GALATASARAY UNIVERSITY

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

NEW PROPOSED APPROACHES FOR THE EFFECTIVE BLOCKCHAIN AND ARTIFICIAL INTELLIGENCE IMPLEMENTATION IN SUPPLY CHAIN

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NEW PROPOSED APPROACHES FOR THE EFFECTIVE BLOCKCHAIN AND ARTIFICIAL INTELLIGENCE IMPLEMENTATION IN SUPPLY CHAIN

(TEDARİK ZİNCİRİNDE ETKİN BLOKZİNCİR VE YAPAY ZEKA UYGULAMASI İÇİN YENİ ÖNERİLEN YAKLAŞIMLAR)

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LIST OF SYMBOLS

AHP	: Analytic Hierarchy Process
AI	: Artificial Intelligence
ANP	: Analytic Network Process
CM	: Cognitive Mapping
CN	: Customer Needs
COCOSO	: Combined Compromise Solution
DEMATEL	: Decision-Making Trial and Evaluation Laboratory
DR	: Design Requirements
GDM	: Group Decision Making
HOQ	: House of Quality
IIFP	: Incomplete Intuitionistic Fuzzy Preference
IOT	: Internet of Things
IOWG	: Induced Ordered Weighted Geometric
MCDM	: Multiple Criteria Decision Making
OWG	: Ordered Weighted Geometric
PBFT	: Practical Byzantine Fault Tolerance
POA	: Proof of Authority
POS	: Proof of Stake
PRISMA	: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RFID	: Radio Frequency Identification
QFD	: Quality Function Deployment
IFQGID	: Intuitionistic Fuzzy Quantifier Guided Importance Degree
OWA	: Ordered Weighting Averaging
IOWA	: Induced Ordered Weighting Averaging
CC-IOWA	: Confidence and Consistency Based Induced Ordered Weighting Averaging
RQ	: Research Question
SC	: Supply Chain
SCM	: Supply Chain Management
SWOT	: Strength, weaknesses, opportunity, and threat
TISM	: Total interpretive structural modelling
TOPSIS	: Technique for Order of Preference by Similarity to Ideal Solution
TRiSM	: Trust, Risk and Security Management
VIKOR	: VIšeKriterijumska Optimizacija I Kompromisno Resenje

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ABSTRACT

Businesses worldwide are increasingly facing significant technological challenges in their Supply Chain (SC) operations. Today, organizations try to use Industry 4.0 technologies such as Internet of Things (IoT), Cloud Computing, Artificial Intelligence (AI), Blockchain, and so to increase productivity and solve business problems associated with data confidentiality, security, and information sharing. Blockchain and AI are two of these innovative technologies in the SC literature.

The comprehensive literature survey on Blockchain and AI technologies in SC revealed that previous literature generally focused on specific issues from specific perspective, making it difficult to provide a comprehensive and systematic view. In addition, there is a shortage of academic publications that Blockchain and AI in SC as integrated technology. Literature indicates that implementation in SCs involves many diverse and critical factors, and requires a comprehensive guide for practitioners. It shows Blockchain and AI applications are inadequate and there is still gap for how to success, and therefore guidance based on customer requirements and effective system design is needed for successful implementation.

Therefore, this dissertation delves into the world of Blockchain and AI technology implementation in SC, and aims to fill these gaps in the current understanding of how to successfully implement these technologies in SCs. It proposes success and risk factors for better understanding of Blockchain and AI, and analyze customer needs (CNs) and design requirements (DRs) for building effective SC structure based on these technologies. As all these topics involve various decision-making processes, a hybrid multiple criteria decision making (MCDM) approach is proposed where Incomplete Intuitionistic Fuzzy Preferences (IIFPs) under missing data are suggested as the backbone of the methodology.

In Chapter 2, Blockchain and AI technologies in SC are examined both separately and together. This chapter provides a comprehensive systematic literature review, investigates the researched themes, delves into the current gaps, and proposes strategies through SWOT analysis. This chapter is also shedding light to the next chapters.

In Chapter 3, a literature review is performed for the theoretical approaches used in this dissertation, and details of these methodologies with computational procedures are given. Utilizing the IIFPs as the basis, the integration of IIFPs with Analytic Network Process (ANP) and House of Quality (HoQ) which is a part of Quality Function Deployment (QFD) are explained. This section provides a crucial examination and framing of the selected research methods, enhancing the conceptual foundation that supports the subsequent analytical work in the dissertation.

In Chapter 4, critical success and risk factors for both Blockchain and AI in SC are evaluated by combining IIFPs with ANP. Based on the literature review and expert views, a comprehensive list of factors are examined and evaluated. This analysis and model of success and risk factors of these technologies in SC provides a holistic framework, considers multiple critical factors, and provides valuable insights for practitioners.

In Chapter 5, after gathering the success and risk points, the dissertation focused on CNs and DRs of Blockchain and AI implementations in SC. This design aspect is tackled by a HoQ application, that combines IIFPs and ANP in its decision making processes. Incorporation of those methods are unique which adds value to the literature. With the experts in the field, case studies are implemented to demonstrate the feasibility of evaluation models.

Chapter 6 involves managerial implications for Blockchain and AI in SC. The motivation is to analyze the results of previous chapters, and give insights about the common and diverse points of these two technologies, as this will direct the literature and enable practitioners to form proper strategies.

This dissertation intertwines its various sections to create an engaging narrative that goes beyond mere summarization. Each section expands on its predecessor, progressively exploring the necessity for Blockchain and AI in SC and the complexities of system design, while studying on tangible and implementable solutions. This integrated approach offers a thorough grasp of the multidimensional factors that should be considered when developing an effective SC system, delivering valuable insights for both academics and industry professionals.

ÖZET

Dünya çapındaki işletmeler, Tedarik Zinciri (TZ) operasyonlarında giderek artan bir şekilde önemli teknolojik zorluklarla karşı karşıya kalmaktadır. Günümüzde kuruluşlar, verimliliği artırmak ve veri gizliliği, güvenliği ve bilgi paylaşımı ile ilgili iş sorunlarını çözmek için Nesnelerin İnterneti (IoT), Bulut Bilişim, Yapay Zeka, Blokzincir gibi Endüstri 4.0 teknolojilerini kullanmaya çalışmaktadır. Blokzincir ve Yapay Zeka, TZ literatüründeki bu yenilikçi teknolojilerden ikisidir.

TZ'deki Blokzincir ve Yapay Zeka teknolojileri üzerine yapılan kapsamlı literatür araştırması, önceki literatür incelemelerinin genellikle belirli bir perspektiften belirli konulara odaklandığını ve kapsamlı ve sistematik bir görünüm sağlamayı zorlaştırdığını ortaya koymuştur. Buna ek olarak, TZ'de Blokzincir ve Yapay Zeka'nin entegre teknoloji olarak kullanıldığı akademik yayınların çok kısıtlı olduğu görülmektedir. Literatür, TZ'lerde uygulamanın birçok farklı ve kritik faktör içerdiğini ve uygulayıcılar için kapsamlı bir rehber gerektirdiğini göstermektedir. Blokzincir ve Yapay Zeka uygulamalarının yetersiz olduğunu ve nasıl başarılı olacağına dair hala boşluk olduğunu, ve bu nedenle başarılı bir uygulama için müşteri gereksinimlerine ve etkili sistem tasarımına dayalı rehberliğe ihtiyaç olduğunu göstermektedir.

Bu nedenle, bu tez TZ'de Blokzincir ve Yapay Zeka teknolojisi uygulaması dünyasını araştırmakta ve bu teknolojilerin TZ'lerde nasıl başarılı bir şekilde uygulanacağına dair mevcut anlayıştaki bu boşlukları doldurmayı amaçlamaktadır. Tez, Blokzincir ve Yapay Zeka'nın daha iyi anlaşılması için başarı ve risk faktörleri önermekte ve bu teknolojilere dayalı etkili TZ yapısı oluşturmak için müşteri ihtiyaçlarını ve tasarım gereksinimlerini analiz etmektedir. Tüm bu konuların çeşitli karar verme süreçlerini içermesinden dolayı,

eksik veriler altında Eksik Sezgisel Bulanık Tercihlerin (ESBT) metodolojinin omurgası olarak önerildiği hibrit bir çok kriterli karar verme (ÇKKV) yaklaşımı önerilmektedir.

İkinci bölümde, TZ'deki Blokzincir ve Yapay Zeka teknolojileri hem ayrı ayrı hem de birlikte incelenmiştir. Bu bölüm kapsamlı bir sistematik literatür taraması sunmakta, araştırılan temaları incelemekte, mevcut boşlukları araştırmakta ve SWOT analizi yoluyla stratejiler önermektedir. Bu bölüm aynı zamanda sonraki bölümlere de ışık tutmaktadır.

Üçüncü bölümde, bu tezde kullanılan teorik yaklaşımlar için bir literatür taraması yapılmakta ve bu metodolojilerin hesaplama prosedürleri ile detayları verilmektedir. ESBT'ler temel alınarak, ESBT'lerin Analitik Ağ Süreci (AAS) ve Kalite Fonksiyonu Göçerimi (KFG)'nin bir parçası olan Kalite Evi (KE) ile entegrasyonu açıklanmaktadır. Bu bölüm, seçilen araştırma yöntemlerinin önemli bir incelemesini ve çerçevesini sunmakta ve tezdeki sonraki analitik çalışmayı destekleyen kavramsal temeli geliştirmektedir.

Dördüncü bölümde, TZ'de hem Blokzincir hem de Yapay Zeka için kritik başarı ve risk faktörleri, ESBT'ler ve AAS birleştirilerek değerlendirilmektedir. Literatür taramasına ve uzman görüşlerine dayanarak, kapsamlı bir faktör listesi incelenmiş ve değerlendirilmiştir. Bu teknolojilerin TZ'deki başarı ve risk faktörlerinin bu analizi ve modeli, bütünsel bir çerçeve sağlar, birden fazla kritik faktörü dikkate alır ve uygulayıcılar için değerli bilgiler sağlar.

Başarı ve risk noktalarını bir araya getirdikten sonra, beşinci bölümde tez, TZ'deki Blokzincir ve Yapay Zeka tewknolojileri uygulamalarının müşteri ihtiyaçlarına ve tasarım gereksinimlerine odaklanmıştır. Bu tasarım yönü, karar verme süreçlerinde ESBT'ler ve AAS'yi birleştiren bir KE uygulaması tarafından ele alınmaktadır. Bu yöntemlerin birleşmesi benzersizdir, ve literatüre değer katmaktadır. Alanındaki uzmanlarla birlikte, değerlendirme modellerinin uygulanabilirliğini göstermek için vaka çalışmaları gerçekleştirilmiştir.

Altıncı bölüm, TZ'de Blokzincir ve Yapay Zeka için yönetimsel çıkarımları içermektedir. Motivasyon, önceki bölümlerin sonuçlarını analiz etmek ve bu iki teknolojinin ortak ve farklı noktaları hakkında fikir vermektir. Çünkü bu literatürü yönlendirecek ve uygulayıcıların uygun stratejiler oluşturmasını sağlayacaktır.

Bu tez, sadece özetlemenin ötesine geçen ilgi çekici bir anlatı oluşturmak için çeşitli bölümlerini iç içe geçirmektedir. Her bölüm, somut ve uygulanabilir çözümler üzerinde çalışırken, TZ'de Blokzincir ve Yapay Zeka'nın gerekliliği ve sistem tasarımının karmaşıklıklarını aşamalı olarak araştırarak odağını genişletir. Bu entegre yaklaşım, etkili bir TZ sistemi geliştirirken göz önünde bulundurulması gereken çok boyutlu faktörlerin kapsamlı bir şekilde kavranmasını sağlar, ve hem akademisyenler hem de endüstri profesyonelleri için değerli bilgiler sunar.

1. INTRODUCTION

Supply chain (SC) stands for the complex network of activities, people, organizations, resources, and information involved in providing service or product to consumer. It encompasses everything from the initial sourcing of raw materials, through production and assembly, to distribution and retail. Therefore, SCs face to many challenging processes. Adapting innovations and new technologies enormously affects and enhances SC processes. Recent literature in SCs has highlighted several innovations including Cloud Computing, Blockchain, Internet of Things (IoT), AI, Big Data, and more (Idrıssi et al. 2024; Sánchez-García et al. 2024). Consequently, Blockchain and AI, which are two emerging technologies, can advance the role of technology-based SC models (Gupta et al. 2023). The adoption of Blockchain and AI technologies in SCs can help on the improvements for transparency, efficiency, and decision-making through the chain. By leveraging these tools, organizations can better respond to market demands, enhance their operational capabilities, and ultimately provide improved service to their customers. This integration is increasingly becoming a competitive necessity in a rapidly evolving market landscape (Verma, 2024).

Based on a research of DHL (2018), SCs are intricate, involving numerous stakeholders globally with varying interests and utilizing numerous tools. These complexities are precisely what Blockchain technology is created to solve. In production management and logistics, Blockchains can mainly be employed in two crutial ways: to increase capability and efficiency (reducing bureaucracy and paperwork, real time data) and facilitate new business models (with payments, digital identities, immutable documents, etc.). In the short run, the Blockchain technology can be expected to intersect with other innovations to amplify its impacts. The physical movement of goods can be more efficiently managed and better synchronized with data flows as Blockchain is joined with Internet of Things (IoT), Artificial Intelligence (AI), and more.

AI has also greatly enhanced SC management (SCM) by providing effective forecasting of demand based on historical data, optimizing production processes for better efficiency, and fostering collaboration between robots and human team members. AI offers valuable insights and enables more informed decision regarding product promotions and pricing. By implementing smart retailing techniques with AI, retailers can minimize waste. Through video analysis and tracking, unusable products can be identified and removed early in the process. Overall, AI has become an integral part of SCM, delivering significant benefits and improvements.

According to various sources in the literature (Naz et al. 2022; Li et al. 2023; Silva et al. 2025), SC systems that incorporate Blockchain and AI have the potential to decrease the need for intermediaries, enhance automation and decision-making, and boost operational efficiency. However, these systems also come with risks such as high costs, adoption barriers, security breaches, and a lack of established practices within the industry. Therefore, implementing these technologies in SCs requires careful consideration of both the benefits and potential drawbacks. The literature suggests that there is a gap in the current understanding of how to successfully implement these technologies in SCs and that there is a need for guidance based on customer requirements and effective system design.

The objectives of the dissertation hence formulated as follows:
(O1) To provide a structured and comprehensive overview of Blockchain, AI, and Blockchain-AI integration in SC field, taxonomy and review of the themes.
(O2) To investigate Blockchain and AI in both critical success and risk points of view, as this will bring practitioners a guidance and roadmap of these technologies in SCs.
(O3) To evaluate customer needs and design requirements comprehensively that users will need about these technologies, as this will give a better understanding and ease out the complexities on implementation in their SCs.
(O4) To analyze the results and give insights about the common or interrrelated points of these two technologies, as this will direct the literature and enable practitioners to form proper strategies.
In line with these objectives, the scope of this dissertation is shown in Figure 1.1.

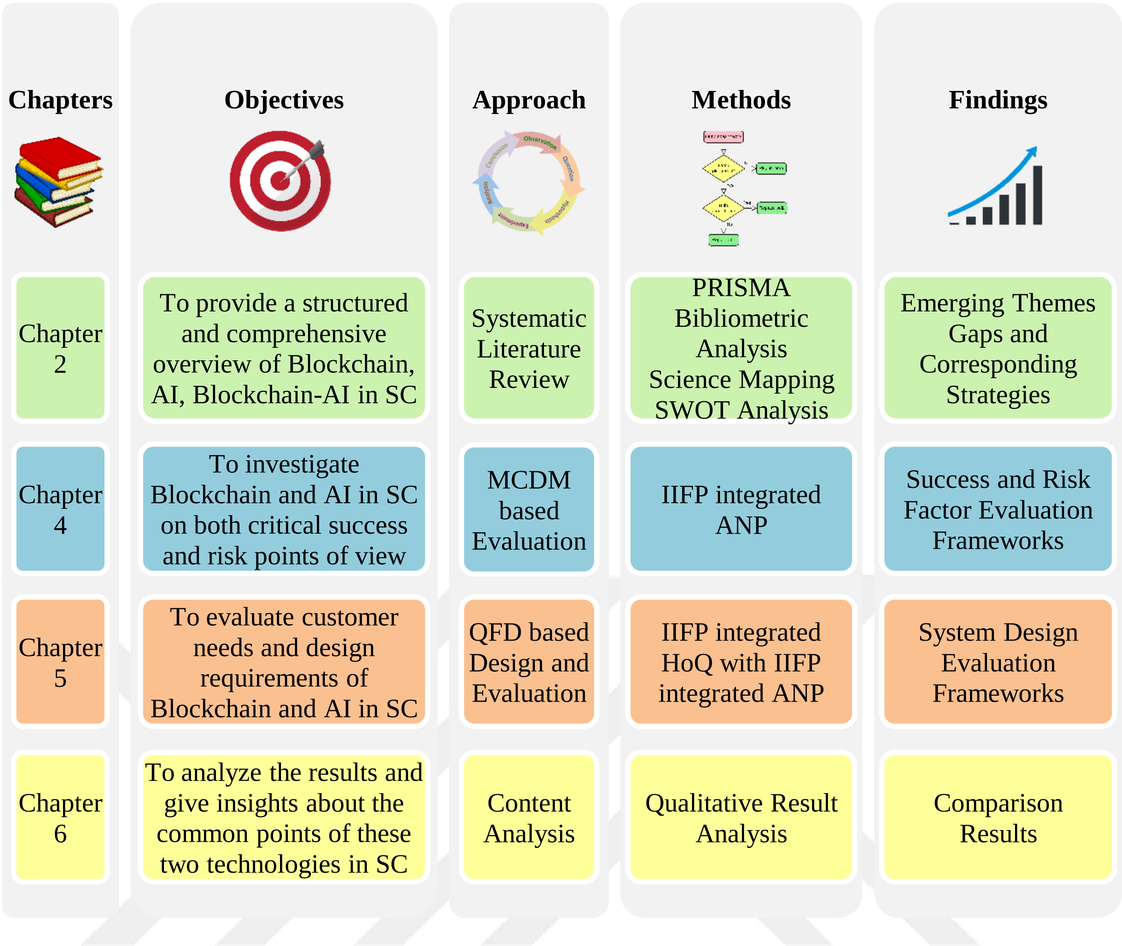


Figure 1.1: Dissertation Framework

The study provides a comprehensive guide for practitioners and researchers on the success and risk factors involved in adoption and implementation of Blockchain and AI in SCs, as well as the design requirements for creating an effective SCM structure using these technologies. To achieve this, a thorough literature survey was conducted, followed by an investigation of the success and risk factors associated with Blockchain and AI in SCs, and an analysis of the design requirements for both technologies in order to create effective digital SCM systems.

