Production and operations management*, 21(1):1–13, 2012. doi:10.1111/j.1937-5956.2011.01251.x. 3, 18, 28

[9] Thomas Y Choi, Dale Rogers, and Bindiya Vakil. Coronavirus is a wake-up call for supply chain management. *Harvard Business Review*, 27(1):364–398, 2020. 3

[10] Shabnam Rezapour, Reza Zanjirani Farahani, and Morteza Pourakbar. Resilient supply chain network design under competition: A case study. *European Journal of Operational Research*, 259(3):1017–1035, 2017. doi:10.1016/j.ejor.2016.11.041. 3

[11] Yash Daultani, Sushil Kumar, Omkarprasad S Vaidya, and Manoj K Tiwari. A supply chain network equilibrium model for operational and opportunism risk mitigation. *International Journal of Production Research*, 53(18):5685–5715, 2015. doi:10.1080/00207543.2015.1056325. 3

[12] Yanfeng Ouyang and Xiaopeng Li. The bullwhip effect in supply chain networks. *European Journal of Operational Research*, 201(3):799–810, 2010. doi:10.1016/j.ejor.2009.03.051. 3

[13] Mikaella Polyviou, George Ramos, and Eugene Schneller. Supply chain risk management: An enterprise view and a survey of methods. In *Supply Chain Risk Mitigation*, pages 27–58. Springer, 2022. doi:10.1007/978-3-031-09183-4_2. 3

[14] Amulya Gurtu, Jestin Johny, and Rupal Chowdhary. Effects of free trade agreements on trade activities of signatory countries. *The Indian Economic Journal*, page 00194662221104750, 2022. doi:10.1177/00194662221104750. 3

[15] D Simchi Levi, C Vassiladis, and I Kyratzoglou. Making the right risk decisions to strengthen operations performance. In *PwC and the MIT Forum for Supply Chain Innovation*, 2013. 3, 4

[16] G Riglietti and L Aguada. Supply chain resilience report. *The Business Continuity Institute*, 2018. 3

[17] William Ho, Tian Zheng, Hakan Yildiz, and Srinivas Talluri. Supply chain risk management: a literature review. *International Journal of Production Research*, 53(16):5031–5069, 2015. doi:10.1080/00207543.2015.1030467. 3, 18, 19, 21, 23, 30, 48

[18] Yiyi Fan and Mark Stevenson. A review of supply chain risk management: definition, theory, and research agenda. *International Journal of Physical Distribution & Logistics Management*, 48(3):205–230, 2018. doi:10.1108/ijpdlm-01-2017-0043. 3, 5, 11, 19, 30

[19] Kannan Govindan. The optimal replenishment policy for time-varying stochastic demand under vendor managed inventory. *European Journal of Operational Research*, 242(2):402–423, 2015. doi:10.1016/j.ejor.2014.09.045. 3

[20] Kefeng Xu, Yan Dong, and Yu Xia. 'too little'or 'too late': the timing of supply chain demand collaboration. *European Journal of Operational Research*, 241(2):370–380, 2015. doi:10.1016/j.ejor.2014.09.006. 3

[21] Mustafa Güller, Emre Koc, Tobias Hegmanns, Michael Henke, and Bernd Noche. A simulation-based decision support framework for real-time supply chain risk management. *International Journal of Advanced Logistics*, 4(1):17–26, 2015. doi:10.1080/2287108x.2015.1008948. 4

[22] Dmitry Ivanov, Boris Sokolov, and Alexandre Dolgui. The ripple effect in supply chains: trade-off 'efficiency-flexibility-resilience'in disruption management. *International Journal of Production Research*, 52(7):2154–2172, 2014. doi:10.1080/00207543.2013.858836. 5

[23] Iris Heckmann, Tina Comes, and Stefan Nickel. A critical review on supply chain risk–definition, measure and modeling. *Omega*, 52:119–132, 2015. doi:10.1016/j.omega.2014.10.004. 5, 20, 37

[24] Soumaya Benaïcha and Atidel B Hadj-Alouane. Super facilities versus chaining in mitigating disruptions impacts. *Computers & Industrial Engineering*, 65(3):351–359, 2013. doi:10.1016/j.cie.2013.03.011. 5

[25] Lena Silbermayr and Stefan Minner. A multiple sourcing inventory model under disruption risk. *International Journal of Production Economics*, 149:37–46, 2014. doi:10.1016/j.ijpe.2013.03.025. 5

[26] Helena Carvalho, Ana P Barroso, Virgínia H Machado, Susana Azevedo, and Virgilio Cruz-Machado. Supply chain redesign for resilience using simulation. *Computers & Industrial Engineering*, 62(1):329–341, 2012. doi:10.1016/j.cie.2011.10.003. 5

[27] Anna Ledwoch, Hakan Yasarcan, and Alexandra Brintrup. The moderating impact of supply network topology on the effectiveness of risk management. *International Journal of Production Economics*, 197:13–26, 2018. doi:10.1016/j.ijpe.2017.12.013. 5

[28] Christoph Bode and Stephan M Wagner. Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. *Journal of Operations Management*, 36:215–228, 2015. doi:10.1016/j.jom.2014.12.004. 5

[29] Oguzhan Kırılmaz and Serpil Erol. A proactive approach to supply chain risk management: Shifting orders among suppliers to mitigate the supply side risks. *Journal of Purchasing and Supply Management*, 23(1):54–65, 2017. doi:10.1016/j.pursup.2016.04.002. 5, 21, 29, 42, 59, 60

[30] Tobias Rebs, Marcus Brandenburg, Stefan Seuring, and Margarita Stohler. Stakeholder influences and risks in sustainable supply chain management: a comparison of qualitative and quantitative studies. *Business Research*, 11(2):197–237, 2018. doi:10.1007/s40685-017-0056-9. 5

[31] Christopher S Tang. Perspectives in supply chain risk management. *International journal of production economics*, 103(2):451–488, 2006. doi:10.1016/j.ijpe.2005.12.006. 6

[32] Gang Li, Huan Fan, Peter KC Lee, and TCE Cheng. Joint supply chain risk management: An agency and collaboration perspective. *International Journal of Production Economics*, 164:83–94, 2015. doi:10.1016/j.ijpe.2015.02.021. 6

[33] Marcus Brandenburg and Tobias Rebs. Sustainable supply chain management: A modeling perspective. *Annals of Operations Research*, 229(1):213–252, 2015. doi:10.1007/s10479-015-1853-1. 6

[34] Mihalis Giannakis and Thanos Papadopoulos. Supply chain sustainability: A risk management approach. *International Journal of Production Economics*, 171:455–470, 2016. doi:10.1016/j.ijpe.2015.06.032. 6, 18, 29

[35] Riccardo Mogre, Federico D'Amico, et al. A decision framework to mitigate supply chain risks: an application in the offshore-wind industry. *IEEE Transactions on Engineering Management*, 63(3):316–325, 2016. doi:10.1109/tem.2016.2567539. 6, 28, 58, 60

[36] M Christopher. Logistics and supply chain management pitman publishing. *London, Edition*, 13:343–376, 1992. 7

[37] Rhonda R Lummus, Robert J Vokurka, and Karen L Alber. Strategic supply chain planning. *Production and inventory management Journal*, 39(3):49, 1998. 7

[38] Charles C Poirier and Stephen E Reiter. *La Supply Chain: Optimiser la chaîne logistique et le réseau interentreprises*. Dunod, 2001. 7

[39] Sunil Chopra and Peter Meindl. Supply chain management. strategy, planning & operation. In *Das summa summarum des management*, pages 265–275. Springer, 2007. doi:10.1007/978-3-8349-9320-5_22. 7

[40] Asoo J Vakharia. E-business and supply chain management. *Decision Sciences*, 33(4):495–504, 2002. doi:10.1111/j.1540-5915.2002.tb01653.x. 7

[41] David Simchi-Levi, Philip Kaminsky, Edith Simchi-Levi, and Ravi Shankar. *Designing and managing the supply chain: concepts, strategies and case studies*. Tata McGraw-Hill Education, 2008. 7

[42] Christine Harland, Richard Brenchley, and Helen Walker. Risk in supply networks. *Journal of Purchasing and Supply management*, 9(2):51–62, 2003. doi:10.1016/s1478-4092(03)00004-9. 8

[43] Mark Hillman. Strategies for managing supply chain risk. *Supply Chain Management Review*, 10(5):11–13, 2006. 8

[44] Nathalie Fabbe-Costes. La gestion des chaînes logistiques multi-acteurs: les dimensions organisationnelles d'une gestion lean et agile, 2007. 8

[45] Hélène Fargier and Caroline Thierry. The use of possibilistic decision theory in manufacturing, planning and control: recent results in fuzzy master production scheduling. *Studies in fuzziness and soft computing. Spingler-Verlag*, 36:45–59, 2000. 8

[46] Karine Rota. *Coordination temporelle de centres gérant de façon autonome des ressources: application aux chaînes logistiques intégrées en aéronautique*. PhD thesis, Toulouse, ENSAE, 1998. 8