To evaluate success and risk factors, the proposed model uses a multiple criteria decision making (MCDM) approach that integrates various algorithms into a specific processing structure. One of these techniques, Analytical network process (ANP), has been successfully applied in various areas to determine the priorities of several variables in decision-making by establishing a network structure and relationship between decision levels (Saaty, 1996; Büyüközkan and Çifçi, 2012). However, decision-makers often provide ambiguous and incomplete data, which is closely related to their subjectivity, practice, and understanding.

This task becomes even more challenging when consulting multiple decision makers, as it creates difficulties in evaluating group decisions. To address this issue, ANP is extended with incomplete intuitionistic fuzzy preferences (IIFPs) to handle complexity and vagueness in the decision-making process (Ureña et al., 2015). To the best of authors' knowledge, prior research has explored the potential of Blockchain and AI in the context of SCM, but has typically treated these technologies separately and analyzed critical factors in isolation. This study, on the other hand, takes a comprehensive approach by examining both concepts and their respective success and risk factors using a novel methodological approach. Moreover, this study employs a unique decision-making perspective by a combination of ANP and IIFPs that has not been addressed in previous research, which has focused primarily on the success or risk factors of Blockchain and AI in SC.

To determine system design requirements, the proposed model utilizes a Quality Function Deployment (QFD) approach that incorporates IIFPs to address the uncertainty involved. The House of Quality (HoQ) methodology is recommended for constructing an effective design structure for Blockchain and AI based SC. As previously mentioned, the integration of these technologies in existing SC systems is still in its nascent stages, and various components for creating a guideline for practitioners are lacking. HoQ, a potent tool, plays a vital role in transforming customer requests into critical operations (Akao, 1990). However, the HoQ process may be hindered when each decision-maker provides different data based on personal opinion, making objective results challenging to achieve. Group decision-making (GDM) can be an effective solution to aggregate obscure and even missing data. Therefore, the HoQ tool is recommended with IIFPs to manage the complexity associated with this process. To the best of authors' knowledge, previous studies have proposed frameworks for analyzing Blockchain and AI in SC, as well as outlining the benefits and barriers of these technologies. However, they have not proposed a comprehensive structure of design requirements based on customer needs or evaluated their proposed frameworks using a combination of HoQ and IIFPs.

The rest of this dissertation is structered with Chapter 2, which gives a theoretical background for Blockchain and AI in SC, and comprehensive literature survey. Then, Chapter 3 reviews the methodology applied and the techniques employed. Chapter 4 demonstrates a case application for success and risk evaluation frameworks for Blockchain and AI, and Chapter 5 demonstrates another case application for evaluating customer needs and design requirements for Blockchain and AI in SC. Afterwards Chapter 6 presents managerial implications and discussions on the results of previous chapters. Finally, Section 7 concludes this thesis.

2. LITERATURE REVIEW ON BLOCKCHAIN AND AI IN SC

In recent years, several Blockchain and AI studies, and their applications have been conducted in the SC literature (Naz et al. 2022; Li et al. 2024a; Silva et al. 2025). Consequently, integration of Blockchain and AI has also started to gain focus in the recent years especially in area of SC (Kumar et al. 2024). However, this dissertation suggests that new literature review is necessary for two main reasons: (1) Previous literature reviews have generally focused on specific issues from specific perspective, making it difficult to provide a comprehensive and systematic view. The overview of literature in Sections 2.1 and 2.2 shows that a majority of studies either investigated effects, advantages, disadvantages of AI and Blockchain in SCs or have specific focus as resilience of SC and so. (2) There is a shortage of academic publications that provide comprehensive review of Blockchain and AI in SC as integrated technology. Consequently, despite Blockchain and AI integrations being such a significant emerging field in SC, the state-of-the-art suggests that the literature for it has still gaps based on these two reasons.

Theoretical and practical contributions of this chapter to fill those gaps can be summarized as:

- Conducting a comprehensive mapping of knowledge domain and research development trends in Blockchain-based and AI-based SC fields,
- Being one of the pioneers for scientific mapping and literature review to investigate the Blockchain and AI usage in SC from a systematic point of view,
- Analyzing and comparing the literature based on separate and combined usage of Blockchain and AI in SCs,
- Usage of SciMAT tool for Blockchain and AI in SC literature for science mapping for the first time.

This chapter addresses these gaps and pioneers Blockchain and AI's diffusion in SC literature. This motivation defined four interlocking research questions (RQs) to study:
(RQ2.1) What are the current themes and focus areas associated with Blockchain in SC?
(RQ2.2) What are the current themes and focus areas associated with AI in SC?
(RQ2.3) What are the current themes and focus areas associated with both Blockchain and AI in SC?
(RQ2.4) Which conclusions can be drawn, and which gaps or future research directions can be found?

Scientific mapping can be described as a visualized representation of how knowledge areas, documents, or authors relate to one another (Cobo et al. 2012). Diverse software tools exist for constructing bibliometric networks (e.g., CiteSpace, VOSviewer). However, in this study, SciMAT is chosen for its detailed science mapping attributes. SciMAT helps to determine and map the intellectual foundation, relevant focus, and emerging trends. It unites techniques of science mapping and performance analysis to examine a study area, visualizing and describing common or specific issues/themes and evolutions over time. Hence in this study, SciMAT is employed to analyze a conceptual science mapping using co-word bibliographic analysis. In addition, VOSviewer (Van Eck and Waltman 2010) is utilized for its flexibility in the layout of several bibliometric analyses. The review starts with the first available study in Scopus and continues until the end of 2024.

Using these tools, the primary object of this article is to ensure a better view of the knowledge base and trends in Blockchain and AI within SC. Other goals are to determine the main thematic clusters of the current field, emphasize the performance and connections between diverse elements of the research area (e.g. publications), discover changes and progressions that took place over time, highlight insufficiently explored fields that require further investigation, and guide practitioners with the insights based on this analysis. This approach to bibliometric analysis and science mapping has several benefits (Cobo et al. 2012). Researchers new to this area can utilize from the outputs to reach an overall insight of the intellectual basis and development trends of Blockchain and AI in SCs. They can also gain a deeper understanding of the research area by the studies emphasized in this analysis. This deeper understanding can help them for a faster and more efficient way to advance ideas for their future investigation. Similarly, since the domain grows fast, the intellectual base needs to be mapped to keep up with recent improvements, learn about dominant and emerging areas, and identify gaps and under-studied fields that need further attention.

The rest of this Chapter 2 continues with Section 2.1, which gives background information about Blockchain and AI in SC. Section 2.2 gives the methodology of this chapter. Then respectively, Section 2.3 gives bibliometric and science mapping analysis for Blockchain within SC field, Section 2.4 gives bibliometric and science mapping analysis for AI within SC field, and Section 2.5 gives bibliometric and science mapping analysis for Blockchain and AI within SC field. Finally Section 2.6 summarizes the gaps and observations based on results, while Section 2.7 completes the chapter with a proposition which is the basis of Chapter 3.

2.1. Background for Literature

2.1.1. Blockchain Overview

Blockchain is a distributed ledger-based exchange service used to move transactions, information, and assets in extensive networks of users without the help of central intermediaries securely. As everybody in the shared Blockchain can reach the same transactions, there is full transparency that highly prevents the participants to cheat the system. It distributes the process of recording transactions and monitoring tangible or intangible assets over networks. These assets can specify information, identities, contracts, and others, which can be identified in digital form (Sharma et al. 2023). Almost any value can be monitored and processed in a distributed ledger, which means lowering transaction risks and costs for every interested party (IBM 2017).

Peer-to-peer data architectures have a history dating back to the 1990s, during which time they gained prominence through file-sharing programs. With the integration of cryptography and game theory mechanisms, Blockchain technology has fundamentally altered the landscape of peer-to-peer architectures. We can now start to move from centralized database structures where all data is stored on a central computer to more decentralized or entirely distributed database structures. By sharing databases among several nodes, a Blockchain basically eliminates the requirement for agents who in other systems play the role of trusted third parties that confirm, record, and enable transactions.

Blockchains consist of a set of linked blocks (process storage units), which is encrypted with public keys (hash) and holds timestamp operations confirmed by the network community. The block header contains metadata, e.g. a unique block ID, its creation time, and a link to the previous block. The content typically includes an approved list of transactions, their quantities, the addresses of the parties, the digital assets and instruction notices (Deloitte 2017). Figure 2.1 demonstrates the architecture of a block in Blockchain.

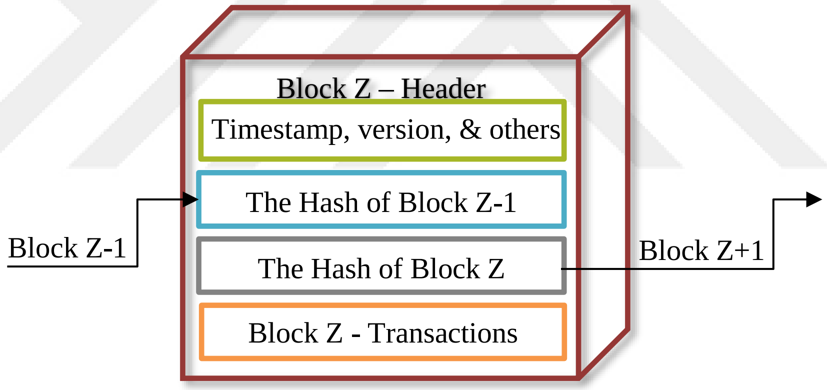


Figure 2.1: A Block Structure of Blockchain

When elements are added to a Blockchain, they cannot be modified. This feature lends Blockchains the distinctive function of being a constant record book of historical activity. Many users can access, review, or add data; however, they cannot modify or delete it. In Blockchain, proof algorithms are widely used for consensus processes as a means of negotiation on a single information value between distributed systems. There are several proof algorithms (e.g. Proof of Stake, Proof of Authority, Proof of Work) and other consensus mechanisms (Silva et al. 2025). In addition, operations in Blockchains can be programmed to spontaneously initiate activities (as payments or other actions) among nodes when specific terms are fulfilled. (Wang et al. 2019b). These program codes are called smart contracts, which are simply automated transaction protocols that are triggered and executed by pre-defined contract conditions. While these structural properties and additional functions form the powerful aspects of Blockchains such as privacy, immutability, traceability; several weaknesses can also be counted as complexity, lack of knowledge and expertise, regulatory difficulties, poor user experience, security issues (cyber-attacks).

2.1.2. Blockchain in SC

SC is the collection of business processes that companies have to transform raw materials into a final product (from farm to fork). It contains high devotion to product development, demand/supply planning, procurement, logistics, and customer service management. In this process, technological innovations have gained wide acceptance in SCs that help the companies to deliver sustainable value and improved performance. SCs can take advantage of advanced technologies to gain a competitive advantage for companies (Wang et al. 2019a).

SC and logistics activities are becoming increasingly complex. In an ordinary SC, facilities as seller, distribution center, etc. include materials, financial and information flows. Several simultaneous operations take place in the areas of SC, such as between the seller and the plant, between the plant and the distribution center. In these processes, trust issues can occur especially in financial record keeping. Blockchain is expected to function as a single origin of data and may aid in integrating all the functions of the SC (Dutta et al. 2020). Blockchain is also treated as a contemporary technology for cost reduction, traceability, security, and quality improvement in the literature lately. These aspects of Blockchain may help SC be more powerful and reliable. In this context, integrating this technology into SCs offers potential gains, which are also investigated in this paper to help readers better understand distributed ledger technologies. The latest state-of-the-art in SC is reviewed in this paper in connection with Blockchain technology.

Lately, many Blockchain studies and applications have been conducted in the SC literature. Researchers used various approaches and also focused on diverse components or parts of Blockchain (Chakraborty et al. 2023). Due to the enlarging volume of Blockchain researches, authors also published review papers. Wang et al. (2019a) studied the literature for implementing Blockchains in future SCs. They examined 29 academic papers and 17 popular Blockchain initiatives in practices to analyze how Blockchain affects SC applications and policies. Another literature analysis by Zhao et al. (2019) reviewed Blockchains and their applications in agri-food chains. Their review of 71 publications revealed that primary reasons to adopt Blockchains in agri-food industry are traceability, production, data security, and management of sustainable water. The major difficulties are defined as high cost, scalability, storage capacity, regulation problems, privacy, lack of skills, and latency and throughput issues. Gurtu and Johny (2019) reviewed the state of the art by investigating the potential of Blockchains in SC. They researched 299 papers about Blockchain (not only in SC basis) which are published through the end of 2018. Although they did not discuss the reviewed SC papers in detail, their study shows that there are almost 30 studies until the end of 2018 concerning Blockchain and SC.

Musigmann et al. (2020) conducted a bibliometric analysis to assess the current state of research on Blockchain technology in Logistics and SCM. Their literature review comprised of 613 papers, which were classified into five clusters: conceptualizing and testing Blockchain applications, theoretical sense making, framing Blockchain into SCs, the technical design of Blockchain applications for real-world logistics and SC applications, and the role of Blockchain within digital SCs. Similarly, Dutta et al. (2020) checked 178 articles and examined the usage of Blockchain integration in SC operations. They focused on the possible societal effects, opportunities, current technologies with main trends and challenges. They also examined multiple industrial sectors such as automotive, healthcare, finance, energy, technology, agriculture, and food. Another review is performed by Pournader et al. (2020) that demonstrates industrial and academic frontiers on Blockchain application in SC, transport, and logistics management. Their literature review comprises four major clusters in the co-citation analysis. These clusters are trade, technology, trust, and transparency-traceability. Lim et al. (2021)

identified 106 publications between 2017-2020 through theme searching, type and content screening and investigated SC themes, industries, illustration types, and research methodologies. Literature review studies highly increased afterwards. Table 2.1 shows some of the recent literature review studies for Blockchain potential in SC field.

Table 2.1: Several recent literature reviews for Blockchain and SC

Author	**Reviewed articles**	**Methodology**	**Topic**
Chakraborty et al. (2023)	477	Network and content analysis	Blockchain adoption in SC operations
Sargent and Breese (2023)	76	Systematic literature review	Blockchain barriers in SC
Sharma et al. (2023)	150	Systematic literature review	Blockchain enabled food SCM
Shin et al. (2023)	148	Technology, Organization, and Environment (TOE) framework	Blockchain in Maritime SC
Jackson et al. (2024)	202	Inductive-deductive content analysis	Blockchain enabled lean automation in SC
Vern et al. (2024)	187	Systematic literature network analysis	Agri-food SC Blockchain opportunities and challenges
Silva et al. (2025)	55	Content analysis	Blockchain adoption from SC collaboration view

2.1.3. AI Overview

AI encompasses the broad notion of developing systems capable of copying or replicating human behavior (Ressi et al., 2024). It specifically denotes the ability of computer algorithms to generate approximations of conclusions without direct human intervention. By teaching machines to tackle a wide array of tasks, AI can sometimes achieve results surpassing human capabilities. Consequently, AI can be described as the machine's ability to emulate human problem-solving, often with greater speed and efficiency (Goścień, 2025).

This innovative technology simulates human intelligence and aptitude through machines, primarily computers, robots, and digital systems. AI-powered applications, systems, and devices have the capability to visually recognize and classify objects. They can comprehend and interact with human speech. These systems are able to acquire knowledge from new data and experiences. They can provide detailed suggestions to both users and experts. Furthermore, they possess the ability to function autonomously, eliminating the need for human intelligence or involvement (e.g. self-driving vehicles). Various AI applications are available in the market, including assistive robots, autonomus vehicles, smart home technologies, and more (Kumar et al., 2024).

As of 2024, the majority of AI experts and professionals are now concentrating on advancements in generative AI, a technology capable of producing original content such as text, images, video, and more (Li et al., 2024a). To gain a comprehensive understanding of AI, it is crucial to first grasp the foundational technologies upon which generative AI tools are constructed: machine learning (ML) and deep learning. Figure 2.2 demonstrates AI as a series of intertwined or derivative concepts that have emerged over a period of more than 70 years.