[47] Thierry Moyaux. *Design, simulation and analysis of collaborative strategies in multiagent systems: The case of supply chain management*. PhD thesis, Université Laval, 2004. URL: http://hdl.handle.net/20.500.11794/17988. 8

[48] James G March and Zur Shapira. Managerial perspectives on risk and risk taking. *Management science*, 33(11):1404–1418, 1987. doi:10.1287/mnsc.33.11.1404. 9

[49] Ranjan DasGupta and Soumya G Deb. Exploring the relationship between risk and performance in listed indian firms. *International Journal of the Economics of Business*, 27(3):411–430, 2020. doi:10.1080/13571516.2020.1767981. 9

[50] RA Bahamid and SI Doh. A review of risk management process in construction projects of developing countries. *IOP Conference Series: Materials Science and Engineering*, 271(1):012–042, nov 2017. doi:10.1088/1757-899x/271/1/012042. 10

[51] Jean Pierre Campagne and Olivier Sénéchal. Les nouvelles exigences de la coopération, 2002. 11

[52] Ila Manuj and John T Mentzer. Global supply chain risk management strategies. *International Journal of Physical Distribution & Logistics Management*, 38(3):192–223, 2008. doi:10.1108/09600030810866986. 12, 18, 19, 20, 25, 58

[53] Bruno S Silvestre. Sustainable supply chain management in emerging economies: Environmental turbulence, institutional voids and sustainability trajectories. *International Journal of Production Economics*, 167:156–169, 2015. doi:10.1016/j.ijpe.2015.05.025. 13

[54] Peter Trkman and Kevin McCormack. Supply chain risk in turbulent environments—a conceptual model for managing supply chain network risk. *International Journal of Production Economics*, 119(2):247–258, 2009. doi:10.1016/j.ijpe.2009.03.002. 18, 22

[55] Benjamin R Tukamuhabwa, Mark Stevenson, Jerry Busby, and Marta Zorzini. Supply chain resilience: definition, review and theoretical foundations for further study. *International Journal of Production Research*, 53(18):5592–5623, 2015. doi:10.1080/00207543.2015.1037934. 18

[56] Dmitry Ivanov. Simulation-based ripple effect modelling in the supply chain. *International Journal of Production Research*, 55(7):2083–2101, 2017. doi:10.1080/00207543.2016.1275873. 18, 34, 40, 104, 108

[57] Masoud Esmaeilikia, Behnam Fahimnia, Joeseph Sarkis, Kannan Govindan, Arun Kumar, and John Mo. A tactical supply chain planning model with multiple flexibility options: an empirical evaluation. *Annals of Operations Research*, 244(2):429–454, 2016. doi:10.1007/s10479-013-1513-2. 18

[58] Irène Kilubi, Kilubi, and Berg. *Strategic Technology Partnering and Supply Chain Risk Management*. Springer, 2018. doi:10.1007/978-3-658-19918-0. 18, 29

[59] Andreas Wieland and Carl Marcus Wallenburg. Dealing with supply chain risks: Linking risk management practices and strategies to performance. *International Journal of Physical Distribution & Logistics Management*, 42(10):887–905, 2012. doi:10.1108/09600031211281411. 18, 29

[60] Djalma Araújo Rangel, Taiane Kamel de Oliveira, and Maria Silene Alexandre Leite. Supply chain risk classification: discussion and proposal. *International Journal of Production Research*, 53(22):6868–6887, 2015. doi:10.1080/00207543.2014.910620. 18

[61] Zhaohui Wu and Mark Pagell. Balancing priorities: Decision-making in sustainable supply chain management. *Journal of operations management*, 29(6):577–590, 2011. doi:10.1016/j.jom.2010.10.001. 18

[62] Jens K. Roehrich, Johanne Grosvold, and Stefan U. Hoejmose. Reputational risks and sustainable supply chain management: Decision making under bounded rationality. *International Journal of Operations & Production Management*, 34(5):695–719, 2014. doi:10.1108/ijopm-10-2012-0449. 18

[63] Quan Zhu, Harold Krikke, and Marjolein CJ Caniëls. Integrated supply chain risk management: A systematic review. *The International Journal of Logistics Management*, 28(4):1123–1141, 2017. doi:10.1108/ijlm-09-2016-0206. 18

[64] Zohreh Khojasteh-Ghamari and Takashi Irohara. Supply chain risk management: A comprehensive review. In *Supply Chain Risk Management*, pages 3–22. Springer, 2018. doi:10.1007/978-981-10-4106-8_1. 18, 37, 59

[65] SL Ting, YK Tse, GTS Ho, SH Chung, and G Pang. Mining logistics data to assure the quality in a sustainable food supply chain: A case in the red wine industry. *International Journal of Production Economics*, 152:200–209, 2014. doi:10.1016/j.ijpe.2013.12.010. 18

[66] Dmitry Ivanov et al. *Structural dynamics and resilience in supply chain risk management*. Springer, 2018. doi:10.1007/978-3-319-69305-7_1. 19, 29, 33

[67] Uta Jüttner, Helen Peck, and Martin Christopher. Supply chain risk management: outlining an agenda for future research. *International Journal of Logistics: Research and Applications*, 6(4):197–210, 2003. doi:10.1080/13675560310001627016. 19

[68] Robert J Trent and Llewellyn R Roberts. *Managing global supply and risk: Best practices, concepts, and strategies*. J. Ross Publishing, 2009. 19

[69] ManMohan S Sodhi and Christopher S Tang. *Managing supply chain risk*, volume 172. Springer Science & Business Media, 2012. doi:10.1007/978-1-4614-3238-8_1. 19

[70] Paula Santos Ceryno, Luiz Felipe Scavarda, Katja Klingebiel, and Gökhan Yüzgülec. Supply chain risk management: a content analysis approach. *International Journal of Industrial Engineering and Management*, 4(3):141–150, 2013. 19

[71] Wafik Hachicha and Manel Elmsalmi. An integrated approach based-structural modeling for risk prioritization in supply network management. *Journal of Risk Research*, 17(10):1301–1324, 2014. doi:10.1080/13669877.2013.841734. 19

[72] Mohd Nishat Faisal, DK Banwet, and Ravi Shankar. Management of risk in supply chains: Scor approach and analytic network process. *Supply Chain Forum: An International Journal*, 8(2):66–79, 2007. doi:10.1080/16258312.2007.11517183. 19

[73] Uta Jüttner. Supply chain risk management: Understanding the business requirements from a practitioner perspective. *The international journal of logistics management*, 2005. doi:10.1108/09574090510617385. 20

[74] Federica Cucchiella and Massimo Gastaldi. Risk management in supply chain: a real option approach. *Journal of Manufacturing Technology Management*, 17(6):700–720, 2006. doi:10.1108/17410380610678756. 21

[75] Monika Mital, Manlio Del Giudice, and Armando Papa. Comparing supply chain risks for multiple product categories with cognitive mapping and analytic hierarchy process. *Technological Forecasting and Social Change*, 131:159–170, 2018. doi:10.1016/j.techfore.2017.05.036. 22

[76] Avinash Samvedi, Vipul Jain, and Felix TS Chan. Quantifying risks in a supply chain through integration of fuzzy ahp and fuzzy topsis. *International Journal of Production Research*, 51(8):2433–2442, 2013. doi:10.1080/00207543.2012.741330. 22, 47, 49, 58, 59

[77] Dina Neiger, Kristian Rotaru, and Leonid Churilov. Supply chain risk identification with value-focused process engineering. *Journal of operations management*, 27(2):154–168, 2009. doi:10.1016/j.jom.2007.11.003. 22

[78] Ming-Chih Tsai, Chun-Hua Liao, and Chia-shing Han. Risk perception on logistics outsourcing of retail chains: model development and empirical verification in taiwan. *Supply Chain Management: An International Journal*, 13(6):415–424, 2008. doi:10.1108/13598540810905679. 22

[79] Arief Adhitya, Rajagopalan Srinivasan, and Iftekhar A Karimi. Supply chain risk identification using a hazop-based approach. *AIChE journal*, 55(6):1447–1463, 2009. doi:10.1002/aic.11764. 22

[80] Michalis Louis and Mark Pagell. Categorizing supply chain risks: Review, integrated typology and future research. In *Revisiting Supply Chain Risk*, pages 329–366. Springer, 2019. doi:10.1007/978-3-030-03813-7_20. 22

[81] Faisal Aqlan and Sarah S Lam. A fuzzy-based integrated framework for supply chain risk assessment. *International Journal of Production Economics*, 161:54–63, 2015. doi:10.1016/j.ijpe.2014.11.013. 23

[82] Roberto Cigolini and Tommaso Rossi. Managing operational risks along the oil supply chain. *Production Planning and Control*, 21(5):452–467, 2010. doi:10.1080/09537280903453695. 23

[83] A Ravi Ravindran, R Ufuk Bilsel, Vijay Wadhwa, and Tao Yang. Risk adjusted multi-criteria supplier selection models with applications. *International Journal of Production Research*, 48(2):405–424, 2010. doi:10.1080/00207540903174940. 23, 47, 49