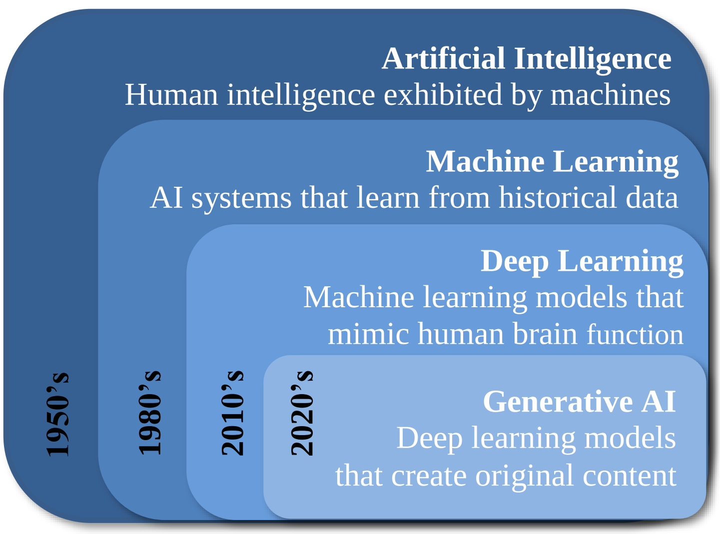


Figure 2.2: AI Concepts[1]

[1] www.ibm.com/think/topics/artificial-intelligence

Beneath the umbrella of AI lies ML, which involves developing models by training algorithms to make predictions or decisions based on data. ML encompasses a wide array of techniques that allow computers to learn from and draw conclusions based on data without explicit programming for specific tasks (Velev and Zlateva, 2023). There are numerous types of ML algorithms, including decision trees, linear regression, random forest, clustering, and others. Each of these methods is tailored to address different types of problems and data sets. However, one of the most widely used types of ML algorithm is the neural network (NN). The most basic form of ML is known as supervised learning, which utilizes labeled data sets to train algorithms for accurate data classification or outcome prediction. The objective is for the model to learn the correlation between inputs and outputs in the training data, enabling it to predict labels for new, unseen data (Li et al., 2024b).

Deep learning, a branch of ML, employs multi-layered NNs that mimic the intricate decision making processes of the human brain. These networks, known as deep NNs, consist of an input layer, numerous hidden layers (typically hundreds), and an output layer, allowing the system to make independent predictions about the data's meaning. This capability for unsupervised learning facilitates ML on an enormous scale, eliminating the need for human intervention (Mishra et al, 2023). Deep learning excels in areas such as natural language processing (NLP) and computer vision, where rapid and precise identification of complex patterns and relationships in large datasets is crucial. Today, various forms of deep learning underpin most AI applications in daily life.

Generative AI, or shortly Gen AI, describes advanced deep learning systems capable of producing sophisticated original content, including extensive text, high-resolution images, lifelike video or audio, and more, based on user inputs or requests. In essence, these models create a simplified representation of their training data and use it to generate new works that are similar but not identical to the original information (Li et al., 2024b). While generative models have been utilized in statistical analysis of numerical data for years, they have evolved over the past decade to process and create more intricate data types.

2.1.4. AI in SC

In today's changing global business environment, the incorporation of AI into SCM has become a game-changing force, transforming business operations and customer service approaches (Liang et al., 2024). As organization strive to boost efficiency, reduce expenses, and elevate service standards, the adoption or implementation of AI technologies provides numerous benefits, ranging from predictive analytics and enhanced demand forecasting to automated inventory control and streamlined logistics. AI facilitates the analysis and generation of insights from data, creating new scenarios and patterns based on data behavior. It can enhance SC adaptability, responsiveness, and efficiency while ensuring transaction transparency for all parties involved (Li et al., 2024a).

The benefits of AI technology in SCs have been examined in different areas as inventory replenishment, demand forecasting, production planning and control, supplier selection, facility location, risk management, operations management, productivity, and sustainability (Naz et al., 2022b; Kumar et al., 2023). AI undoubtedly has many advantages for SCM and logistics, including automation of activities and reduction of human intervention, the ability to bring desired transparency and visibility, increased flexibility in value chains, cost reduction, optimization of resources, fraud reduction, improved inventory management, security and traceability to the SC, and more. These benefits help businesses operate more accurately and gain the trust of their partners and customers (Shatat and Shatat, 2022; Kumar et al., 2023).

In recent years, several AI studies and applications have also been conducted in the SC literature. Researchers used varied methodologies and even focused on different sides or methods of AI (Li et al., 2024; Lin and Wang, 2024). The volume of them are rather less than Blockchain, but similarly several authors also published AI review papers. Initially, Min (2009) studied diverse fields of AI which are appropriate for handling problems related to SCM to explore the potential advantages of AI for SC. Those sub-fields includes supply management and purchasing, inventory planning and control, transportation network design, order-picking, demand forecasting and planning, customer relationship management. After Min, Toorajipour et al. (2021) proposed a study to review AI in SCM and identify the contributions. They analyzed 64 articles and categorized them based on SC field (as marketing, logistics, production, SC) and AI techniques (fuzzy logic, neural networks, multi agent based systems are the top 3). Naz et al. (2022b) conducted a literature review from 162 articles to explore the potential of AI for sustainable and resilient SCs post COVID-19, and also for risk management. Their propositions are mostly on increasing the AI based models in this area. Naz et al. (2022a) also reviewed the AI applications for sustainable SCs based on 353 articles in the field. Their findings about emerging themes in the field are: carbon emmissions, optimization, sustainable transportation, vehicle routing, remanufacturing, data analytics, reverse logistics, sustainable supplier selection, proposed models, and decision making. More studies that are recent are listed in Table 2.2.

Table 2.2: Several recent literature reviews for AI and SC

Author	**Reviewed articles**	**Methodology**	**Topic**
Riahi et al. (2021)	136	Descriptive bibliometric analysis	AI applications in SC
Kassa et al. (2023)	106	Systematic literature review	AI for SC resilience
Zamani et al. (2023)	23	Systematic literature review	AI and big data analytics for SC resilience
Harrir and Triqui Sari (2024)	127	Systematic literature review	AI applications and tools in SCM
Yadav et al. (2024)	54	Systematic literature review	AI applications for information management in sustainable SCM
Taha Kandil (2025)	58	Social network analysis	AI for alleviating SC bullwhip effect

2.1.5. Blockchain and AI Convergence and Overview in SC

Blockchain's data management is currently enhanced through hashing algorithms for data mining, which employs a brute-force approach to discover the right combination. On the other hand, AI presents a more effective solution by simplifying the data managing process and minimizing the intricacy of existing methods. The incorporation of AI into Blockchain technology optimizes energy usage by refining data mining, thereby reducing time, effort, and power consumption. Moreover, AI improves Blockchain scalability through sophisticated decentralized systems for learning and innovative techniques for data-sharing, enhances efficiency and creating opportunities for new and established businesses (Kumar et al., 2024). AI also increases transaction efficiency by identifying the node most likely to provide the solution first, allowing other nodes to cease operations, thus reducing costs and improving system performance. While Blockchain is renowned for its robust security, AI further strengthens security measures using real-time data transformation, natural image recognition, and language processing, ensuring secure data transactions (Lin and Wang, 2024). In the future, AI will handle advanced data management tasks, such as monitoring data usage, controlling access, and ensuring smooth data flow on Blockchain, functioning as data gates to improve the overall system. These advancements underscore the potential of AI-enhanced Blockchain systems to benefit businesses and revolutionize the AI landscape.

These mutual benefits are gaining attention and literature reviews about Blockchain and AI in SCs have started to deep dive into these benefits (Gupta et al., 2023). When Blockchain's benefits as transparency across the SC, security, immutability, decentralization, and improved tracking of goods, shipments and inventory unite with AI's benefits as predictive maintenance, SC optimization, automated decision making, demand forecasting, and risk management; organizations can create a more efficient, transparent, and secure SC that drives business growth and customer satisfaction.

In the literature, there are several systematic literature reviews existing for Blockchain and AI integration, however to the best of authors' knowledge, only two researches exist for integration of Blockchain and AI for SC. Charles et al. (2023) reviewed this area based on 42 articles, and tried to study integration, use cases, and future directions. They summarized this area in four clusters as food - agriculture, emerging technologies, security - governance, risk - resilience - sustainability. Lately Idrissi et al. (2024) performed a systematic review for Blockchain, AI and Iot in transportation and logistics. They analyzed 18 studies and classified them in six clusters in logistics area: application of Industry 4.0 technologies, Blockchain applications, Blockchain - IoT combination, Blockchain and AI combination, Blockchain - AI - IoT combination, transformative effects of these three technologies.

As stated in previous two sections, authors in the literature generally have researched the usage of Blockchain and AI in SCs separately, as if these two technologies are on opposite ends. Charles et al. (2023) and Idrissi et al. (2024) only investigated the integration of these two concepts. Furthermore, this paper provides a broader view on the area as it combines all three to reach results and directions from separate literature to the combined.

2.2. Materials and Methods

2.2.1. Review Methodology

Here, the research target is determined to examine Blockchain-SC and AI-SC studies in the literature both separately and combined. This study's review methodology is illustrated in Figure 2.3, and the steps are explained.

(1) Searching Online Databases and Engines: Identified databases are investigated to pinpoint academic papers. In this step, several boundary conditions (such as sources to be used, period to be considered) are defined.

- Academic materials are searched in a scientific database: Scopus, which provides exhaustive coverage of literature.
- Conference materials, dissertations, and other non-peer-reviewed journal publications that may cause overlap and redundancy are excluded. This study classifies peer-reviewed or published journal articles.
- Searching with queries in online databases is the most common way of determining the most related articles nowadays. Here for Blockchain investigation, "Blockchain" and "Supply Chain" words are searched in abstract-title-keywords with queries. For AI investigation, "Artificial Intelligence or AI" and "Supply Chain" words are searched with queries. Lastly, for joint search, all

those words are searched. Studies without these selected terms are not included in this paper.

- Data are restricted by language: English.
- Author analysed studies from the first available study that can be reached online to the last study in 2024.

(2) Material collection and relativeness decision: After researching the literature and defining the unit analysis of every single paper, only the ones that apply to the restrictions above are collected. In addition, studies only focus directly on Blockchain, and SC are selected. The remaining articles are eliminated as their dominant themes are irrelevant even though they have the right keywords. Steps (1) and (2) are shown in Figure 1 by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow that is the minimal number of proof-based components for reporting in systematic reviews.

(3) Bibliometric analysis and science mapping: Performance analysis, usually based on the output of publications and citations, has been widely used in the bibliometric evaluation (Reyes-Gonzales et al. 2016). This method is based on the citation of a paper by other researchers as an acknowledgment of authority. In this step, collected papers are assessed from several aspects, i.e., publications, keywords, and subjected themes. A significant measure in the bibliometric analysis is science mapping. This step reflects the characteristics of the research dynamically and structurally, and shows the architectural side of the academic field. Science mapping analysis in this study follows these steps: dataset review, network extraction and normalization, mapping, analysis, and visualization.

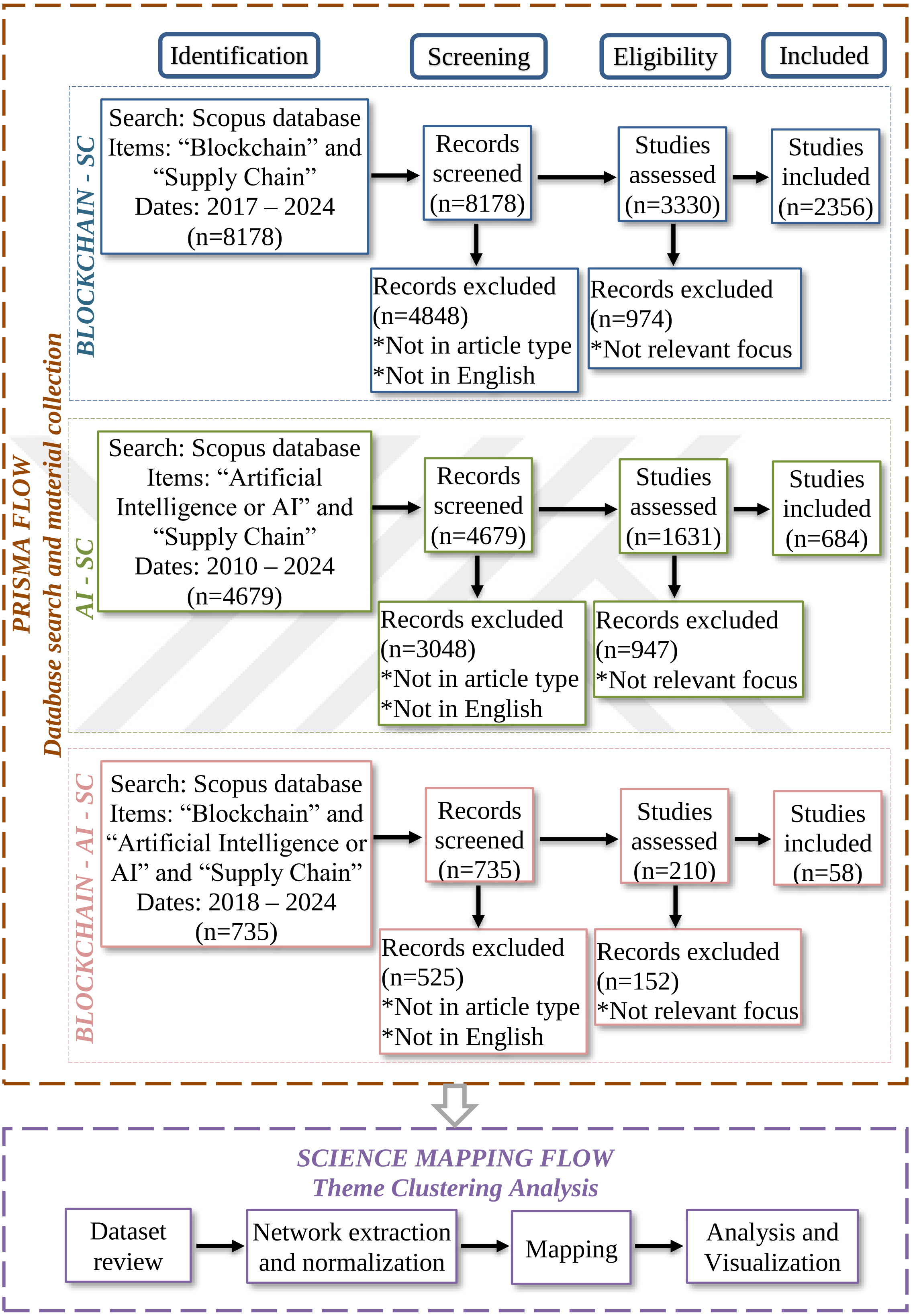


Figure 2.3: Review methodology guided by PRISMA flow

2.2.2. Science Mapping Workflow

Dataset Review: By finalizing the search for the keywords, all the relevant data are collected from Scopus, which contains all the available bibliographical information for each article found. Afterwards, the SciMAT period manager was used to create consecutive time periods to identify the evolution of Blockchain-AI-SC research fields in the mapping of science analysis. While sub-periods commonly covered similar amounts of data, the lower amount of publications in the early stages directed the authors to divide the entire period into comparable sub-periods was a more appropriate option. Therefore, the entire period was split into sub-periods until 2020, 2021, 2022, 2023, and 2024 respectively for separate reviews of Blockchain and AI. This lead to a longer first analysis period than the remaining, however, it was essential for the analysis data to be sufficient and more meaningful for the identification of key research themes. Thus, the volumes of publications in the first sub-period were increased and made more available for comparison. This separation let the evolution of the subject to be studied from the very beginning to the latest research. On the other hand, as the combined review is based on less volume of articles than the separate reviews (only 58) and the publication years are relatively less, the combined review of Blockchain-AI-SC was split into only three periods as until 2022, 2023, and 2024.

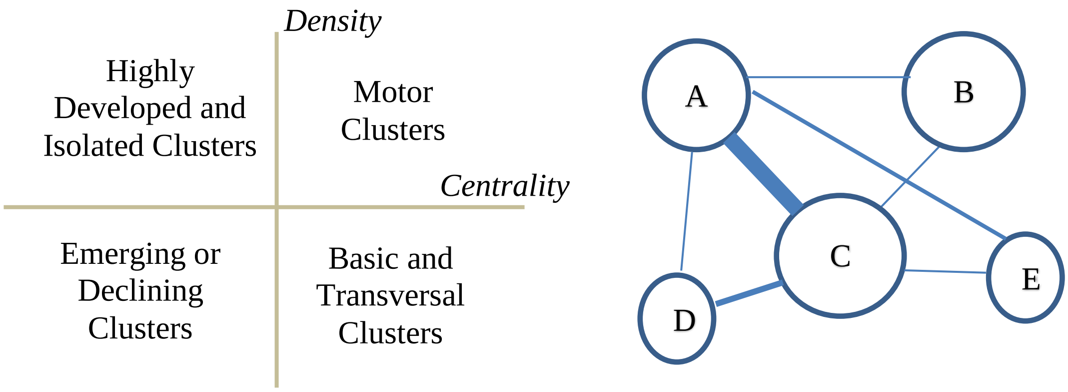
Network extraction and normalization: Following the preprocessing of review data, an analysis unit is utilized to construct a network. The knowledge base offers five group options for users to choose from as the unit of analysis: Author, Reference, Author-Reference, Source-Reference, or Word. However, only one can be selected at a time (Cobo et al. 2012). The Word group, being the most frequently used, was chosen for this study. Words can be extracted from various sections such as the title, abstract, author's keywords, body, or any combination thereof. Network creation can employ various methods, including co-occurrence and coupling. The type of bibliometric network generated depends on the chosen analysis unit and relationship type. In this research, words serve as the analysis unit, and co-occurrence as the relation, resulting in a co-word bibliometric network. After establishing the relationship network between the selected analysis units, normalization is essential to adjust for differences in occurrence frequencies of analysis units. Bibliometric normalization employs similarity measures (Van Eck and Waltman 2010), such as Salton's cosine, Jaccard's index, or Equivalence index. For this study, the Equivalence index was selected based on its common usage.

Co-word analysis is founded on the principle that the presence of keywords together reveals the content of documents within a research field. These keyword co-occurrences can be used to construct co-word networks (Cobo et al. 2012), which can then be linked to research themes through clustering techniques. The analysis involves calculating how often keywords appear together. This is done by determining the number of documents in the corpus where two specific keywords are found simultaneously.

Mapping: Following the network normalization process, various methods can be employed to create science maps, as clustering algorithms or principal component analysis. In this phase, an algorithm for clustering is utilized to construct the map. The simple centers algorithm is chosen for the clustering process.

Analysis and visualization: Various techniques are employed for visualization and to display science mappings and the outcomes of different analyses. The results of mapping stage can be demonstrated as thematic networks, while clusters identified within a network can be grouped by strategic diagram. The strategic diagram (Figure 2.4(a)) portrays the clusters defined for each period in a two-dimensional space and groups them based on centrality and density measures. Each set in the strategic diagram can be enhanced with bibliometric measures selected during the setup process (Cobo et al. 2012).

Figure 2.4(a) depicts various research themes: motor themes (crucial and well-established for the research area's structure), highly developed but isolated themes (advanced yet peripheral to the field's overall progress), emerging or declining themes (underdeveloped and marginal), and basic and transversal themes (significant for the discipline but not yet fully evolved). Each cluster's associated network is also illustrated (see Figure 2.4(b) for a graph showing the connections between its components). By examining the evolution of research themes over time, researchers can identify the main areas of development in the field, trace their origins, and understand how they relate to one another.



(a) (b)

Figure 2.4: (a) Themes in strategic diagram (b) Network of themes (Source: Cobo et al., 2012)

2.3. Result and Analysis for Blockchain-SC Literature

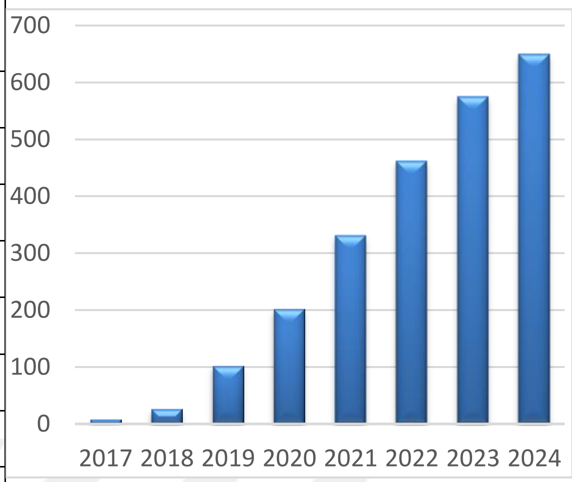
The research focus of this section is to evaluate research on Blockchain and SCs, to map its underlying intellectual structure and knowledge development and evolution, and then to suggest strategies for further development. To accomplish these tasks, a series of analyzes are performed. The primary interest of is to evaluate published research on Blockchain and SC using logical search tactics from a trusted source to collect all relevant data as an answer of RQ2.1.

2.3.1. Blockchain-SC Publication Trends Analysis

Table 2.3 illustrates the count of articles published each year between 2017 and 2024. It is observed that the amount of papers published during the past years is consistently increasing. It is also observed that this area has gained more attention from researchers, especially after 2022. Based on the percentage it can be said that almost half of the publications in research area are built in last two years

Table 2.3: Publication analysis for Blockchain and SC

Publication Year	**Count**	**Percentage**
2017	8	0.34%
2018	26	1.10%
2019	102	4.33%
2020	202	8.57%
2021	331	14.05%
2022	462	19.61%
2023	575	24.41%
2024	650	27.59%



Since both these terms are used as search terms in our article collection, it is not surprising that Blockchain and SC-based keywords are in the top six of keyword statistics. Next to these, traceability and transparency duo and sustainability show that Blockchain mainly addresses these aspects in current SCs. Therefore, these positive effects of Blockchain in SCs have become popular keywords in articles (Zhao et al. 2019; Aggarwal et al. 2024). In addition, Blockchain integration to SCs with IoT and smart contracts are also trend topics through the extensive usage of these keywords. IoT has been used many times with Blockchain technology in the articles for effective ways of tracking and tracing (Chaudhari et al. 2024). Smart contracts allow for self-executing scripts located in the Blockchain, lead to the integration of these concepts in SC negotiations and allows for convenient, distributed, and highly automated flows (Shao and Marwa, 2024). Food SCs and sales are also among the most focused SC areas for Blockchain adaption (Sharma et al. 2023). Finally yet importantly, decision making arises in Blockchain and SC articles (Öztürk & Yildizbaşi, 2020, Chaudhari et al. 2024).

2.3.2. Blockchain-SC Keyword Co-Occurrence Analysis

The keyword statistics process is part of the data collection for highlighting the most used expressions in the keyword section. A total number of 5622 different keywords are examined, gathered from all 2356 studies. The most 15 popular keywords are “blockchain, block-chain, supply chain management, supply chains, blockchain technology, supply chain, traceability, smart contract, internet of things, decision making, transparency, sustainability, food supply, sales, and sustainable development”.

In keyword co-occurrence analysis, the objective is to visualize and cluster the keywords. Keywords show the main scopes of the articles examined and define the key topics of a scientific field (Su & Lee, 2010). Figure 2.3 shows the bibliometric map of keywords by VOSviewer. The top keywords can also be seen in this network with larger spheres. In this analysis, the author keyword is used as a unit of analysis, and the threshold value is determined as 10. 159 keywords have met the threshold from 5622 keywords.

Since both these terms are used as search terms in our article collection, it is not surprising that Blockchain and SC-based keywords are in the top six of keyword statistics. Next to these, traceability and transparency duo and sustainability show that Blockchain mainly addresses these aspects in current SCs. Therefore, these positive effects of Blockchain in SCs have become popular keywords in articles (Zhao et al. 2019; Aggarwal et al. 2024). In addition, Blockchain integration to SCs with IoT and smart contracts are also trend topics through the extensive usage of these keywords. IoT has been used many times with Blockchain technology in the articles for effective ways of tracking and tracing (Chaudhari et al. 2024). Smart contracts allow for self-executing scripts located in the Blockchain, leading to the integration of these concepts in SC negotiations and allowing for convenient, distributed, and heavily automated workflows (Shao and Marwa, 2024). Food SCs and sales are also among the most focused SC areas for Blockchain adaption (Sharma et al. 2023). Finally yet importantly, decision making arises in Blockchain and SC articles (Öztürk & Yildizbaşi, 2020, Chaudhari et al. 2024).

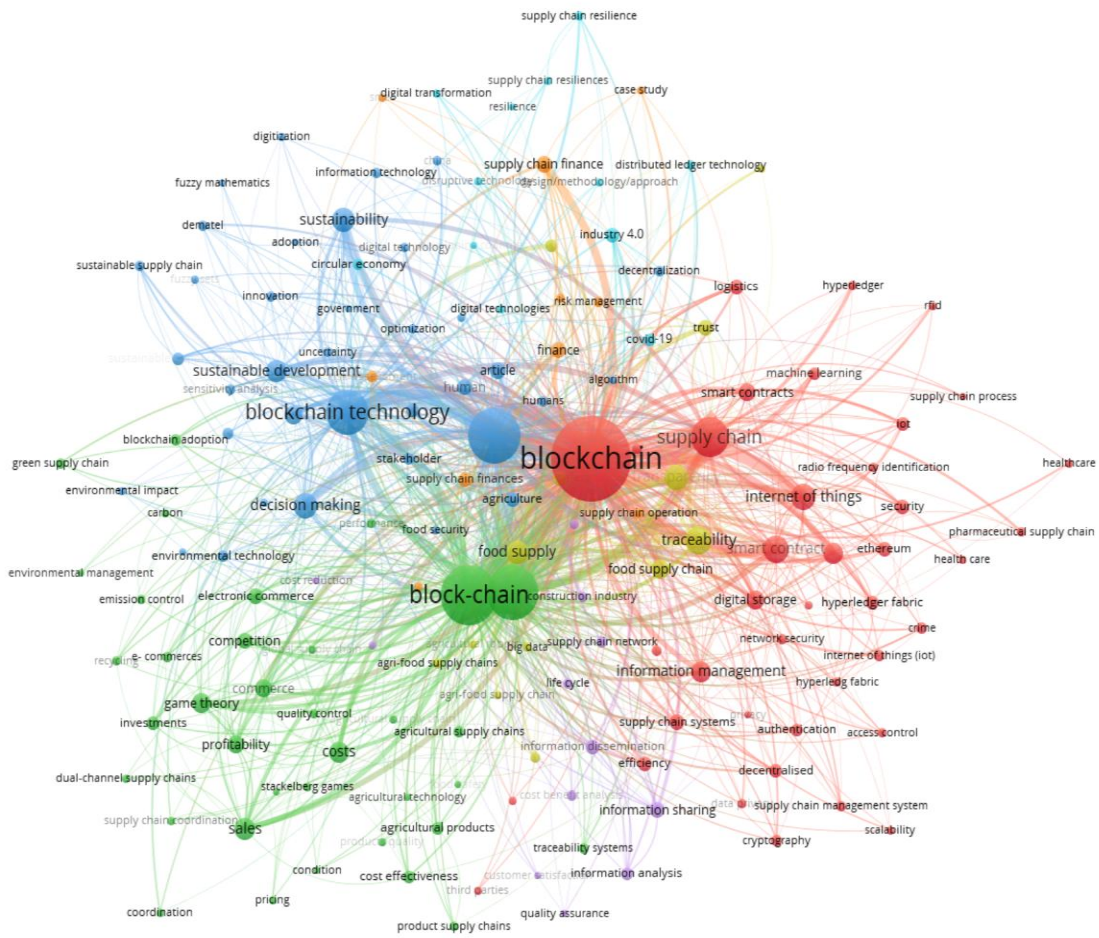


Figure 2.5: Map of keywords network for Blockchain and SC

2.3.3. Visualization of Blockchain-SC Themes through Science Mapping

Here, an analysis is provided for science mapping and the relationships between terms in Blockchain and SC-related fields, and it answers the RQ2.1 of this study. The analyzes of thematic areas for 2356 articles are given in Figure 2.6. This theme analysis can help to describe the contents in the field in each of the periods, and the evolution of these themes over the entire analysis period.

Based on the periodical view of themes, it can be seen that until 2021, the focus is mainly on digitalization and sustainability themes in Blockchain-SC studies. While sustainability exists as a core theme (Pandey et al. 2024), digitalization is under emerging themes that are underdeveloped and marginalized, with low centrality and low density (Rivera et al. 2024). In 2022, it is seen that environment is in more focus as a highly developed and isolated theme in Blockchain - SC studies. Also decision support system theme is being on focus until 2021, and after one period it starts to emerge again in 2022. All these periods Blockchain based themes as ethereum, hyperledger-fabric, consensus, decentralized systems, digital storage have come to fore in different periods. However, internet of things (IoT) integrations seem as main theme in almost all periods until today.

If the latest year literature is checked particularly, the biggest portion of focus themes can be seen as agriculture, IoT and sustainability. These are either motor or central themes with strong evolution (IoT), or basic themes with great influence or development potential (agriculture and sustainability). Figure 2.7 shows a detail view of the relations of these three themes with others. Sustainability theme demonstrates that it is mostly covering SC governance and green activities, and here fuzzy methods have started to be preferred which can be seen in the literature (Chaudhari et al. 2024). Agriculture theme shows that agriculture and food SCs are the two basic types studied for Blockchain, and the literature supports this analysis as those studies are the mostly seen ones (Aggarwal et al. 2024). Here, there are two important points that can be mentioned which are technology adoption and critical success factor. Lastly, IoT theme relations show that Blockchain integration investigations are now being moved to not only to IoT but also to other industry 4.0 technologies which involves also AI.

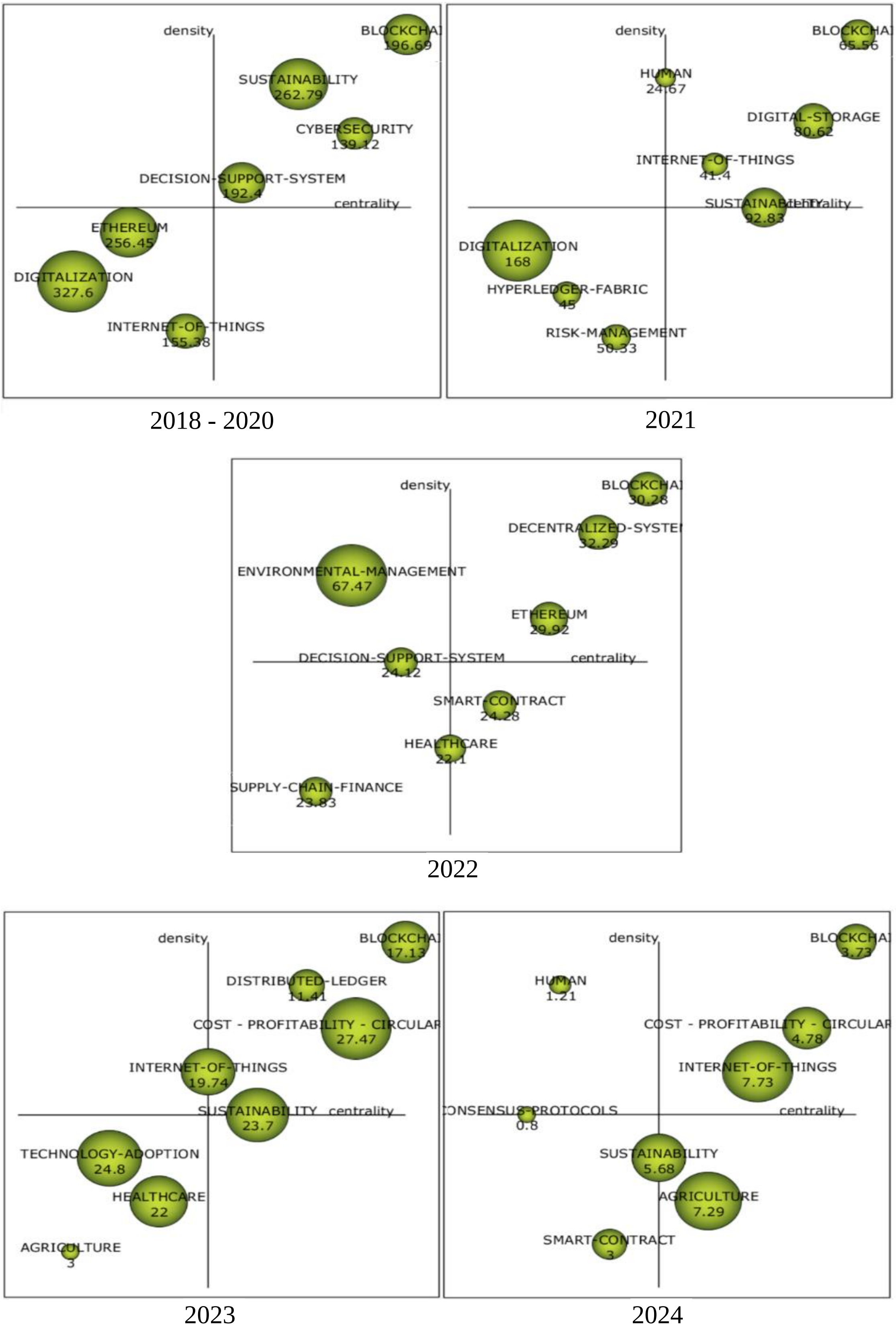


Figure 2.6: Thematic analysis for Blockchain and SC

Figure 2.7: Detail relations for top three themes of Blockchain and SC in 2024

2.3.4. Blockchain-SC methodology analysis

Based on the theme analysis in previous section, it can be seen that decision support system and fuzzy subjects come to fore in Blockchain and SC based studies. Therefore, a technical analysis for those items can be performed here for the 2356 studies that are subject to this research. Based on authors's individual analysis, 286 of those studies have decision making subject within it, and 122 of them are conducted in fuzzy environment. Figure 2.8 shows the different methods used in these papers.