[84] Desheng Dash Wu and David Olson. Enterprise risk management: a dea var approach in vendor selection. *International Journal of Production Research*, 48(16):4919–4932, 2010. doi:10.1080/00207540903051684. 23

[85] PL Meena and SP Sarmah. Multiple sourcing under supplier failure risk and quantity discount: A genetic algorithm approach. *Transportation Research Part E: Logistics and Transportation Review*, 50:84–97, 2013. doi:10.1016/j.tre.2012.10.001. 23

[86] Alex J Ruiz-Torres, Farzad Mahmoodi, and Amy Z Zeng. Supplier selection model with contingency planning for supplier failures. *Computers & Industrial Engineering*, 66(2):374–382, 2013. doi:10.1016/j.cie.2013.06.021. 23

[87] Atanu Chaudhuri, Bhaba Krishna Mohanty, and Kashi Naresh Singh. Supply chain risk assessment during new product development: a group decision making approach using numeric and linguistic data. *International Journal of Production Research*, 51(10):2790–2804, 2013. doi:10.1080/00207543.2012.654922. 23

[88] Hülya Behret, Başar Öztayşi, and Cengiz Kahraman. A fuzzy inference system for supply chain risk management. In *Practical applications of intelligent systems*, pages 429–438. Springer, 2011. doi:10.1007/978-3-642-25658-5_52. 23

[89] Jiho Yoon, Srinivas Talluri, Hakan Yildiz, and William Ho. Models for supplier selection and risk mitigation: a holistic approach. *International Journal of Production Research*, 56(10):3636–3661, 2018. doi:10.1080/00207543.2017.1403056. 28, 29

[90] Kathryn E Stecke and Sanjay Kumar. Sources of supply chain disruptions, factors that breed vulnerability, and mitigating strategies. *Journal of Marketing Channels*, 16(3):193–226, 2009. doi:10.1080/10466690902932551. 28

[91] Olivier Lavastre, Angappa Gunasekaran, and Alain Spalanzani. Supply chain risk management in french companies. *Decision Support Systems*, 52(4):828–838, 2012. doi:10.1016/j.dss.2011.11.017. 28

[92] Andreas Wieland. Selecting the right supply chain based on risks. *Journal of Manufacturing Technology Management*, 24(5):652–668, 2013. doi:10.1108/17410381311327954. 28

[93] Amanda J Schmitt and Brian Tomlin. Sourcing strategies to manage supply disruptions. In *Supply chain disruptions*, pages 51–72. Springer, 2012. doi:10.1007/978-0-85729-778-5_3. 28

[94] Zümbül Atan and Lawrence V Snyder. Inventory strategies to manage supply disruptions. In *Supply Chain Disruptions*, pages 115–139. Springer, 2012. doi:10.1007/978-0-85729-778-5_5. 28

[95] Aliakbar Hasani and Amirhossein Khosrojerdi. Robust global supply chain network design under disruption and uncertainty considering resilience strategies: A parallel memetic algorithm for a real-life case study. *Transportation Research Part E: Logistics and Transportation Review*, 87:20–52, 2016. doi:10.1016/j.tre.2015.12.009. 28

[96] Guido JL Micheli, Riccardo Mogre, and Alessandro Perego. How to choose mitigation measures for supply chain risks. *International Journal of Production Research*, 52(1):117–129, 2014. doi:10.1080/00207543.2013.828170. 29, 37, 42

[97] Fran Ackermann, Susan Howick, John Quigley, Lesley Walls, and Tom Houghton. Systemic risk elicitation: Using causal maps to engage stakeholders and build a comprehensive view of risks. *European Journal of Operational Research*, 238(1):290–299, 2014. doi:10.1016/j.ejor.2014.03.035. 29, 58

[98] Fazleena Badurdeen, Mohannad Shuaib, Ken Wijekoon, Adam Brown, William Faulkner, Joseph Amundson, IS Jawahir, Thomas J. Goldsby, Deepak Iyengar, and Brench Boden. Quantitative modeling and analysis of supply chain risks using bayesian theory. *Journal of Manufacturing Technology Management*, 25(5):631–654, 2014. doi:10.1108/jmtm-10-2012-0097. 29, 35, 38, 42

[99] Myles D Garvey, Steven Carnovale, and Sengun Yeniyurt. An analytical framework for supply network risk propagation: A bayesian network approach. *European Journal of Operational Research*, 243(2):618–627, 2015. doi:10.1016/j.ejor.2014.10.034. 29

[100] Abroon Qazi, John Quigley, Alex Dickson, and Barbara Gaudenzi. A new modelling approach of evaluating preventive and reactive strategies for mitigating supply chain risks. In *International Conference on Computational Logistics*, pages 569–585. Springer, 2015. doi:10.1007/978-3-319-24264-4_39. 29

[101] Abroon Qazi, John Quigley, Alex Dickson, Barbara Gaudenzi, and Şule Önsel Ekici. Evaluation of control strategies for managing supply chain risks using bayesian belief networks. In *2015 International Conference on Industrial Engineering and Systems Management (IESM)*, pages 1146–1154. IEEE, 2015. doi:10.1109/iesm.2015.7380298. 29

[102] Jörn-Henrik Thun and Daniel Hoenig. An empirical analysis of supply chain risk management in the german automotive industry. *International journal of production economics*, 131(1):242–249, 2011. doi:10.1016/j.ijpe.2009.10.010. 29

[103] Petra Hoffmann, Holger Schiele, and Koos Krabbendam. Uncertainty, supply risk management and their impact on performance. *Journal of purchasing and supply management*, 19(3):199–211, 2013. doi:10.1016/j.pursup.2013.06.002. 30

[104] Andreas Bühler, Carl Marcus Wallenburg, and Andreas Wieland. Accounting for external turbulence of logistics organizations via performance measurement systems. *Supply Chain Management: An International Journal*, 21(6):694–708, 2016. doi:10.1108/scm-02-2016-0040. 30

[105] Rick Siow Mong Goh, Zhaoxia Wang, Xiaofeng Yin, Xiuju Fu, Loganathan Ponnambalam, Sifei Lu, and Xiaorong Li. Riskvis: Supply chain visualization with risk management and real-time monitoring. In *2013 IEEE International Conference on Automation Science and Engineering (CASE)*, pages 207–212. IEEE, 2013. doi:10.1109/coase.2013.6653910. 30

[106] Christopher W Craighead, Jennifer Blackhurst, M Johnny Rungtusanatham, and Robert B Handfield. The severity of supply chain disruptions: design characteristics and mitigation capabilities. *Decision Sciences*, 38(1):131–156, 2007. doi:10.1111/j.1540-5915.2007.00151.x. 33

[107] Mark Goh, Joseph YS Lim, and Fanwen Meng. A stochastic model for risk management in global supply chain networks. *European Journal of Operational Research*, 182(1):164–173, 2007. doi:10.1016/j.ejor.2006.08.028. 33

[108] Bob Ritchie and Clare Brindley. Supply chain risk management and performance: a guiding framework for future development. *International Journal of Operations & Production Management*, 27(3):303–322, 2007. doi:10.1108/01443570710725563. 33

[109] Teresa Wu, Simin Huang, Jennifer Blackhurst, Xiaoling Zhang, and Shanshan Wang. Supply chain risk management: An agent-based simulation to study the impact of retail stockouts. *IEEE Transactions on Engineering Management*, 60(4):676–686, 2013. doi:10.1109/tem.2012.2190986. 33, 40, 104, 108

[110] M Teresa Melo, Stefan Nickel, and Francisco Saldanha-Da-Gama. Facility location and supply chain management–a review. *European journal of operational research*, 196(2):401–412, 2009. doi:10.1016/j.ejor.2008.05.007. 33

[111] Christian Almeder, Margaretha Preusser, and Richard F Hartl. Simulation and optimization of supply chains: alternative or complementary approaches? *OR spectrum*, 31(1):95–119, 2009. doi:10.1007/s00291-007-0118-z. 34

[112] Siyang Gao and Weiwei Chen. A partition-based random search for stochastic constrained optimization via simulation. *IEEE Transactions on Automatic Control*, 62(2):740–752, 2017. doi:10.1109/tac.2016.2570119. 34

[113] Frank Meisel and Christian Bierwirth. The design of make-to-order supply networks under uncertainties using simulation and optimisation. *International Journal of Production Research*, 52(22):6590–6607, 2014. doi:10.1080/00207543.2014.904533. 34

[114] Dmitry Ivanov, Alexander Pavlov, Alexandre Dolgui, Dmitry Pavlov, and Boris Sokolov. Disruption-driven supply chain (re)-planning and performance impact assessment with consideration of pro-active and recovery policies. *Transportation Research Part E: Logistics and Transportation Review*, 90:7–24, 2016. doi:10.1016/j.tre.2015.12.007. 34

[115] T Aven. Assessing uncertainties beyond expected values and probabilities. In *Risk analysis*. Wiley, 2008. 35