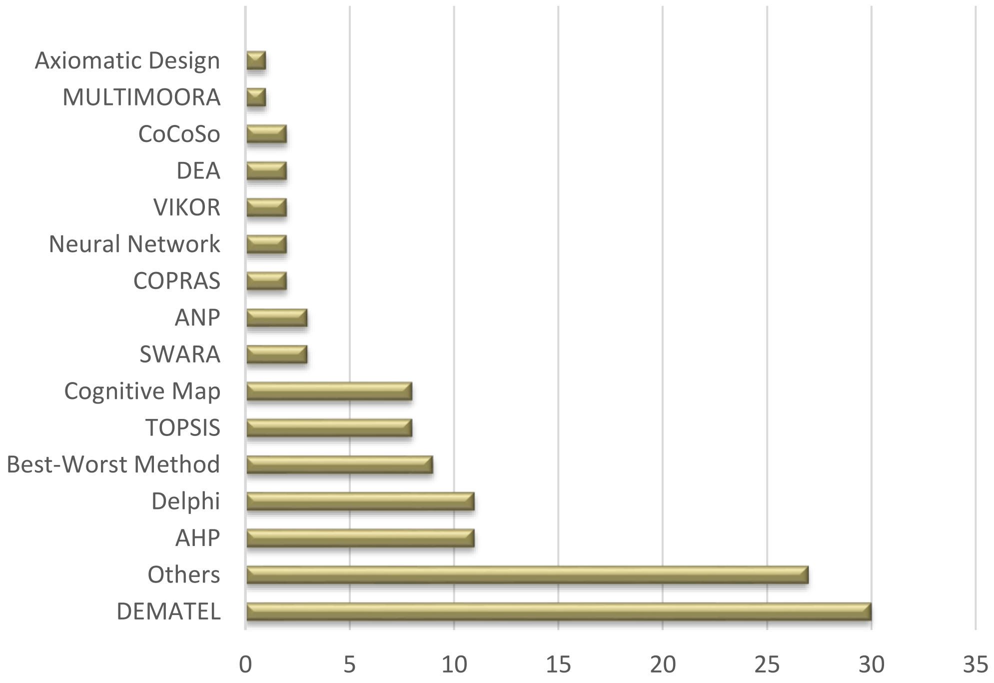


Figure 2.8: Fuzzy decision making methods used in Blockchain and SC studies

2.4. Result and Analysis for AI-SC Literature

The research focus of this section is to evaluate research on AI and SCs, to map its underlying intellectual structure and knowledge development and evolution, and then to suggest strategies for further development. To accomplish these tasks, a series of analyzes are performed. The primary interest is to evaluate published research on AI and SC using logical search tactics from a trusted source to collect all relevant data as an answer of RQ2.2.

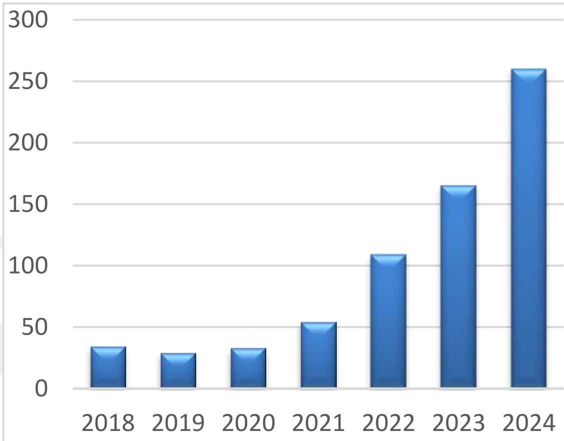
2.4.1. AI-SC Publication Trends Analysis

Table 2.4 illustrates the volume of articles published each year between 2010 and 2024. The number of articles between 2010 and 2018 are gathered under 2018 due to the low amount. Here also the number of papers published during years is consistently increasing, but AI seems less investigated area than Blockchain. It is also observed that, this area also has gained more attention from researchers, especially after 2022 like Blockchain.

However, as AI is an older technology than Blockchain, the studies in SC area was not a discovery like Blockchain in the initial year of 2017. While around 50 publications were made every year until 2021, this number doubled and increased even more after 2022.

Table 2.4: Publication Analysis for AI and SC

Publication Year	**Count**	**Percentage**
Until 2018	34	4.97%
2019	29	4.24%
2020	33	4.82%
2021	54	7. 09%
2022	109	15.94%
2023	165	24.12%
2024	260	38.01%



2.4.2. AI-SC Keyword Co-Occurrence analysis

Here, a total number of 6082 different keywords are examined, taken from all 684 papers. Although the number of studies are less than Blockchain, the number of different keywords are more in AI. The most 15 popular keywords are “artificial intelligence, supply chains, supply chain management, decision support systems, decision making, machine learning, supply chain, sustainable development, internet of things, sustainability, industry 4.0, blockchain, decision support system, machine-learning and big data”. Figure 2.9 shows the bibliometric map of keywords by VOSviewer. In this analysis, the author keyword is used as a unit of analysis, and the threshold value is determined again as 10. 763 keywords have met the threshold from 6082 keywords.

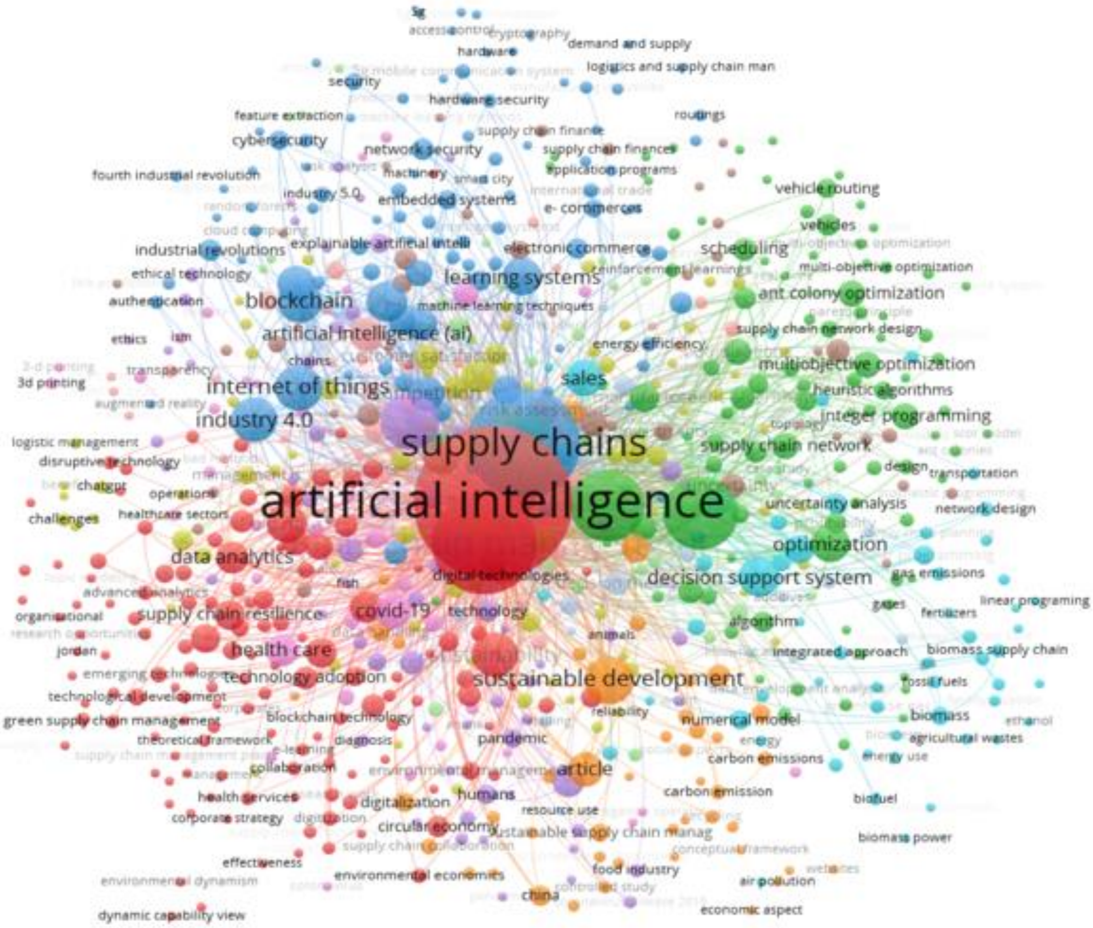


Figure 2.9: Map of keywords network for AI and SC

AI is one of industry 4.0 technologies and ML is a main component of it. Therefore, these two keywords are in top 15 apart from variety of AI and SC keywords. In addition, relation with IoT seems also a trend topic. IoT has been used many times with also AI technology in the articles for the performance of SC (Alheadary, 2024; Lin and Wang, 2024). As AI uses big data and decision making to make analysis and predictions, these two keywords are also expected to be on top of the list. Last but not least, sustainability and sustainable development as key enablers of SC, are parts of top keywords and popular subjects in the focused AI and SC studies (Li et al. 2024).

2.4.3. Visualization of AI-SC Themes through Science Mapping

Similar to Section 2.3.3, an analysis for AI and SC-related fields is also provided here for science mapping and the relationships between terms which it answers the RQ2.2 of this study. The analyzes of thematic areas for 684 articles are given in Figure 2.10.

Based on the periodical view of themes, it can be seen that until 2022, the focus is mainly on resilience, sustainability and environment themes in AI - SC studies. Sustainability is again in the core themes similar to Blockchain analysis (Naz et al. 2022a). As AI helps in digitalization, decision making, information gathering and analysis, it is no surprise that these themes exist in motor and well developed quadrants (Dubey et al. 2022).

After 2022, it is seen that new themes are emerging as technology adoption, success factors, operation and risk management. These subjects needs to be carefully investigated to have successful integration and implementation of AI. In the literature, several articles can be seen that study these subjects (Mishra et al. 2023). This analysis also shows that even Blockchain and industry 4.0 technologies are in emerging themes that are under investigation or to be investigated in AI-SC area.

If the latest year literature examined particularly, the biggest portion of focus themes can be seen as operation management, healthcare, and fuzzy logic. These are either motor or central themes with strong evolution (operations management and fuzzy logic), or basic themes with great influence or development potential (healthcare). Figure 2.11 shows a detail view of the relations of these three themes with others.

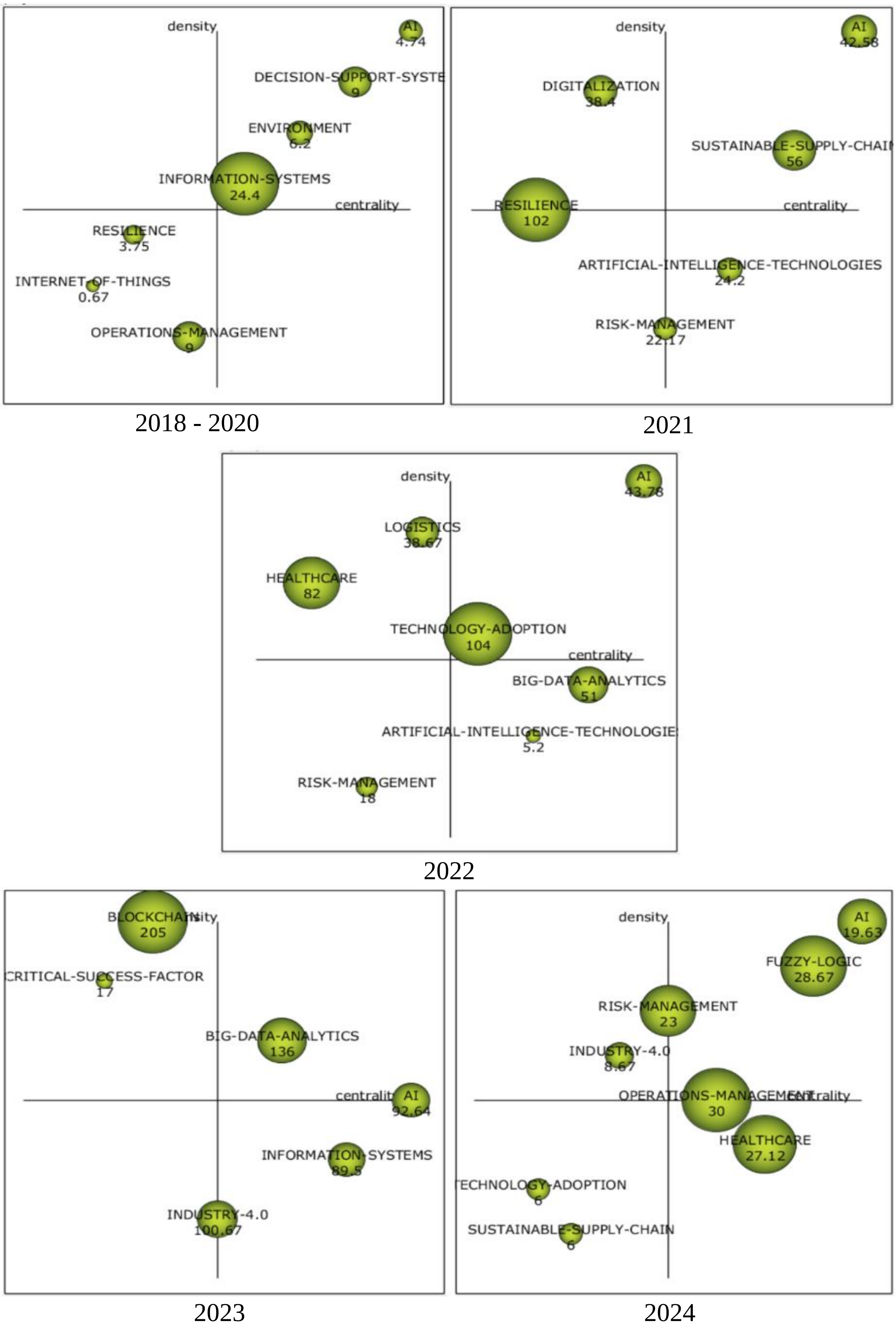


Figure 2.10: Thematic analysis for AI and SC

Operations management and healthcare themes generally demonstrates the studies that have these subjects are mostly about SC activities as finance, resilience, collaboration, data sharing and analytics. It can be seen from fuzzy logic theme that the topics come to fore in this last year is decision making, strategic frameworks and critical factors. Fuzzy methods have started to be preferred also in AI-SC literature (Virmani et al. 2024). As these topics are emerging in fuzzy theme, they need more attention and investigation for the development of these areas.

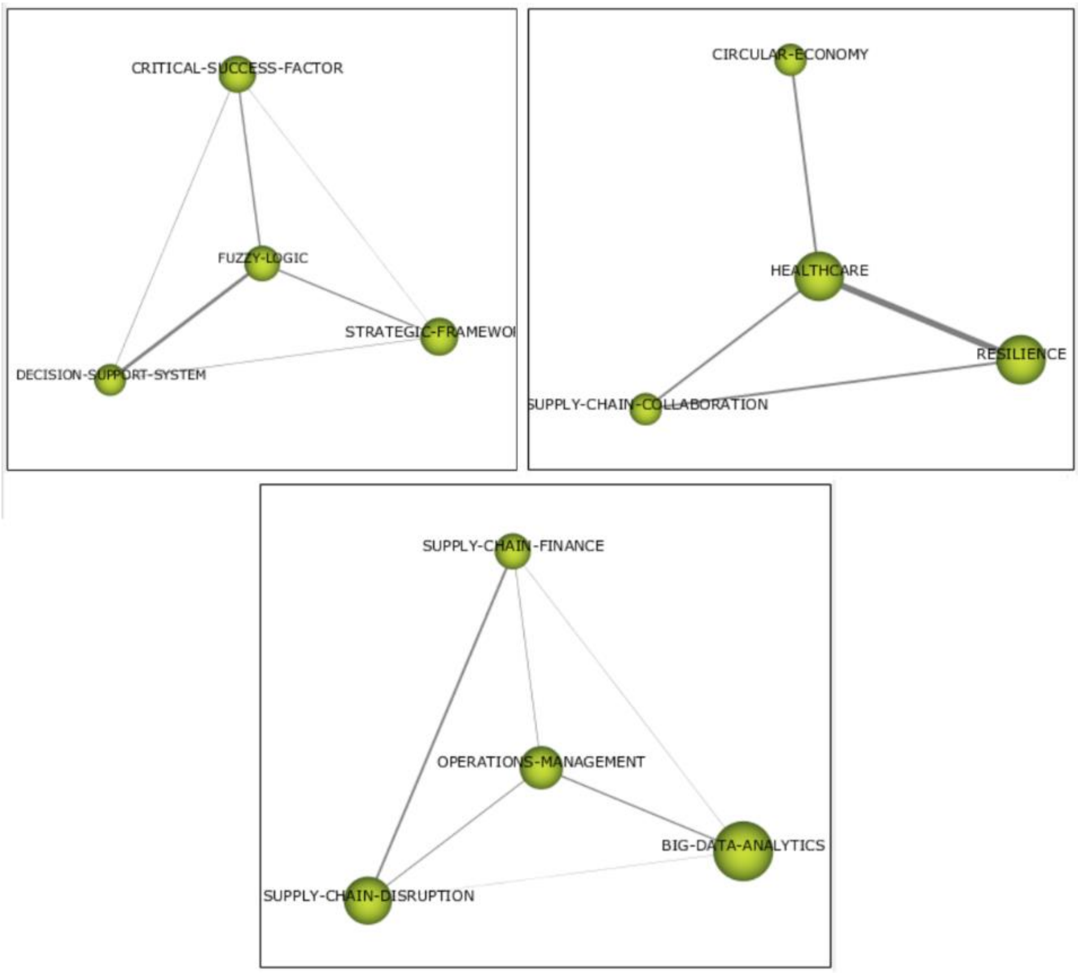


Figure 2.11: Detail relations for top three themes of AI and SC in 2024

2.4.4. AI-SC Methodology Analysis

According to the results on the theme analysis in Section 4.2.3, it can be seen that similar to the previous Blockchain analysis, decision support system and fuzzy subjects come to fore also in AI and SC based studies. Therefore, same technical analysis is performed here for the 684 studies that are subject to this research. Based on authors's individual analysis, 102 of those studies have decision making subject within it, and 25 of them are conducted in fuzzy environment. Figure 2.12 shows the different methods used in these papers.

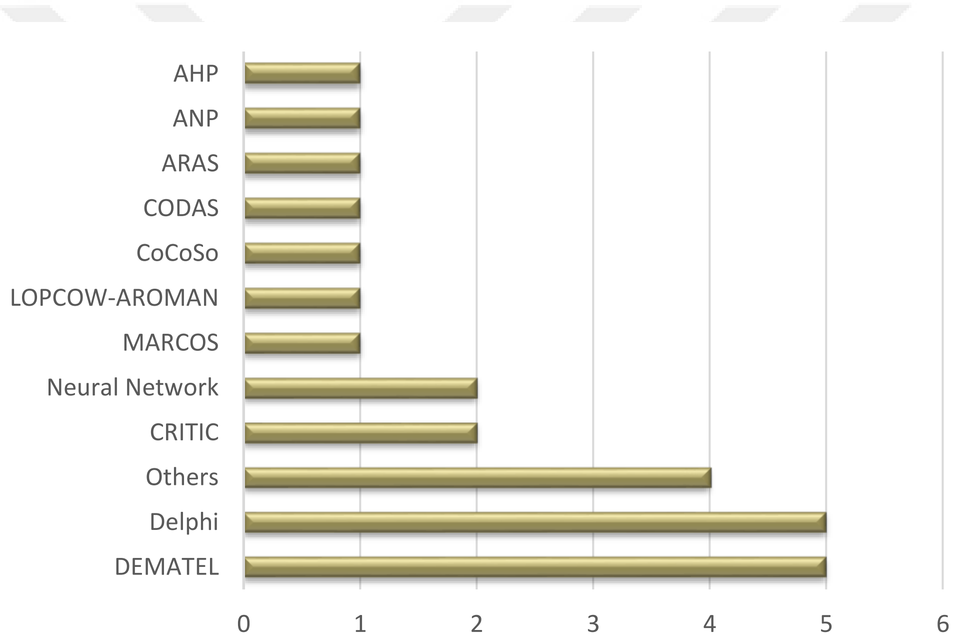


Figure 2.12: Fuzzy decision making methods used in AI and SC studies

2.5. Result and Analysis for Blockchain-AI-SC Literature

The research focus of this section is to evaluate research on Blockchain, AI, and SCs, to map its underlying intellectual structure and knowledge development and evolution, and then to suggest strategies for further development. To accomplish these tasks, a series of analyzes are performed. The primary interest is to evaluate published research on

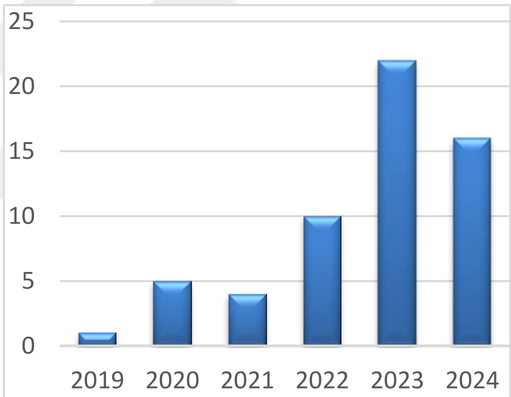
Blockchain, AI, and SC using logical search tactics from a trusted source to collect all relevant data as an answer of RQ2.3.

2.5.1. Blockchain-AI-SC Publication Trends Analysis

Table 2.5 illustrates the volume of papers published each year between 2019 and 2024. Except 2024, the number of papers published during the past years tend to increase. It is observed that 2023 was the peak period for the attention on this area from researchers. Based on the percentage, more than half of the publications in research area are built in last two years.

Table 2.5: Publication Analysis for Blockchain, AI, and SC

Publication Year	Count	Percentage
2019	1	1.72%
2020	5	8.62%
2021	4	6.90%
2022	10	17.24%
2023	22	37.93%
2024	16	27.59%



2.5.2. Blockchain-AI-SC Keyword Co-Occurrence Analysis

As this is rather new and emerging research area, it includes less published papers and also less keywords accordingly. A total number of 641 different keywords are examined, gathered from all 58 studies. The most 15 popular keywords are “artificial intelligence, blockchain, block-chain, supply chains, supply chain management, internet of things, industry 4.0, digital storage, machine-learning, supply chain, machine learning, competition, internet of things (iot), sustainable development, artificial intelligence (ai)”. Figure 2.13 shows the bibliometric map of keywords by VOSviewer. In this analysis, the author keyword is used as a unit of analysis, and the threshold value is determined as 3 due to the low number of papers. 45 keywords have met the threshold from 641 keywords.

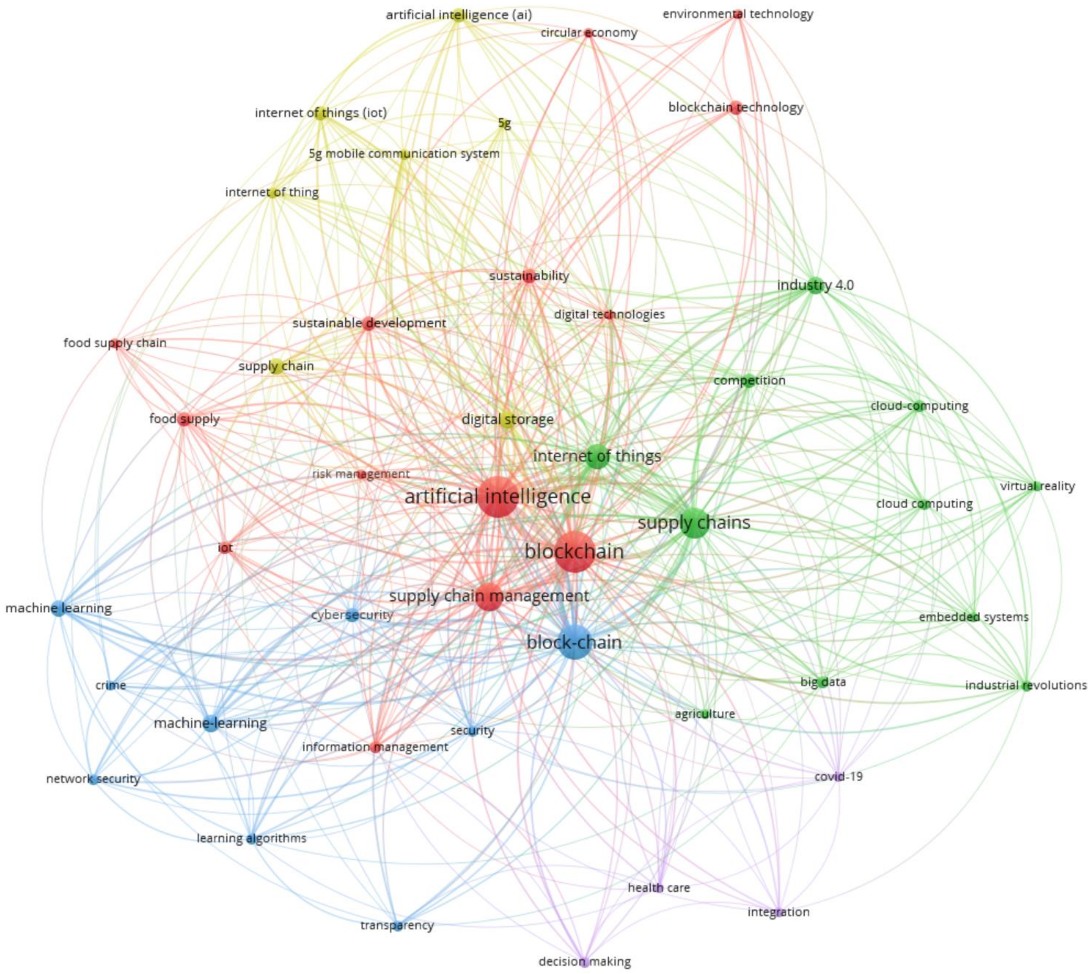


Figure 2.13: Map of keywords network Blockchain, AI, and SC

All of the top keywords are not surprising and appeared in previous Blockchain or AI based literature within SC, as they are related to the topics directly. The only different keyword that come to fore is competition. This literature demonstrates that this integration bring competitive advantage in SC operations for companies and practitioners (Anitha and Rai, 2022).

2.5.3. Visualization of Blockchain-AI-SC Themes through Science Mapping

Here, an analysis is provided for science mapping and the relationships between terms in Blockchain, AI, and SC-related fields, and it answers the RQ2.3 of this study. The analyzes of thematic areas for 58 articles are given in Figure 2.14. Based on the periodical view of themes, it can be seen that until 2022, there are three main focus themes which are big data, economic growth and industry 4.0. In 2023, SC digitalization come to fore, and in 2024 sustainability exists as rather developed and isolated theme within Blockchain-AI-SC studies (Idrissi et al. 2024).

Figure 2.14: Thematic analysis Blockchain, AI, and SC

These themes show similarity with the previous separate literature analyzes of Blockchain and AI, which is expected due to the SC integration. For SC, these two topics always gain attention in the literature and is necessary for the success of SC operations and performance (Hong and Xiao 2024). The theme smart-systems draws attention in all of the periods. It involves different research areas as smart applications and technology, smart logistics, smart agriculture, smart manufacturing (Anitha and Rai 2022). Focusing particularly to the latest year literature, Figure 2.15 shows a detail view of the relations of the themes with others.

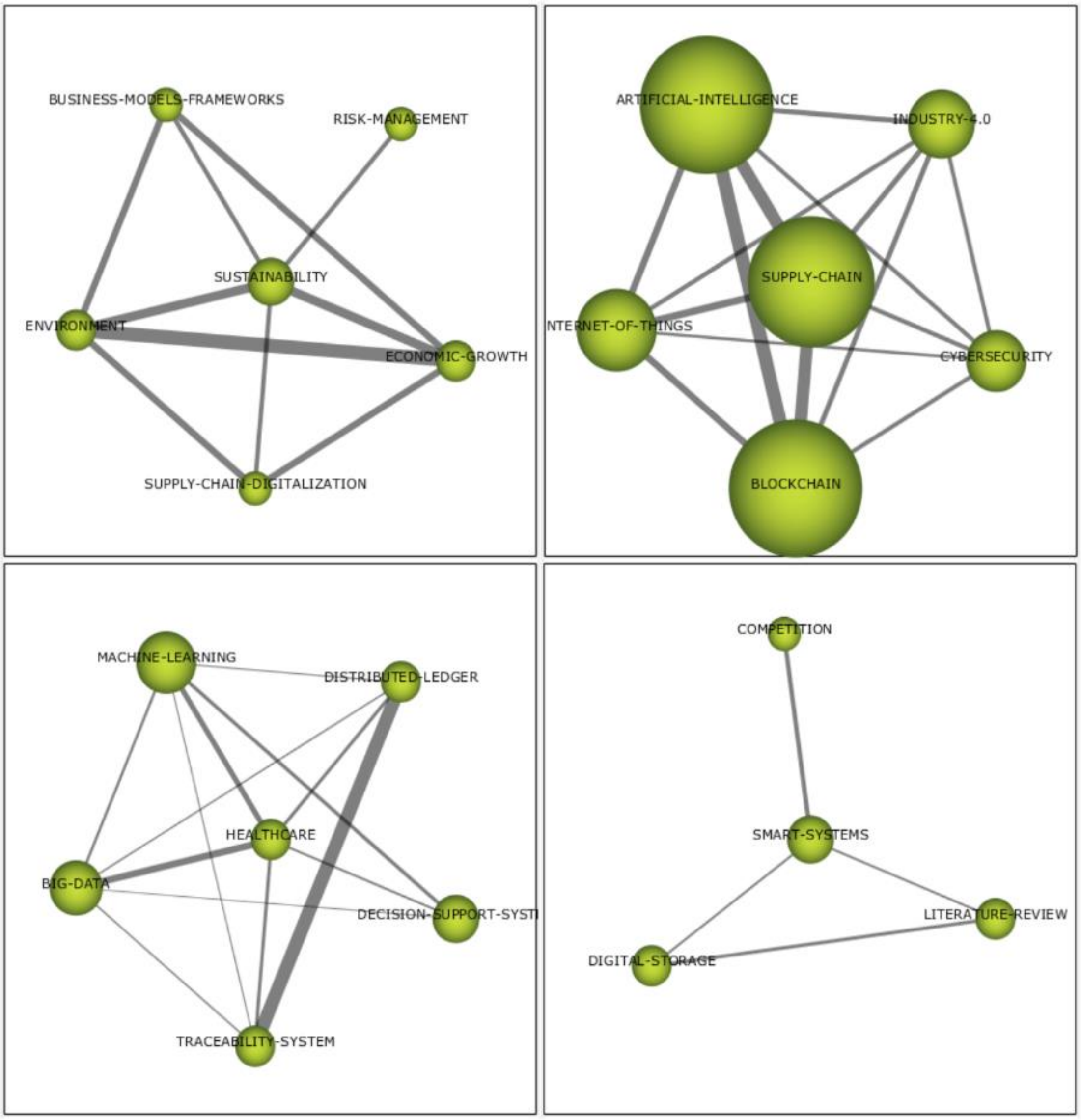


Figure 2.15: Detail relations for themes of Blockchain, AI, and SC in 2024

Sustainability theme demonstrates that, in 2024 literature, it is mostly covering topics of SC such as digitalization, environment, circular economy and growth, and risk management. Here, it can be seen that literature demonstrates Blockchain and AI in SC play transformative role and advance sustainable business models and frameworks (Sánchez-García et al. 2024). SC theme shows the papers strongly investigate Blockchain, AI, IoT, and other industry 4.0 technologies. These sub-themes also have relation with cybersecurity. Healthcare and smart systems have less attention however still in basic themes. All the five sub-themes connected with healthcare demonstrates the relation and support of Blockchain and AI especially investigated in health SC studies (Polshettiwar et al. 2024). Smart systems theme also shows the link of competition and stronger digital storage in SCs when these two technologies are together. Digital storage and smart systems are also drawing attention and investigated in literature review studies (Idrissi et al. 2024).

2.6. Findings and Research Gaps

The aim of this literature review was to identify gaps and research directions for Blockchain-AI-SC literature (RQ2.4). This analysis shows that Blockchain and AI literature in SC are more developed compared to combined literature. The combined literature is in very early stages. There are some emerging topics in both literature, and those still need further investigation and development as research gaps. These gaps (RG) can be summarized as follows.

(RG1) Lack of Success Factors for Blockchain and AI in SC

When the combined literature is examined, majority of the studies are conceptual research studies and explaining the subject or literature reviews (Kumar et al. 2024). Figure 2.5 for Blockchain and Figure 2.9 for AI demonstrates that during the improvement of the areas, critical factors and their assessments come to fore. Examination of critical success factors is an important research area, and should be cautiously determined and examined to improve the success of implementations. Based on authors' information, there are some studies in Blockchain literature (Huang et al. 2022; Pandey et al. 2024) and few for AI (Dora et al. 2022), and they have evaluated these two technologies separately in general.

Not many studies exist that evaluates both of the technologies and their collaboration in SC in terms of success factors.

(RG2) Lack of Risk Factors for Blockchain and AI in SC

Similar gap is here for the risk factors. When Figures 2.4, 2.5, 2.8, and 2.13 are seen, risk management is always among the focus themes and some challenges as SC finance, costs, technology adoption, big data handling, cybersecurity arise. The literature also points those Blockchain and AI challenges (Sodhi et al., 2022). However, a clear research gap can be seen in risk factor evaluation for Blockchain and AI in SCs that would guide SC practitioners and reduce impacts. Based on authors' information, there are several risk factor assessment studies in Blockchain literature (Karaşan et al., 2021) and few for AI (Mishra et al., 2023), but again they are based on one technology separately. Not many studies exist that evaluates both of the technologies and their collaboration in SC in terms of risk factors.

(RG3) Lack of Technology Adoption Analysis for Blockchain and AI in SC

In the analysis, it can be seen that technology adaption theme is also coming to fore at some periods. Technology adoption appears with its own set of challenges in any of technology integration to SCs. For both Blockchain and AI, not all businesses can practice these technologies in their SCs successfully and reap the potential advantages. The CNs and associated DRs for effectively designing and integrating these technologies into SC need to be investigated with systematic approach. While Figures 2.4, 2.5, and 2.8 demonstrates in this focus is emerging, but yet there are not much studies handling the issue effectively with a design methodology. Literature includes some adoption studies (Mishra et al., 2023; Ressi et al., 2024), but they usually investigate drivers, barriers, or effects of these technologies in SCs instead of evaluating CNs and design answers for effective implementation of these technologies.

(RG4) Lack of Handling Multiple Criteria Evaluation Challenges

Based on the analysis results, MCDM studies showed attention of the researchers in both Blockchain-SC and AI-SC studies. They used different methodologies for their evaluation, however there is lack in the combination of these technologies in SC field with MCDM approaches. In addition, as these researches will include different three different fields of expertise, they should involve and combine group decision making techniques in order to minimize expert related bias and to better handle conflicting evaluations and indicators.

(RG5) Lack of Efficient Addressing of User Evaluations and Ambiguity

Analysis on Blockchain-SC and AI-SC studies demonstrated that fuzzy expressions gained increase, however there is a gap for the ambiguity on the processes of decision making which is the support of different expert backgrounds and evaluations. In the process of providing preferences and evaluation especially in Blockchain-AI-SC based decision making problems, experts or experts can be from different profiles. Some can be SC experts, some may have proficiency more on technical side to provide Blockchain and/or AI expertise. As the field combines all three and demonstrates a comprehensive scope, experts can potentially provide ambiguous preferences that is deeply related to their subjectiveness, practice, and understanding. They may not have detailed viewpoints, and they may prioritize diverse or complementary aspects for evaluation and some aspects may be missing. However based on authors' analysis, in the literature for Blockchain-AI-SC, there is no MCDM study that makes this fusion effectively. This throws light on the gap in these literatures.