[116] Jie Zhang and Qiong Zhu. Fmea based potential risk analysis of lower cost region sourcing. In *2006 IEEE International Conference on Service Operations and Logistics, and Informatics*, pages 158–163. IEEE, 2006. doi:10.1109/soli.2006.235388. 35

[117] Xianshun Chen, Yew-Soon Ong, Puay-Siew Tan, NengSheng Zhang, and Zhengping Li. Agent-based modeling and simulation for supply chain risk management-a survey of the state-of-the-art. In *2013 IEEE International Conference on Systems, Man, and Cybernetics*, pages 1294–1299. IEEE, 2013. doi:10.1109/smc.2013.224. 35, 106

[118] Ulrich Hauptmanns. A decision-making framework for protecting process plants from flooding based on fault tree analysis. *Reliability Engineering & System Safety*, 95(9):970–980, 2010. doi:10.1016/j.ress.2010.04.008. 35

[119] Yong Lin and Li Zhou. The impacts of product design changes on supply chain risk: a case study. *International Journal of Physical Distribution & Logistics Management*, 41(2):162–186, 2011. doi:10.1108/09600031111118549. 35

[120] James Scott, William Ho, Prasanta K Dey, and Srinivas Talluri. A decision support system for supplier selection and order allocation in stochastic, multi-stakeholder and multi-criteria environments. *International Journal of Production Economics*, 166:226–237, 2015. doi:10.1016/j.ijpe.2014.11.008. 35, 58, 60

[121] Tobias Schoenherr, VM Rao Tummala, and Thomas P Harrison. Assessing supply chain risks with the analytic hierarchy process: Providing decision support for the offshoring decision by a us manufacturing company. *Journal of Purchasing and Supply Management*, 14(2):100–111, 2008. doi:10.1016/j.pursup.2008.01.008. 35

[122] Robert J Chapman. *Simple tools and techniques for enterprise risk management*, volume 553. John Wiley & Sons, 2011. doi:10.1002/9781118467206. 36

[123] Jay H Lee. Energy supply planning and supply chain optimization under uncertainty. *Journal of Process Control*, 24(2):323–331, 2014. doi:10.1016/j.jprocont.2013.09.025. 37

[124] Faisal Aqlan and Sarah S Lam. Supply chain risk modelling and mitigation. *International Journal of Production Research*, 53(18):5640–5656, 2015. doi:10.1080/00207543.2015.1047975. 37, 42

[125] Abdolmajid Yolmeh and Najmeh Salehi. An outer approximation method for an integration of supply chain network designing and assembly line balancing under uncertainty. *Computers & Industrial Engineering*, 83:297–306, 2015. doi:10.1016/j.cie.2015.03.002. 37, 42

[126] Mahdi Sharifzadeh, Marti Cortada Garcia, and Nilay Shah. Supply chain network design and operation: Systematic decision-making for centralized, distributed, and mobile biofuel production using mixed integer linear programming (milp) under uncertainty. *Biomass and Bioenergy*, 81:401–414, 2015. doi:10.1016/j.biombioe.2015.07.026. 37, 42

[127] Tadeusz Sawik. Selection of a dynamic supply portfolio in make-to-order environment withrisks. *Computers & Operations Research*, 38(4):782–796, 2011. doi:10.1016/j.cor.2010.09.011. 37

[128] Sadoullah Ebrahimnejad, Seyed Meysam Mousavi, and Hamed Seyrafianpour. Risk identification and assessment for build–operate–transfer projects: A fuzzy multi attribute decision making model. *Expert systems with Applications*, 37(1):575–586, 2010. doi:10.1016/j.eswa.2009.05.037. 37

[129] Arash Shahin, Arezou Kianersi, and Azarakhsh Shali. Prioritizing key supply chain risks using the risk assessment matrix and shannon fuzzy entropy—with a case study in the home appliance industry. *Journal of Advanced Manufacturing Systems*, 17(03):333–351, 2018. doi:10.1142/s0219686718500208. 37, 42

[130] Sanjoy Kumar Paul, Ruhul Sarker, and Daryl Essam. A reactive mitigation approach for managing supply disruption in a three-tier supply chain. *Journal of Intelligent Manufacturing*, 29(7):1581–1597, 2018. doi:10.1007/s10845-016-1200-7. 38, 42

[131] Benjamin P-C Yen and Bingcong Zeng. A hierarchical assessment method using bayesian network for material risk detection on green supply chain. In *2010 IEEE International Conference on Industrial Engineering and Engineering Management*, pages 1184–1188. IEEE, 2010. doi:10.1109/ieem.2010.5674342. 38

[132] Yusen Xia, Karthik Ramachandran, and Haresh Gurnani. Sharing demand and supply risk in a supply chain. *IIE Transactions*, 43(6):451–469, 2011. doi:10.1080/0740817x.2010.541415. 38, 42

[133] Antuela A Tako and Stewart Robinson. The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision support systems*, 52(4):802–815, 2012. doi:10.1016/j.dss.2011.11.015. 39

[134] “arena simulation software”. http://www.arenasimulation.com, consulté le 18 Avril 2019. 39

[135] “model and simulate discrete-event systems”. http://www.mathworks.fr/products/simevents, consulté le 18 Avril 2019. 39

[136] "model and simulate systems". http://www.anylogic.fr, consulté le 18 Avril 2019. 39

[137] "model and simulate systems ". http:/www.promodel.com, consulté le 18 Avril 2019. 39

[138] Cameron A MacKenzie, Kash Barker, and Joost R Santos. Modeling a severe supply chain disruption and post-disaster decision making with application to the japanese earthquake and tsunami. *IIE Transactions*, 46(12):1243–1260, 2014. doi:10.1080/0740817x.2013.876241. 40

[139] Houtian Ge, James Nolan, and Richard Gray. Identifying strategies to mitigate handling risks in the canadian grain supply chain. *Canadian Journal of Agricultural Economics/Revue canadienne d'agroeconomie*, 63(1):101–128, 2015. doi:10.1111/cjag.12039. 40

[140] Dhanan Sarwo Utomo, Bhakti Stephan Onggo, and Stephen Eldridge. Applications of agent-based modelling and simulation in the agri-food supply chains. *European Journal of Operational Research*, 269(3):794–805, 2018. doi:10.1016/j.ejor.2017.10.041. 40

[141] Paolo Trucco, Boris Petrenj, and Seyoum Eshetu Birkie. Assessing supply chain resilience upon critical infrastructure disruptions: a multilevel simulation modelling approach. In *Supply Chain Risk Management*, pages 311–334. Springer, 2018. doi:10.1007/978-981-10-4106-8_18. 40

[142] Wolfgang Burgholzer, Gerhard Bauer, Martin Posset, and Werner Jammernegg. Analysing the impact of disruptions in intermodal transport networks: A micro simulation-based model. *Decision Support Systems*, 54(4):1580–1586, 2013. doi:10.1016/j.dss.2012.05.060. 40, 105, 108

[143] FF Schlüter, E Hetterscheid, and M Henke. A simulation-based evaluation approach for digitalization scenarios in smart supply chain risk management. *Journal of Industrial Engineering and Management Science*, 2018(1):179–206, 2018. doi:10.1109/icimsa.2017.7985579. 40

[144] Yang-Byung Park, Sung-Joon Yoon, and Jun-Su Yoo. Development of a knowledge-based intelligent decision support system for operational risk management of global supply chains. *European Journal of Industrial Engineering*, 12(1):93–115, 2018. doi:10.1504/ejie.2018.089878. 40, 59, 60

[145] Surya Prakash, Sameer Kumar, Gunjan Soni, Vipul Jain, and Ajay Pal Singh Rathore. Closed-loop supply chain network design and modelling under risks and demand uncertainty: an integrated robust optimization approach. *Annals of Operations Research*, pages 1–28, 2018. doi:10.1007/s10479-018-2902-3. 42

[146] Arun Vinayak and Cameron A Mackenzie. A quantitative model for analyzing market response during supply chain disruptions. In *Supply Chain Risk Management*, pages 139–153. Springer, 2018. doi:10.1007/978-981-10-4106-8_9. 42

[147] Kannan Govindan and Mohammad Fattahi. Investigating risk and robustness measures for supply chain network design under demand uncertainty: A case study of glass supply chain. *International Journal of Production Economics*, 183:680–699, 2017. doi:10.1016/j.ijpe.2015.09.033. 42

[148] Jiarui Fang, Lei Zhao, Jan C Fransoo, and Tom Van Woensel. Sourcing strategies in supply risk management: An approximate dynamic programming approach. *Computers & Operations Research*, 40(5):1371–1382, 2013. doi:10.1016/j.cor.2012.08.016. 42

[149] Reza Babazadeh and Jafar Razmi. A robust stochastic programming approach for agile and responsive logistics under operational and disruption risks. *International Journal of Logistics Systems and Management*, 13(4):458–482, 2012. doi:10.1504/ijlsm.2012.050158. 42

[150] Florian Kellner, Bernhard Lienland, and Sebastian Utz. An a posteriori decision support methodology for solving the multi-criteria supplier selection problem. *European Journal of Operational Research*, 272(2):505–522, 2019. doi:10.1016/j.ejor.2018.06.044. 42

[151] Abroon Qazi, John Quigley, Alex Dickson, and Şule Önsel Ekici. Exploring dependency based probabilistic supply chain risk measures for prioritising interdependent risks and strategies. *European Journal of Operational Research*, 259(1):189–204, 2017. doi:10.1016/j.ejor.2016.10.023. 42

[152] S Alamdar, M Rabbani, and J Heydari. Optimal decision problem in a three-level closed-loop supply chain with risk-averse players under demand uncertainty. *Uncertain Supply Chain Management*, 7(2):351–368, 2019. doi:10.5267/j.uscm.2018.7.002. 42

[153] Yong-Wu Zhou, Jicai Li, and Yuanguang Zhong. Cooperative advertising and ordering policies in a two-echelon supply chain with risk-averse agents. *Omega*, 75:97–117, 2018. doi:10.1016/j.omega.2017.02.005. 42, 103, 108

[154] Cengiz Kahraman and İrem Uçal Sari. *Intelligence Systems in Environmental Management: Theory and Applications*. Springer, 2017. doi:10.1007/978-3-319-42993-9. 43

[155] Mohamed Abdelgawad and Aminah Robinson Fayek. Fuzzy reliability analyzer: quantitative assessment of risk events in the construction industry using fuzzy fault-tree analysis. *Journal of Construction Engineering and Management*, 137(4):294–302, 2010. doi:10.1061/(asce)co.1943-7862.0000285. 43

[156] Gerd J Hahn and Heinrich Kuhn. Value-based performance and risk management in supply chains: A robust optimization approach. *International Journal of Production Economics*, 139(1):135–144, 2012. doi:10.1016/j.ijpe.2011.04.002. 43, 46

[157] Adel Azar and Khadijeh Mostafaee Dolatabad. A method for modelling operational risk with fuzzy cognitive maps and bayesian belief networks. *Expert Systems with Applications*, 115:607–617, 2019. doi:10.1016/j.eswa.2018.08.043. 43, 46

[158] Jing Luan, Zhong Yao, Futao Zhao, and Xin Song. A novel method to solve supplier selection problem: Hybrid algorithm of genetic algorithm and ant colony optimization. *Mathematics and Computers in Simulation*, 156:294–309, 2019. doi:10.1016/j.matcom.2018.08.011. 43, 46

[159] Sanjoy Kumar Paul. Supplier selection for managing supply risks in supply chain: a fuzzy approach. *The International Journal of Advanced Manufacturing Technology*, 79(1-4):657–664, 2015. doi:10.1007/s00170-015-6867-y. 43, 46

[160] Bimal Nepal and Om Prakash Yadav. Bayesian belief network-based framework for sourcing risk analysis during supplier selection. *International Journal of Production Research*, 53(20):6114–6135, 2015. doi:10.1080/00207543.2015.1027011. 44, 46

[161] Liguo Fei, Yong Deng, and Yong Hu. Ds-vikor: A new multi-criteria decision-making method for supplier selection. *International Journal of Fuzzy Systems*, pages 1–19, 2018. doi:10.1007/s40815-018-0543-y. 44, 46

[162] Abdullah Salamai, Morteza Saberi, Omar Hussain, and Elizabeth Chang. Risk identification-based association rule mining for supply chain big data. In *International Conference on Security, Privacy and Anonymity in Computation, Communication and Storage*, pages 219–228. Springer, 2018. doi:10.1007/978-3-030-05345-1_18. 44, 46

[163] George Baryannis, Sahar Validi, Samir Dani, and Grigoris Antoniou. Supply chain risk management and artificial intelligence: state of the art and future research directions. *International Journal of Production Research*, pages 1–24, 2018. doi:10.1080/00207543.2018.1530476. 44

[164] Abroon Qazi, Alex Dickson, John Quigley, and Barbara Gaudenzi. Supply chain risk network management: A bayesian belief network and expected utility based approach for managing supply chain risks. *International Journal of Production Economics*, 196:24–42, 2018. doi:10.1016/j.ijpe.2017.11.008. 44, 46

[165] Ritesh Ojha, Abhijeet Ghadge, Manoj Kumar Tiwari, and Umit S Bititci. Bayesian network modelling for supply chain risk propagation. *International Journal of Production Research*, 56(17):5795–5819, 2018. doi:10.1080/00207543.2018.1467059. 44, 46

[166] Nafaa Jabeur, Taiseera Al-Belushi, Mohamed Mbarki, and Hana Gharrad. Toward leveraging smart logistics collaboration with a multi-agent system based solution. *Procedia Computer Science*, 109:672–679, 2017. doi:10.1016/j.procs.2017.05.374. 44, 46, 103, 104, 108

[167] Maurício Fontoura Blos, Robson Marinho da Silva, and Hui-Ming Wee. A framework for designing supply chain disruptions management considering productive systems and carrier viewpoints. *International Journal of Production Research*, 56(15):5045–5061, 2018. doi:10.1080/00207543.2018.1442943. 44, 46

[168] YP Tsang, KL Choy, CH Wu, GTS Ho, Cathy HY Lam, and PS Koo. An internet of things (iot)-based risk monitoring system for managing cold supply chain risks. *Industrial Management & Data Systems*, 118(7):1432–1462, 2018. doi:10.1108/imds-09-2017-0384. 44, 46

[169] Xiaobing Huang, Xiaolian Liu, and Yuanqian Ren. Enterprise credit risk evaluation based on neural network algorithm. *Cognitive Systems Research*, 52:317–324, 2018. doi:10.1016/j.cogsys.2018.07.023. 46

[170] DK Sreekantha and RV Kulkarni. Expert system design for credit risk evaluation using neuro-fuzzy logic. *Expert Systems*, 29(1):56–69, 2012. doi:10.1111/j.1468-0394.2010.00562.x. 46

[171] Reza Kiani Mavi, Mark Goh, and Neda Kiani Mavi. Supplier selection with shannon entropy and fuzzy topsis in the context of supply chain risk management. *Procedia-Social and Behavioral Sciences*, 235:216–225, 2016. doi:10.1016/j.sbspro.2016.11.017. 46

[172] Yan Shang, David Dunson, and Jing-Sheng Song. Exploiting big data in logistics risk assessment via bayesian nonparametrics. *Operations Research*, 65(6):1574–1588, 2017. doi:10.1287/opre.2017.1612. 46

[173] Anirban Ganguly, Debdeep Chatterjee, and Harish V Rao. Evaluating the risks associated with supply chain agility of an enterprise. *International Journal of Business Analytics (IJBAN)*, 4(3):15–34, 2017. doi:10.4018/ijban.2017070102. 46

[174] Davide Moroni, Gabriele Pieri, and Marco Tampucci. Environmental decision support systems for monitoring small scale oil spills: Existing solutions, best practices and current challenges. *Journal of Marine Science and Engineering*, 7(1):19, 2019. doi:10.3390/jmse7010019. 46

[175] Morteza Yazdani, Pascale Zarate, Adama Coulibaly, and Edmundas Kazimieras Zavadskas. A group decision making support system in logistics and supply chain management. *Expert systems with Applications*, 88:376–392, 2017. doi:10.1016/j.eswa.2017.07.014. 47, 49, 59

[176] Qingxing Dong and Orrin Cooper. An orders-of-magnitude ahp supply chain risk assessment framework. *International Journal of Production Economics*, 182:144–156, 2016. doi:10.1016/j.ijpe.2016.08.021. 47, 49

[177] Mohamed Abdel-Basset, M Gunasekaran, Mai Mohamed, and Naveen Chilamkurti. A framework for risk assessment, management and evaluation: Economic tool for quantifying risks in supply chain. *Future Generation Computer Systems*, 90:489–502, 2019. doi:10.1016/j.future.2018.08.035. 47, 49

[178] N Viswanadham and A Samvedi. Supplier selection based on supply chain ecosystem, performance and risk criteria. *International Journal of Production Research*, 51(21):6484–6498, 2013. doi:10.1080/00207543.2013.825056. 47, 49

[179] Zhen Hong and CKM Lee. A decision support system for procurement risk management in the presence of spot market. *Decision Support Systems*, 55(1):67–78, 2013. doi:10.1016/j.dss.2012.12.031. 47, 49, 58, 60

[180] Xiaojun Wang, Hing Kai Chan, Rachel WY Yee, and Ivan Diaz-Rainey. A two-stage fuzzy-ahp model for risk assessment of implementing green initiatives in the fashion supply chain. *International Journal of Production Economics*, 135(2):595–606, 2012. doi:10.1016/j.ijpe.2011.03.021. 47

[181] Avinash Samvedi and Vipul Jain. A study on the interactions between supply chain risk management criteria using fuzzy dematel method. *International Journal of Operational Research*, 18(3):255–271, 2013. doi:10.1504/ijor.2013.056685. 47

[182] Hu-Chen Liu, Long Liu, Nan Liu, and Ling-Xiang Mao. Risk evaluation in failure mode and effects analysis with extended vikor method under fuzzy environment. *Expert Systems with Applications*, 39(17):12926–12934, 2012. doi:10.1016/j.eswa.2012.05.031. 47