(RG6) Lack of Practical Applications

Industry 4.0 technologies, Blockchain, and AI is being increasingly used in SC for digitalization, sustainability, and resilience purposes. Here, scientific literature can encourage and leverage more case study researches. Although there are several studies in the literature which provides real applications for the usage of these technologies in SC (Cannas et al. 2024), case studies still inadequate and involves potential to grow especially for the combined usage of these technologies.

2.7. Proposition Based on Findings and Research Gaps

2.7.1. SWOT Based Analysis

All the gaps determined in Section 2.6 based on the literature review and science mapping analysis in Sections 2 and 4, lead the authors to a proposition of a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis which can be a basis of further investigations. This SWOT analysis in Figure 2.16 presents a basis to fill the gaps explained in previous section. In addition, with the light of this analysis, further directions on investigating and evaluating critical success and risk factors for Blockchain and AI integration in SCs, analyzing CNs for Blockchain and AI adoption, evaluating technical DRs for implementation of them can be achieved. The features in SWOT analysis can be listed as follows (Öztürk and Yildizbaşi, 2020; Erol et al. 2021; Dora et al. 2022; Huang et al. 2022; Mishra et al. 2023; Kumar et al. 2023; Kumar et al. 2024; Ressi et al. 2024; Silva et al. 2024).

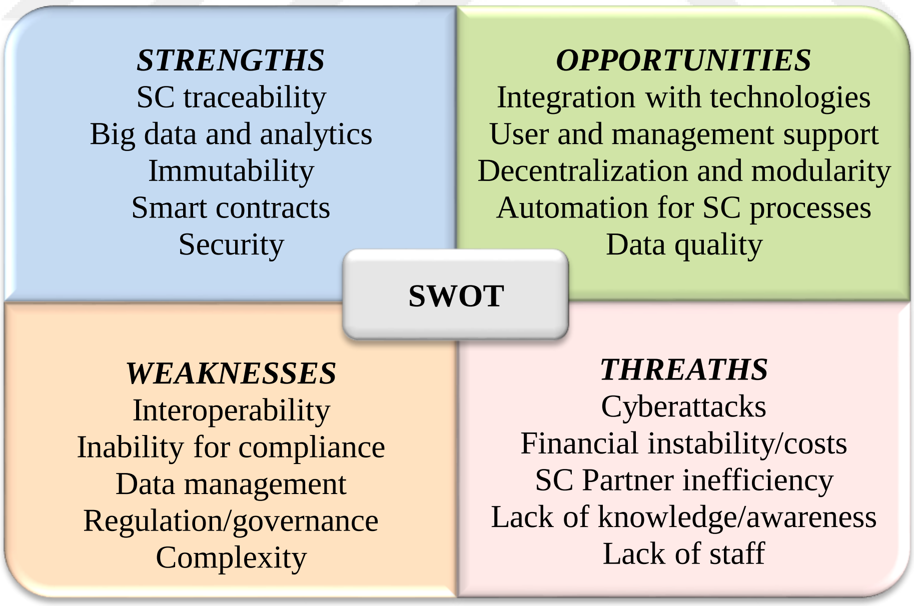


Figure 2.16: SWOT analysis for constructing the basis of Blockchain-AI-SC integration

- Strengths:

Traceability: Enabling transparent real-time tracking of goods, inventory, and shipments.
Security: Ensuring the data safety and preventing data breaches, cyberattacks, counterfeit, anomalies, and other forms of tampering.
Immutability: When data is recorded on the Blockchain, this cannot be changed or removed. It provides tamper-proof transactions across the SC.
Smart contracts: Small codes to automate transactions in Blockchain that also helps to reduce costs and increase efficiency.
Big data and analytics: Analyzing historic data and market trends to accurately forecast demand, enabling effective inventory management and data accuracy for AI insights.

- Weaknesses:

Interoperability: Problems in the capability of different networks and systems to communicate, exchange and leverage data between one another.
Compliance: Inability to replace or comply with the existing technology.
Data management: Deficiency of preventing data manipulation, data leak, data theft and challenges on maintaining data accuracy.
Regulation/governance: Difficulties for managing and implementing changes, lack of regulation and standardization.
Complexity: Difficulty of understanding how these technologies work, complexity of the techniques.

- Opportunities:

Integration: Compatibility and being interoperable within each stakeholder and with other technologies and applications.
User and management support: User intention and acceptance, also leadership readiness and support to embrace novel technologies.
Data quality: Making transactions and data reliable, keeping the data accurate, consistent, and free from human error.
Decentralization: Modular architecture, operational model, and decentralized design.
Automation: Automation of manual processes including AI-ML models.

- Threats:

Cyberattacks: Network and sybil attacks that bypass the Blockchain's security protocols, adversarial attacks that deceives AI systems using manipulated training data.

Financial instability/costs: Blockchain and AI operation costs (such as design, development, migration, maintenance costs), big data integration and scaling costs.

SC partner efficiency: Support, collaboration, and coordination problems among actors.

Lack of knowledge: Deficiency of workforce proficient, expertise, knowledge, and skills in these technologies.

Lack of staff: Deficiency of talented and trained developers, job losses and lack of human interaction as AI automates.

2.7.2. SWOT Based Strategies and Directions

The four SWOT components can be combined to examine four strategic policies that are known as SO, ST, WO, WT strategies which are shown in Figure 2.17.

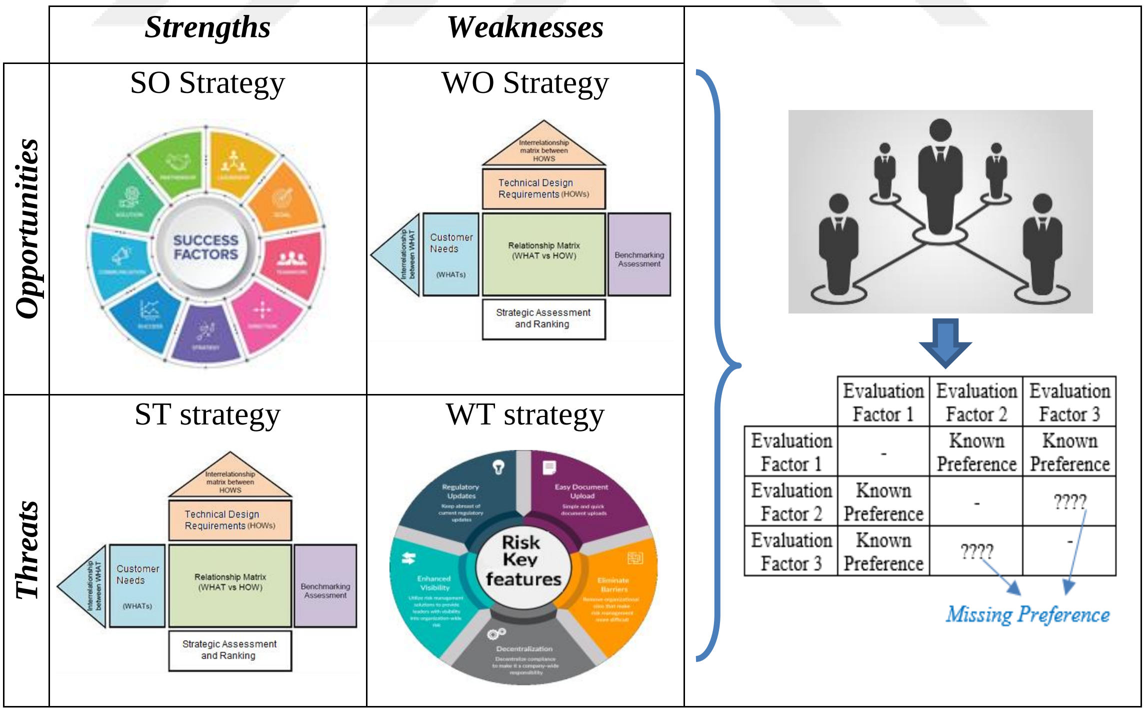


Figure 2.17: SWOT strategies for Blockchain-AI-SC implementation

WT strategy: Considering threats and weaknesses components, defining risk factors for Blockchain-AI in SC and constructing a MCDM framework for those factors can minimize both weaknesses and threats. Such framework can give the most prioritized risk factors and practitioners can focus on those themes for building solutions and preventing risk. This risk factors evaluation process can also be the answer to fill the gap RG1.

SO strategy: Considering strengths and opportunities components, defining critical success factors for Blockchain-AI in SC and constructing a MCDM framework for those factors can maximize both strengths and opportunities. Based on the output of this evaluation process, practitioners can focus on the most advantageous factors and make use of them strategically. This critical success factors evaluation process can also be the answer to fill the gap RG2.

WT and SO strategies involve MCDM process due to success and risk factor evaluations that can fill the gap RG4. Building the frameworks with experts and conducting a case study will also help to fill the gap RG6. In this process, practitioners and researchers should implement group decision making methods which supports the fusion of different preferences or the handling of missing preferences. Here, fuzzy approaches especially with incomplete preferences can deal with the missing evaluations of experts or experts in this process, and can be the answer to fill the gap RG5.

WO strategy: Considering weaknesses and opportunities components, how to minimize weaknesses and maximize opportunities can be solved via the integration of Blockchain and AI itself. The external opportunities or the opportunity that a technology causes can support other technology’s weakness.

ST strategy: Considering strengths and threats components, how to maximize strengths and minimize threats can be solved again via the integration itself. The strength of one technology’s attribute can minimize the effect of an external threat or a threat that a technology causes.

For the WO and ST strategies, this implementation or technology adoption of Blockchain and AI should be evaluated with a strategic design approach which effectively evaluates CNs and responding DRs. These CNs and DRs can be evaluated by a QFD methodology, which can also be the answer to fill the gap RG3. Building the QFD frameworks with experts and conducting a case study will again help to fill the gap RG6. The solution to fill the gap RG5 can be performed also here to handle the ambiguity and missing preferences of experts while building and evaluating the QFD model.

By considering various academic studies together for Blockchain-based SCs in recent literature, this section concluded research gaps to guide future research. Based on this literature review, strategy outputs, and as well as author's experience, future research directions should involve the studies on how to utilize Blockchains in SC to obtain competitive advantage. The results shows that literature specifies various advantages as being capable of eliminating intermediaries, improving automation and decision making, having operational efficiency, being more transparent and traceable. However, it also specifies risks as cost, adoption problems, security attacks, and inadequate industrial practice. Therefore, implementation in SCs involves both success and risk factors, and requires a comprehensive guide for practitioners, which will be handled in Chapter 4. Despite several studies that attempted to propose exploratory models or designs, gaining a clear strategic vision of these technologies is not easy, and results again shows that there are inadequate number of studies for this. Hence, Chapter 5 will intend to assess CNs and DRs that can lead to efficient technology integration into SCs.

3. PROPOSED ANALYTICAL APPROACHES

In order to make the most of Blockchain and AI technologies in SCs, it is crucial to carefully assess their fundamental components. Therefore, before developing frameworks of this dissertation, the literature and explanation of used techniques are given.

3.1. IIFP

The approach proposed by Ureña et al. (2015) aims to handle uncertainty and inconsistency in decision making processes by considering both confidence and consistency levels of decision-makers' preferences. In this approach, IIFP relations are used to represent experts' preferences, where each expert provides their preferences in the form of intuitionistic fuzzy sets. These preference relations capture not only the preference but also the non-preference and hesitation levels of experts towards alternatives. By leveraging intuitionistic fuzzy sets, this approach enables experts to express their preferences in a more nuanced manner, considering both known and unknown (incomplete, missing) evaluations as well as the uncertainty associated with their choices.

The core concept of the approach lies in the integration of confidence and consistency levels into the process of aggregating individual preferences into a coherent group preference. The confidence level reflects the trustworthiness or reliability of a expert's preferences, indicating the degree of certainty associated with their assessments. On the other hand, the consistency level measures the level of agreement or alignment among decision-makers' preferences, highlighting the harmony or discordance in their viewpoints.

By considering these two critical dimensions—confidence and consistency—the proposed method by Ureña et al. seeks to enhance the robustness and quality of group decision-making outcomes. The inclusion of confidence levels helps in weighing the impact of individual preferences based on the reliability of decision-makers, while the consistency analysis aids in identifying areas of agreement or divergence among the group members. This dual-focus approach enables a more nuanced and comprehensive evaluation of group preferences, leading to more informed and reliable decision outcomes.

In the broader context of research on IIFPs, the field has seen significant advancements in recent years. Scholars have explored various methodologies and algorithms to handle incomplete and uncertain preference information in decision making processes (Ye and Ye, 2014; Liu and Xu, 2017). Researchers have proposed methods for GDM, multi-attribute decision analysis, and consensus reaching with IIFPs, aiming to improve the efficiency and accuracy of decision making in complex and uncertain environments, and some of these literature can be seen shown in Table 3.1. It shows that literature utilizes from IIFPs, and combines them with other approaches that involves MCDM methods or optimization models. This study also combined IIFPs with two approaches: ANP and HoQ, which do not exist and novel in literature.

3.2. IIFP extended ANP

ANP is an MCDM tool and is the generalized form of Analytic hierarchy process (AHP) (Saaty, 1996), another popular MCDM method. In AHP, relationships between evaluation factors are required and there is a hierarchical structure. It only considers the interrelationships between decision levels without considering the interdependencies within the elements. Due to this hierarchical structure, AHP does not provide the opportunity to examine interdependent relationships within factors. Decision-making trial and evaluation laboratory (DEMATEL) is also used for multi-criteria evaluations, however, it only considers the interdependencies within the clusters without capturing the interrelationships between clusters (Orji et al., 2020).

Table 3.1: Literature for IIFP studies

Reference	**Object**	**Application**	**Methodology**
Wang and Li (2016)	To propose a quadratic-program-based framework for GDM	Numerical example	IIFP, Programming Model
Chen and Xu (2019)	To present an approach to GDM problems with IIFPs	Numerical example	IIFP
Wang et al. (2019b)	To develop a decision making method where information is incomplete	Numerical example	IIFP, VIšeKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)
Zhang et al. (2020)	To present optimization models for estimating missing values by maximizing consistency level	Numerical example	IIFP, Programming Model
Zhang et al. (2022)	To improve the efficiency of decision making by proposing 2 stage approach	Numerical example	IIFP, Programming Model, Knowledge-unit based case-based reasoning (KU-CBR)
Zhang and Pedrycz (2022)	To form a GDM method based on the consistency and consensus analysis	Numerical example	Interval valued IIFP, Programming Model
Lu et al. (2023)	To form a GDM method based on the consistency and consensus analysis	Numerical example	IIFP, Programming Model
Zhang et al. (2023)	To form a GDM method based on the consistency and consensus analysis	Numerical example	Interval valued IIFP, Programming Model
Gong et at. (2024)	To establish a consensus model by constructing dynamic trust networks to address large scale GDM problem	Numerical Example	IIFP, Social Network Analysis

The main motivation that ANP method is chosen for this study is that it more capable of capturing and modelling the interrelationships among clusters and the elements within clusters than these mentioned methods. In ANP, each decision network includes clusters, their elements and the relationships between them (Gao et al., 2023). For this reason, ANP is seen as a very powerful method in decision making in dynamic environments and is used as a common tool in decision making problems in the field of SC (Büyüközkan and Çifçi, 2012; Orji et al., 2020).

Evaluation and prioritization of success and risk factors for Blockchain and AI in SC is a strategic and multi-criteria task that involves conflicting preferences. Therefore, this process require the support of MCDM models. As a matter of fact, MCDM studies are increasing in number in the Blockchain and AI literature which are shown in Table 3.2. There have also been studies that applied the ANP method, since success and risk factors are not fully independent from each other and can interact. Evaluation frameworks working with these factors therefore must be able to handle such mutual interactions. These interactions can come from both within the elements of a cluster and between clusters (Orji et al., 2020). The studies in Table 3.2 all demonstrate that this tool can effectively handle relations and dependencies between evaluated factors.

3.3. IIFP extended HoQ

HoQ is commonly used for technology selection, quality improvement, risk assessment, and design parameter evaluation (Çevik Onar et al., 2016; Mottaeva and Borisova, 2019; Pandey, 2020). Its key advantages include time savings, customer-centric focus, reduced design changes, prioritization of multiple design parameters, and assistance in the benchmarking process (Pandey, 2020).

The conventional HoQ architecture requires numerous individuals to express their personal preferences on a specific subject. During this process, decision-makers are likely to have diverse and subjective opinions based on their experiences. The use of terms such as “good”, “fair”, and “perfect” is common in evaluations. To account for the opinions of various evaluators and linguistic variables, the assessment should be conducted in an ambiguous environment. To achieve this objective, a GDM framework is suggested as an alternative to create a neutral environment for decision-making. This extension highlights the significant advantages of HoQ.