[183] Sobhan Sarkar, Vishal Lakha, Irshad Ansari, and Jhareswar Maiti. Supplier selection in uncertain environment: a fuzzy mcdm approach. In *Proceedings of the First International Conference on Intelligent Computing and Communication*, pages 257–266. Springer, 2017. doi:10.1007/978-981-10-2035-3_27. 47, 49

[184] Hui Li, Kangyin Dong, Hongdian Jiang, Renjin Sun, Xiaoyue Guo, and Yiqiao Fan. Risk assessment of china's overseas oil refining investment using a fuzzy-grey comprehensive evaluation method. *Sustainability*, 9(5):696, 2017. doi:10.3390/su9050696. 47, 49

[185] Fatih Boran. An integrated intuitionistic fuzzy multi criteria decision making method for facility location selection. *Mathematical and Computational Applications*, 16(2):487–496, 2011. doi:10.3390/mca16020487. 48

[186] Reza Rostamzadeh, Mehdi Keshavarz Ghorabaee, Kannan Govindan, Ahmad Esmaeili, and Hossein Bodaghi Khajeh Nobar. Evaluation of sustainable supply chain risk management using an integrated fuzzy topsis-critic approach. *Journal of Cleaner Production*, 175:651–669, 2018. doi:10.1016/j.jclepro.2017.12.071. 48, 49

[187] Sachin K Mangla, Pradeep Kumar, and Mukesh Kumar Barua. Flexible decision modeling for evaluating the risks in green supply chain using fuzzy ahp and irp methodologies. *Global Journal of Flexible Systems Management*, 16(1):19–35, 2015. doi:10.1007/s40171-014-0081-x. 48

[188] Majid Azadi, Mostafa Jafarian, Reza Farzipoor Saen, and Seyed Mostafa Mirhedayatian. A new fuzzy dea model for evaluation of efficiency and effectiveness of suppliers in sustainable supply chain management context. *Computers & Operations Research*, 54:274–285, 2015. doi:10.1016/j.cor.2014.03.002. 48, 49

[189] Desheng D Wu, David L Olson, and Cuicui Luo. A decision support approach for accounts receivable risk management. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 44(12):1624–1632, 2014. doi:10.1109/tsmc.2014.2318020. 48, 59, 60

[190] Filip Caron, Jan Vanthienen, and Bart Baesens. Comprehensive rule-based compliance checking and risk management with process mining. *Decision Support Systems*, 54(3):1357–1369, 2013. doi:10.1016/j.dss.2012.12.012. 48

[191] Dmitry Ivanov, Alexandre Dolgui, Boris Sokolov, and Marina Ivanova. Literature review on disruption recovery in the supply chain. *International Journal of Production Research*, 55(20):6158–6174, 2017. doi:10.1080/00207543.2017.1330572. 48

[192] Sachin Kumar Mangla, Pradeep Kumar, and Mukesh Kumar Barua. Risk analysis in green supply chain using fuzzy ahp approach: A case study. *Resources, Conservation and Recycling*, 104:375–390, 2015. doi:10.1016/j.resconrec.2015.01.001. 49

[193] R Rajesh and V Ravi. Modeling enablers of supply chain risk mitigation in electronic supply chains: A grey–dematel approach. *Computers & Industrial Engineering*, 87:126–139, 2015. doi:10.1016/j.cie.2015.04.028. 49

[194] Yuan-Hsu Lin and Ming-Lang Tseng. Assessing the competitive priorities within sustainable supply chain management under uncertainty. *Journal of cleaner production*, 112:2133–2144, 2016. doi:10.1016/j.jclepro.2014.07.012. 49

[195] Alexander Pavlov, Dmitry Ivanov, Alexandre Dolgui, and Boris Sokolov. Hybrid fuzzy-probabilistic approach to supply chain resilience assessment. *IEEE Transactions on Engineering Management*, 65(2):303–315, 2018. doi:10.1109/tem.2017.2773574. 49

[196] Robert H Bonczek, Clyde W Holsapple, and Andrew B Whinston. The evolving roles of models in decision support systems. *Decision Sciences*, 11(2):337–356, 1980. doi:10.1111/j.1540-5915.1980.tb01143.x. 50

[197] Michael S Scott-Morton and Peter GW Keen. Decision support systems: an organizational perspective. *Reading: Addison-Wesley*, 1978. 50

[198] N Jan Van Eck and L Waltman. Manual for vosviewer version 1.6. 8. *CWTS Meaningful Metrics. Universiteit Leiden*, 2018. 57

[199] Fikri Dweiri, Sameer Kumar, Sharfuddin Ahmed Khan, and Vipul Jain. Designing an integrated ahp based decision support system for supplier selection in automotive industry. *Expert Systems with Applications*, 62:273–283, 2016. doi:10.1016/j.eswa.2016.06.030. 58, 60

[200] Thomas J Kull and Srinivas Talluri. A supply risk reduction model using integrated multicriteria decision making. *IEEE Transactions on Engineering Management*, 55(3):409–419, 2008. doi:10.1109/tem.2008.922627. 58

[201] Riccardo Accorsi, Riccardo Manzini, and Fausto Maranesi. A decision-support system for the design and management of warehousing systems. *Computers in Industry*, 65(1):175–186, 2014. doi:10.1016/j.compind.2013.08.007. 58

[202] Edmundas Kazimieras Zavadskas, Zenonas Turskis, Tatjana Vilutienė, and Natalija Lepkova. Integrated group fuzzy multi-criteria model: Case of facilities management strategy selection. *Expert Systems with Applications*, 82:317–331, 2017. doi:10.1016/j.eswa.2017.03.072. 58, 60

[203] Yaner Fang and Biying Shou. Managing supply uncertainty under supply chain cournot competition. *European Journal of Operational Research*, 243(1):156–176, 2015. doi:10.1016/j.ejor.2014.11.038. 59, 60

[204] Hamed Fallah, Hamidreza Eskandari, and Mir Saman Pishvaee. Competitive closed-loop supply chain network design under uncertainty. *Journal of Manufacturing Systems*, 37:649–661, 2015. doi:10.1016/j.jmsy.2015.01.005. 59, 60

[205] Jinzhao Shi, Ju'e Guo, and Richard YK Fung. Decision support system for purchasing management of seasonal products: A capital-constrained retailer perspective. *Expert Systems with Applications*, 80:171–182, 2017. doi:10.1016/j.eswa.2017.03.032. 59

[206] Muhammad Naveed Khan, Pervaiz Akhtar, and Yasmin Merali. Strategies and effective decision-making against terrorism affecting supply chain risk management and security: A novel combination of triangulated methods. *Industrial Management & Data Systems*, 118(7):1528–1546, 2018. doi:10.1108/imds-09-2017-0449. 59

[207] Athakorn Kengpol and Sopida Tuammee. The development of a decision support framework for a quantitative risk assessment in multimodal green logistics: an empirical study. *International Journal of Production Research*, 54(4):1020–1038, 2016. doi:10.1080/00207543.2015.1041570. 59, 60

[208] Sarah Ben Othman, Hayfa Zgaya, Mariagrazia Dotoli, and Slim Hammadi. An agent-based decision support system for resources' scheduling in emergency supply chains. *Control Engineering Practice*, 59:27–43, 2017. doi:10.1016/j.conengprac.2016.11.014. 59, 60

[209] Samira Mokhtar, Parisa A Bahri, Sorousha Moayer, and Adrian James. A novel decision-making approach for supplier selection under risks. In *Computer aided chemical engineering*, volume 40, pages 1267–1272. Elsevier, 2017. doi:10.1016/b978-0-444-63965-3.50213-0. 59, 60

[210] Lionel Dupont, Christophe Bernard, Faiza Hamdi, and Faouzi Masmoudi. Supplier selection under risk of delivery failure: a decision-support model considering managers' risk sensitivity. *International Journal of Production Research*, 56(3):1054–1069, 2018. doi:10.1080/00207543.2017.1364442. 59, 60

[211] Adile Yesim Yayla, Asil Oztekin, Alev Taskin Gumus, and Angappa Gunasekaran. A hybrid data analytic methodology for 3pl transportation provider evaluation using fuzzy multi-criteria decision making. *International Journal of Production Research*, 53(20):6097–6113, 2015. doi:10.1080/00207543.2015.1022266. 59, 60

[212] NORAINI CHE PA, BOKOLO ANTHONY JNR, YUSMADI YAH JUSOH, HAIZAN NOR, ROZI NOR, MOHD ARIS, and TEH NORANIS. A risk mitigation decision framework for information technology organizations. *Journal of Theoretical & Applied Information Technology*, 95(10), 2017. 59, 60

[213] Kang Zhao, Kevin Scheibe, Jennifer Blackhurst, and Akhil Kumar. Supply chain network robustness against disruptions: Topological analysis, measurement, and optimization. *IEEE Transactions on Engineering Management*, 66(1):127–139, 2019. doi:10.1109/tem.2018.2808331. 60

[214] Liam Gardner and James Colwill. A framework and decision support tool for improving value chain resilience to critical materials in manufacturing. *Production & Manufacturing Research*, 6(1):126–148, 2018. doi:10.1080/21693277.2018.1432428. 60

[215] Dilupa Nakandala, Henry Lau, Jingjing Zhang, and Angappa Gunasekaran. A pragmatic decision model for inventory management with heterogeneous suppliers. *Enterprise Information Systems*, 12(5):603–619, 2018. doi:10.1080/17517575.2018.1432766. 60

[216] Lena Silbermayr and Stefan Minner. Dual sourcing under disruption risk and cost improvement through learning. *European Journal of Operational Research*, 250(1):226–238, 2016. doi:10.1016/j.ejor.2015.09.017. 60

[217] Lotfi A Zadeh. Fuzzy sets. *Information and control*, 8(3):338–353, 1965. doi:10.1016/s0019-9958(65)90241-x. 65, 66

[218] Krassimir Atanassov. Review and new results on intuitionistic fuzzy sets. *preprint Im-MFAIS-1-88, Sofia*, 5(1), 1988. 65, 67

[219] James J Buckley. *Fuzzy probability and statistics*, volume 196. Springer, 2006. 66

[220] Florentin Smarandache. Neutrosophy. *arXiv preprint math/0010099*, 2000. 67

[221] Charles Ashbacher. Introduction to neutrosophic logic, proquest information & learning. *Ann Arbor*, 2002. 68

[222] Thomas L Saaty et al. Decision making with the analytic hierarchy process. *International journal of services sciences*, 1(1):83–98, 2008. doi:10.1504/ijssci.2008.017590. 80

[223] Thomas L Saaty. A scaling method for priorities in hierarchical structures. *Journal of mathematical psychology*, 15(3):234–281, 1977. doi:10.1016/0022-2496(77)90033-5. 85

[224] Peter JM Van Laarhoven and Witold Pedrycz. A fuzzy extension of saaty's priority theory. *Fuzzy sets and Systems*, 11(1-3):229–241, 1983. doi:10.1016/s0165-0114(83)80082-7. 87

[225] Nouran M Radwan, M Badr Senousy, and M Riad Alaa El Din. *Neutrosophic AHP multi criteria decision making method applied on the selection of learning management system*. Infinite Study, 2016. 88, 92

[226] Desmond Jun Yi Tey, Yee Fei Gan, Ganeshsree Selvachandran, Shio Gai Quek, Florentin Smarandache, Mohamed Abdel-Basset, Hoang Viet Long, et al. A novel neutrosophic data analytic hierarchy process for multi-criteria decision making method: A case study in kuala lumpur stock exchange. *IEEE Access*, 7:53687–53697, 2019. doi:10.1109/access.2019.2912913. 88, 90, 91, 92

[227] Haibin Wang, Florentin Smarandache, Yanqing Zhang, and Rajshekhar Sunderraman. *Single valued neutrosophic sets*. Infinite study, 2010. 89

[228] Nital P Nirmal and Mangal G Bhatt. Selection of automated guided vehicle using single valued neutrosophic entropy based novel multi attribute decision making technique. In Florentin Smarandache and Surapati Pramanik, editors, *New Trends in Neutrosophic Theory and Applications*, chapter 8, pages 105–114. Pons Edit ions, 5, Quai du Batelage, Brussells, Belgium, European Union, 2016. 89

[229] Jacques Ferber. *Les systèmes multi-agents: vers une intelligence collective*. InterEditions, 1997. 98, 99

[230] Michael Wooldridge. Intelligent agents. *Multiagent systems: A modern approach to distributed artificial intelligence*, 1:27–73, 1999. 98, 109, 110

[231] Jianxi Fu and Yuanlue Fu. An adaptive multi-agent system for cost collaborative management in supply chains. *Engineering applications of artificial intelligence*, 44:91–100, 2015. doi:10.1016/j.engappai.2015.05.002. 103, 105, 108

[232] Izunildo Cabral and Antonio Grilo. Impact of business interoperability on the performance of complex cooperative supply chain networks: A case study. *Complexity*, 2018, 2018. doi:10.1155/2018/9213237. 103, 108

[233] Thierry Moyaux, Brahim Chaib-draa, and Sophie D'Amours. Multi-agent coordination based on tokens: Reduction of the bullwhip effect in a forest supply chain. In *Proceedings of the second international joint conference on Autonomous agents and multiagent systems*, pages 670–677. ACM, 2003. doi:10.1145/860575.860683. 103

[234] Mualla Gonca Avci and Hasan Selim. A multi-agent system model for supply chains with lateral preventive transshipments: Application in a multi-national automotive supply chain. *Computers in Industry*, 82:28–39, 2016. doi:10.1016/j.compind.2016.05.005. 104, 108

[235] J-H Lee and C-O Kim. Multi-agent systems applications in manufacturing systems and supply chain management: a review paper. *International Journal of Production Research*, 46(1):233–265, 2008. doi:10.1080/00207540701441921. 104

[236] M Hajian Heidary, A Aghaie, and A Jalalimanesh. A simulation–optimization approach for a multi-period, multi-objective supply chain with demand uncertainty and an option contract. *Simulation*, 94(7):649–662, 2018. doi:10.1177/0037549718761588. 104, 105, 108

[237] Partha Priya Datta, Martin Christopher, and Peter Allen. Agent-based modelling of complex production/distribution systems to improve resilience. *International Journal of Logistics Research and Applications*, 10(3):187–203, 2007. doi:10.1080/13675560701467144. 104

[238] Marcin Lewandowski and Ali Asgary. Risk assessment of the timber supply chain in southern ontario using agent-based simulation. In *Innovative Solutions for Sustainable Supply Chains*, pages 317–332. Springer, 2018. doi:10.1007/978-3-319-94322-0_12. 104, 108

[239] Pascal Forget, Sophie D'Amours, and Jean-Marc Frayret. Multi-behavior agent model for planning in supply chains: An application to the lumber industry. *Robotics and Computer-Integrated Manufacturing*, 24(5):664–679, 2008. doi:10.1016/j.rcim.2007.09.004. 104

[240] Mehdi Amini, Tina Wakolbinger, Michael Racer, and Mohammad G Nejad. Alternative supply chain production–sales policies for new product diffusion: An agent-based modeling and simulation approach. *European Journal of Operational Research*, 216(2):301–311, 2012. doi:10.1016/j.ejor.2011.07.040. 104

[241] Juan Villada and Yris Olaya. A simulation approach for analysis of short-term security of natural gas supply in colombia. *Energy Policy*, 53:11–26, 2013. doi:10.1016/j.enpol.2012.08.032. 104, 108

[242] D Moser, D Pinto, and A Cipriano. Developing a multiagent based decision support system for realtime multi-risk disaster management. *World Academy of Science, Engineering and Technology, International Journal of Social, Behavioral, Educational, Economic, Business and Industrial Engineering*, 9(3):831–835, 2015. 104, 108

[243] Partha Priya Datta and Martin G Christopher. Information sharing and coordination mechanisms for managing uncertainty in supply chains: a simulation study. *International Journal of Production Research*, 49(3):765–803, 2011. doi:10.1080/00207540903460216. 104

[244] Gérard P Cachon. Supply chain coordination with contracts. *Handbooks in operations research and management science*, 11:227–339, 2003. doi:10.1016/s0927-0507(03)11006-7. 104

[245] Roland Zimmermann. *Agent-based supply network event management*. Springer Science & Business Media, 2006. doi:10.1007/3-7643-7487-x. 105, 146, 153

[246] Maurício F Blos, Robson M Da Silva, and Paulo E Miyagi. Application of an agent-based supply chain to mitigate supply chain disruptions. *IFAC-PapersOnLine*, 48(3):640–645, 2015. doi:10.1016/j.ifacol.2015.06.154. 105, 108

[247] Mihalis Giannakis and Michalis Louis. A multi-agent based framework for supply chain risk management. *Journal of Purchasing and Supply Management*, 17(1):23–31, 2011. doi:10.1016/j.pursup.2010.05.001. 105, 106, 108

[248] Franck Taillandier, Patrick Taillandier, Esra Tepeli, Denys Breysse, Rasool Mehdizadeh, and Fadi Khartabil. A multi-agent model to manage risks in construction project (smacc). *Automation in Construction*, 58:1–18, 2015. doi:10.1016/j.autcon.2015.06.005. 105, 108

[249] Mengjuan Xu, Xinping Wang, and Lindu Zhao. Predicted supply chain resilience based on structural evolution against random supply disruptions. *International Journal of Systems Science: Operations & Logistics*, 1(2):105–117, 2014. doi:10.1080/23302674.2014.934748. 105, 108

[250] Behzad Behdani and Rajagopalan Srinivasan. Managing supply chain disruptions: an integrated agent-oriented approach. In *Computer Aided Chemical Engineering*, volume 40, pages 595–600. Elsevier, 2017. doi:10.1016/b978-0-444-63965-3.50101-x. 105, 108

[251] Ion Smeureanu, Gheorghe Ruxanda, Andreea Diosteanu, Camelia Delcea, and Liviu Adrian Cotfas. Intelligent agents and risk based model for supply chain management. *Technological and Economic Development of Economy*, 18(3):452–469, 2012. doi:10.3846/20294913.2012.702696. 105, 108

[252] Richard Peters and Hermann Többen. A reference-model for holonic supply chain management. In *International Conference on Industrial Applications of Holonic and Multi-Agent Systems*, pages 221–232. Springer, 2005. doi:10.1007/11537847_20. 105

[253] Rajveer Basra, Kevin Lu, and Petr Skobelev. Resolving scheduling issues of the london underground using a multi-agent system. *International journal of intelligent systems technologies and applications*, 2(1):3–19, 2006. doi:10.1504/ijista.2007.011569. 105

[254] Francisco P Maturana, Raymond J Staron, Pavel Tichỳ, Petr Šlechta, and Pavel Vrba. A strategy to implement and validate industrial applications of holonic systems. In *International Conference on Industrial Applications of Holonic and Multi-Agent Systems*, pages 111–120. Springer, 2005. doi:10.1007/11537847_10. 105

[255] Pezhman Ghadimi, Farshad Ghassemi Toosi, and Cathal Heavey. A multi-agent systems approach for sustainable supplier selection and order allocation in a partnership supply chain. *European Journal of Operational Research*, 269(1):286–301, 2018. doi:10.1016/j.ejor.2017.07.014. 105, 108

[256] Chunxia Yu and TN Wong. An agent-based negotiation model for supplier selection of multiple products with synergy effect. *Expert Systems with Applications*, 42(1):223–237, 2015. doi:10.1016/j.eswa.2014.07.057. 105, 108

[257] Javad Soroor, Mohammad J Tarokh, Farid Khoshalhan, and Sara Sajjadi. Intelligent evaluation of supplier bids using a hybrid technique in distributed supply chains. *Journal of Manufacturing Systems*, 31(2):240–252, 2012. doi:10.1016/j.jmsy.2011.09.002. 105, 108

[258] Jinghua Li, Miaomiao Sun, Duanfeng Han, Xiaoyuan Wu, Boxin Yang, Xuezhang Mao, and Qinghua Zhou. Semantic multi-agent system to assist business integration: An application on supplier selection for shipbuilding yards. *Computers in Industry*, 96:10–26, 2018. doi:10.1016/j.compind.2018.01.001. 105, 108

[259] Dongfei Fu, Hai-Tao Zhang, Ying Yu, Clara Mihaela Ionescu, El-Houssaine Aghezzaf, and Robin De Keyser. A distributed model predictive control strategy for the bullwhip reducing inventory management policy. *IEEE Transactions on Industrial Informatics*, 15(2):932–941, 2019. doi:10.1109/tii.2018.2826066. 105, 108

[260] Ahmet Kara and Ibrahim Dogan. Reinforcement learning approaches for specifying ordering policies of perishable inventory systems. *Expert Systems with Applications*, 91:150–158, 2018. doi:10.1016/j.eswa.2017.08.046. 105

[261] NI Arvitrida. A review of agent-based modeling approach in the supply chain collaboration context. *IOP Conference Series: Materials Science and Engineering*, 337(1):012015, 2018. doi:10.1088/1757-899x/337/1/012015. 106

[262] Roberto Dominguez, Salvatore Cannella, Ana P Barbosa-Póvoa, and Jose M Framinan. Information sharing in supply chains with heterogeneous retailers. *Omega*, 79:116–132, 2018. doi:10.1016/j.omega.2017.08.005. 108

[263] Cansu Yildirim, Bengu Sevil Oflaç, and Oznur Yurt. The doer effect of failure and recovery in multi-agent cases: service supply chain perspective. *Journal of Service Theory and Practice*, 28(3):274–297, 2018. doi:10.1108/jstp-05-2016-0094. 108

[264] Bo Yan, Zhuo Chen, and Hanwen Kang. Coordination model of quality risk control of the aquatic supply chain based on principal-agent theory. *Supply Chain Management: An International Journal*, 22(5):393–410, 2017. doi:10.1108/scm-10-2016-0375. 108

[265] Lei Zhou, Xianhua Wu, Zeshui Xu, and Hamido Fujita. Emergency decision making for natural disasters: An overview. *International journal of disaster risk reduction*, 27:567–576, 2018. doi:10.1016/j.ijdrr.2017.09.037. 108

[266] Stewart Robinson, Stavrianna Dimitriou, and Kathy Kotiadis. Addressing the sample size problem in behavioural operational research: simulating the newsvendor problem. *Journal of the Operational Research Society*, 68(3):253–268, 2017. doi:10.1057/s41274-016-0016-3. 108

[267] Bernhard Bauer and Jörg P Müller. Methodologies and modeling languages. *Agent-Based Software Development*, pages 77–131, 2004. 110, 111

[268] James Odell, H Van Dyke Parunak, and Bernhard Bauer. Representing agent interaction protocols in uml. In *Proc. of First International Workshop on Agent-Oriented Software Engineering*. Citeseer, 1999. doi:10.1007/3-540-44564-1_8. 111

[269] Kassem Saleh and Christo El-Morr. M-uml: an extension to uml for the modeling of mobile agent-based software systems. *Information and Software Technology*, 46(4):219–227, 2004. doi:10.1016/j.infsof.2003.07.004. 111

[270] Michael Wooldridge, Nicholas R Jennings, and David Kinny. The gaia methodology for agent-oriented analysis and design. *Autonomous Agents and multi-agent systems*, 3:285–312, 2000. 111

[271] Scott A DeLoach, Mark F Wood, and Clint H Sparkman. Multiagent systems engineering. *International Journal of Software Engineering and Knowledge Engineering*, 11(03):231–258, 2001. doi:10.1142/s0218194001000542. 112

[272] Juan Pavón. Ingenias: Développement dirigé par modèles des systèmes multi-agents. *Habilitationa diriger des recherches de l'Université Pierre et Marie Curie*, 2006. 113

[273] Fabio Bellifemine, Agostino Poggi, and Giovanni Rimassa. Jade–a fipa-compliant agent framework. In *Proceedings of the 4th International Conference and Exhibition on the Practical Application of Intelligent Agents and Multi-Agents (PAAM'99)*, pages 97–108. London, UK, 1999. URL: http://jmvidal.cse.sc.edu/library/jade.pdf. 119

[274] FIPA Query Interaction Protocol Specification. Foundation for intelligent physical agents, 2000, 2004. 119, 120

[275] Telecomunicazioni SpA. Foundation for intelligent physical agents, 2001. 119

[276] Ahlem Meziani, Abdelhabib Bourouis, and Mohamed Sedik Chebout. Neutrosophic data analytic hierarchy process for multi criteria decision making: Applied to supply chain risk managment. In *2022 International Conference on Advanced Aspects of Software Engineering (ICAASE)*, pages 1–6. IEEE, 2022. 93, 132

[277] Sandro Emmenegger, Knut Hinkelmann, Emanuele Laurenzi, and Barbara Thönssen. Towards a procedure for assessing supply chain risks using semantic technologies. In *International Joint Conference on Knowledge Discovery, Knowledge Engineering, and Knowledge Management*, pages 393–409. Springer, 2012. doi:10.1007/978-3-642-54105-6_26. 142

[278] Claire Palmer, Esmond N Urwin, Ali Niknejad, Dobrila Petrovic, Keith Popplewell, and Robert IM Young. An ontology supported risk assessment approach for the intelligent configuration of supply networks. *Journal of Intelligent Manufacturing*, 29(5):1005–1030, 2018. doi:10.1007/s10845-016-1252-8. 142

[279] Shoufeng Cao, Kim Bryceson, and Damian Hine. Improving supply chain risk visibility and communication with a multi-view risk ontology. In *Supply Chain Forum: An International Journal*, volume 21, pages 1–15. Taylor & Francis, 2020. doi:10.1080/16258312.2020.1717990. 142

[280] Natalya Fridman Noy, Monica Crubézy, Ray W Fergerson, Holger Knublauch, Samson W Tu, Jennifer Vendetti, and Mark A Musen. Protégé-2000: an open-source ontology-development and knowledge-acquisition environment. In *AMIA... annual symposium proceedings. AMIA Symposium*, pages 953–953, 2003. 143

[281] Fabio Luigi Bellifemine, Giovanni Caire, and Dominic Greenwood. *Developing multi-agent systems with JADE*. John Wiley & Sons, 2007. 159, 160

[282] Franco Zambonelli, Nicholas R Jennings, and Michael Wooldridge. Developing multi-agent systems: The gaia methodology. *ACM Transactions on Software Engineering and Methodology (TOSEM)*, 12(3):317–370, 2003. doi:10.1145/958961.958963. 159

[283] Ahlem Meziani, Abdelhabib Bourouis, and Mohamed Sedik Chebout. Neutromas4scrm: a combined multi-agent system with neutrosophic data analytic hierarchy process framework for supply chain risk management. *Journal of Intelligent & Fuzzy Systems*, (Preprint):1–22, 2023. 168