Table 3.2: Literature for ANP based Blockchain and AI studies

Reference	**Object**	**Area**	**Methodology**
Orji et al. (2020)	To propose a framework for critical success factors affecting Blockchain adoption	Freight logistics	ANP
Shardeo et al. (2020)	To analyze critical success factors for Blockchain adoption	Freight logistics	Fuzzy ANP and modified Total Interpretive Structural Modeling (mTISM)
Yadav and Singh (2021)	To validate the implementation of Blockchain technology over traditional methods	SC	Fuzzy ISM, Fuzzy ANP
Zarour et al. (2020)	To evaluate the effect of Blockchain for security of records	E-healthcare	Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and fuzzy ANP
Liu et al. (2021)	To select alternatives for green Blockchain investments	Renewable Energy	Fuzzy DEMATEL-ANP, VIKOR
Ozdemir et al. (2021)	To examine the role of Blockchain to reduce the effect of barriers	Humanitarian SC	Intuitionistic fuzzy (IF)-DEMATEL and IF-ANP
Raval et al. (2022)	To evaluate key performance indicators for Blockchain	Infrastructure Projects	ANP
Gao et al. (2023)	To propose a strategic analysis for Blockchain internal and external factors	Construction Industry	ANP and SWOT analysis
Wang et at. (2023)	To investigate the role and function of AI tools	Construction Industry	Fuzzy Delphi-ANP-TOPSIS

GDM is a method of selecting from multiple alternatives, which involves a group of decision makers. The complexity of GDM problems has led to a greater focus on resolving ambiguities and reducing uncertainties in recent decades. Previously, fuzzy approaches have been proposed to address the vagueness of customers' desires in decision-making. Intuitionistic fuzzy preference relations offer a flexible and straightforward way for decision-makers to express their preferences for a range of alternative options while also allowing for the expression of degrees of uncertainty and hesitancy in the decision-making process, as seen in the work of Büyüközkan and Güleryüz (2016).

Compared to the use of fuzzy preference relations, the application of intuitionistic fuzzy preference relations in decision-making is relatively restricted. This is because of the computational complexity involved in utilizing membership, non-membership, and hesitation degrees to model decision-makers' subjective preferences. Despite this, intuitionistic fuzzy preferences are becoming increasingly popular due to their ability to handle uncertainty or vagueness. In fact, several studies have applied intuitionistic fuzzy preferences, as shown in Table 3.3.

Intuitionistic preference relations are commonly employed in decision-making processes in practical settings, as they assist users in overcoming uncertain situations. However, in real-world applications, these relations can be limited due to the constraints of expert knowledge and experience. Consequently, numerous studies have been conducted to address incomplete fuzzy relations, and this research utilizes IIFPs to handle missing information in the HoQ.

There is currently no research that seeks to combine the HoQ method and IIFPs, as per the available literature. The HoQ approach primarily focuses on transforming customers' preferences into DRs, with linguistic relationships playing a vital role in the process. Incorporating IIFPs would enhance the HoQ method's ability to reflect opinions more accurately during the design phase. Given that Blockchain and AI are still emerging technologies, experts' knowledge and experience in these fields are limited compared to more established technologies. Consequently, using IIFPs in this area can also help address the issue of incomplete information that experts may provide.

Table 3.3: Literature review on papers applying intuitionistic HoQ

Author	**Integrated Method**	**Topic**	**Application**	**Area**
Aikhuele and Turran (2016)	TOPSIS	Failure detection	Illustrative example	Product component
Wang (2016)	Analytical network process and data envelopment analysis	Innovative design evaluation	Empirical example	Green fuel battery
Van et al. (2018)	Neutrosophic Sets and TOPSIS	Green supplier evaluation	Case Study	Transportation Parts
Yu et al. (2018)	Choquet integral	Product design	Illustrative example	Steering wheel for electric vehicles
Efe (2019)	Cognitive map (CM) and VIKOR	Product selection	Case Study	Dishwasher machine
Deveci et al. (2019)	Principal Component Analysis	Evaluation of service quality	Case Study	Public bus transportation
Liu et al. (2019)	VIKOR	Sustainable supplier selection	Case Study	NEV battery
Chunhua et al. (2020)	AHP	Product design	Illustrative example	CNC design

3.4. Proposed Methodologies and Computational Steps

3.4.1. Preliminaries of IIFP

Definition 1. An intuitionistic fuzzy set X over a universe of F is given by (Atanassov, 1986):

$$\mathrm{X} = \{x, \langle \mu_x(x), v_x(x) \rangle; x \in F\} \tag{3.4.1}$$

where $\mu_{\mathrm{x}}: F \to [0,1]$, and $v_{\mathrm{x}}: F \to [0,1]$ verify

$$0 \leq \mu_x(x) + v_x(x) \leq 1 \ \forall \mathrm{x} \in \mathrm{F}. \tag{3.4.2}$$

Here, $\mu_x(x)$ and $v_x(x)$ indicate the membership and non-membership degrees of x to X. An intuitionistic fuzzy set transforms to a fuzzy set when $\mu_x(x) = 1 - v_x(x) \ \forall x \in F$. However, when at least a value of $x \in F$ exists such that $\mu_x(x) < 1 - v_x(x)$, an additional parameter needs to be taken into consideration to work with intuitionistic fuzzy sets: the hesitancy degree,

$$\tau_x(x) = 1 - \mu_x(x) - v_x(x), \tag{3.4.3}$$

indicating the amount of lacking information to determine the membership of x to X.

Definition 2. For two intuitionistic fuzzy sets X and Y with $X > 0,\ Y > 0$ and $\lambda > 0$, a number of arithmetic operations are specified as (Xu and Yager 2006):

$$X + Y = \left(\mu_x(x) + \mu_y(x) - \mu_x(x)\mu_y(x),\ v_x(x)v_y(x)\right) \tag{3.4.4}$$

$$X \times Y = \left(\mu_x(x)\mu_y(x),\ v_x(x) + v_y(x) - \ v_x(x)v_y(x)\right) \tag{3.4.5}$$

$$\lambda X = \left(1 - \left(1 - \mu_x(x)\right)^{\lambda},\ \upsilon_x(x)^{\lambda}\right). \quad (3.4.6)$$

Definition 3. An intuitionistic fuzzy preference relation can be represented by a matrix $\mathrm{R} = \left(r_{\mathrm{ij}}\right)$ with $r_{\mathrm{ij}} = \left(\mu_{\mathrm{ij}}, \upsilon_{\mathrm{ij}}\right)\ \forall \mathrm{i}, \mathrm{j} = 1,2, \dots, \mathrm{n}$. Note that when the hesitancy function is equal to null function, we have (Szmidt and Kacprzyk, 2002):

$$\mu_{\mathrm{ij}} + \upsilon_{\mathrm{ij}} = 1\ \forall i, j, \quad (3.4.7)$$

and thereby, intuitionistic fuzzy preference relation $\mathrm{R} = \left(r_{\mathrm{ij}}\right)$ is mathematically equivalent to the fuzzy preference relation. An intuitionistic fuzzy preference is specified as reciprocal when the two following terms are applied: $\mu_{\mathrm{ii}} = \upsilon_{\mathrm{ii}} = 0.5\ \forall \mathrm{i} \in \{1, \dots, n\}$, $\mu_{\mathrm{ji}} = \upsilon_{\mathrm{ij}}\ \forall \mathrm{i}, \mathrm{j} \in \{1, \dots, n\}$.

3.4.2. Steps for IIFP extended ANP

The first proposed evaluation approach of the study includes five steps which can be seen in Figure 3.1. To give a brief explanation, Step 1 includes the formation of criteria framework and relations within factors. Then Step 2 is the place where expert preferences are gathered and factor comparison starts, and Step 3 has the completion and computation of evaluations. Lastly Step 4 and 5 involve the attainment of the priorities for the evaluated factors. The details for computational steps of the proposed approach (Figure 3.1) can be given as follows.

Step 1: First step is to define the evaluation criteria and represent them as a network with relationships. These relationships can be determined based on influence of one node of the network to the other.

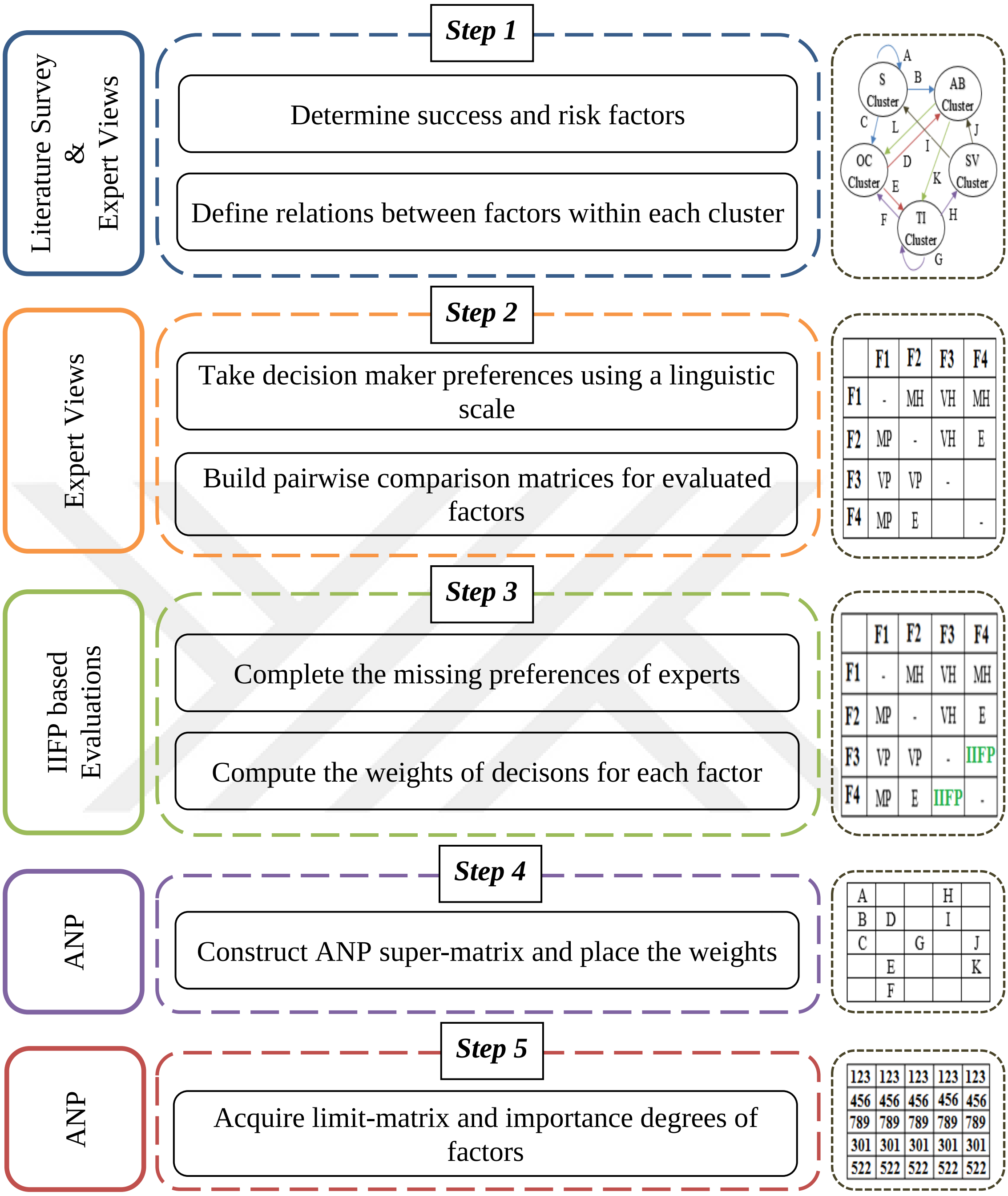


Figure 3.1: Steps of the proposed IIFP-ANP evaluation approach

Step 2: In this step, experts establish the relations among the evaluation factors. They construct comparison matrices (pairwise) regarding influence and direction within necessary factors by forming a $n \times n$ matrix R, in which r_{ij} is represented as the degree of factor i affects factor j.

For this, a scale of comparison values, as given in Table 3.4, helps experts to form the relationship matrices. This scale serves to represent the comparative strength for each pair of elements:

$$R = \begin{bmatrix} r_{\mathrm{ij}} & \cdots & r_{\mathrm{in}} \\ \vdots & \ddots & \vdots \\ r_{\mathrm{nj}} & \cdots & r_{\mathrm{nn}} \end{bmatrix} \tag{3.4.8}$$

where $r_{\mathrm{ij}} = (\mu_{\mathrm{ij}}, v_{\mathrm{ij}})\ \forall \mathrm{i}, \mathrm{j} = 1,2, \ldots, \mathrm{n}$ ferlects the relation among factors.

Table 3.4: Corresponding linguistic terms for evaluation

Linguistic term	Abbreviation	Intuitionistic Fuzzy Preferences
Extremely Poor	EP	(0, 0.99)
Very Poor	VP	(0.10, 0.85)
Fairly Poor	FP	(0.20, 0.70)
Poor	P	(0.30, 0.60)
Medium Poor	MP	(0.40, 0.55)
Equal	E	(0.50, 0.50)
Medium High	MH	(0.55, 0.40)
High	H	(0.60, 0.30)
Fairly High	FH	(0.70, 0.20)
Very High	VH	(0.85, 0.10)
Extremely High	EH	(0.99, 0)

Step 3: Here, the relationships given by experts are calculated. The comparative weights regarding importance are measured by following IIFP steps (Ureña et al., 2015).

Step 3.1: This step calculates the ungiven values in the assessment matrices given by experts. Here, the goal is to maximize or at least maintain the experts' global consistencies when estimating their preferences which are lacking. This is modelled and calculated by Tanino's (Tanino, 1984) "multiplicative transitivity" term. Here, the prediction process can be simplified by considering membership values $r_{ij} = (\mu_{ij}, v_{ij})$ as $r_{ij} = (\mu_{ij})$, a subvariety of reciprocal IF preferences (RIFPs). A known RIFP relation can help as an intermediary value, and estimation on an unknown (incomplete) preference can be computed:

$$A_{ij}^{y} = \{y \neq i, j | (i, y), (y, j) \in EV\} \tag{3.4.9}$$

where EV is the pairs of elements for which the expert provides evaluation preferences. The evaluation value $r_{ij}(i \neq j)$, that is lacking as $er_{ij}(i \neq j)$ can be estimated by an equation which is based on multiplicative transitivity feature with using an intermediate value

$$er_{ij}^{y} = \begin{cases} 0, & (r_{iy}, r_{yj}) \in \{(0,1), (1,0)\} \\ \dfrac{r_{iy} . r_{yj}}{r_{iy} . r_{yj} + (1 - r_{iy}) . (1 - r_{yj})}, & \text{Otherwise.} \end{cases} \tag{3.4.10}$$

$$er_{ij} = \frac{\sum_{y=1}^{s} er_{ij}^{y}}{s} \tag{3.4.11}$$

where s reflects the amount of computed intermediary values.

Step 3.2: It calculates the consistency of evaluations. The consistency level of a RIFP is computed as:

$$C_{ij} = 1 - d(r_{ij}, mr_{ij}) \; \forall \mathrm{i} \neq \mathrm{j} \tag{3.4.12}$$

where $d(r_{\mathrm{ij}}, mr_{\mathrm{ij}})$ indicates the distance between multiplicative consistent preference value mr_{ij} and the preference value r_{ij}. On the basis of multiplicative transitivity, mr_{ij} can be represented as:

$$mr_{ij}^{y} = \frac{r_{iy} . r_{yj} . r_{ji}}{r_{jy} . r_{yi}} \tag{3.4.13}$$

As the value of C_{ij} increases, the consistency of the preference value r_{ij} also increases. Then Eqs. (3.4.14) and (3.4.15) serve to compute the finalized levels of consistency for RIFP relation matrix R:

$$C_{\mathrm{i}} = \frac{\sum_{j=1}^{n} C_{\mathrm{ij}}}{\mathrm{n} - 1} \tag{3.4.14}$$

$$C^{R} = \frac{\sum_{i=1}^{n} C_{\mathrm{i}}}{\mathrm{n}} \tag{3.4.15}$$

where $i \neq j$. When $C < 0.5$, then it means the evaluations of experts which are formed in Step 2 are inconsistent. These evaluation preferences should be updated and recalculated until they are found as consistent.

Step 3.3: Here, experts' confidence degrees are calculated. Given a RIFP relation, to determine the confidence degrees of expert preferences, the hesitancy degrees are used:

$$CF_{\mathrm{ij}} = 1 - \tau_{\mathrm{ij}} \tag{3.4.16}$$

with τ_{ij} as it is related to r_{ij} (i ≠ j). Then with Eqs. (3.4.17) and (3.4.18), the finalized degrees of confidence for RIFP relation matrix R are computed:

$$CF_{\mathrm{i}} = \frac{\sum_{j=1}^{n} CF_{\mathrm{ij}}}{\mathrm{n}-1} \tag{3.4.17}$$

$$CF^{R} = \frac{\sum_{i=1}^{n} CF_{\mathrm{i}}}{\mathrm{n}} \tag{3.4.18}$$

Step 3.4: The calculation of the confidence-consistency-driven aggregation occurs in this step. The combined evaluation of an expert group is found by unifying their single preferences and applying an appropriate aggregation operator. Several aggregation functions can be seen in the literature as ordered weighting geometric (OWG), ordered weighting averaging (OWA), induced OWA (IOWA), and so which are some common ways to combine inputs. This process is performed with confidence and consistency IOWA (CC-IOWA) operator that makes use of consistency and confidence properties to re-rank the aggregation preferences of experts and generate weights to unite their preferences. The CC-IOWA includes the set of confidence-consistency index value $CC^{R}\ \forall R = 1,2,\dots,\mathrm{k}$ related with the set of k experts, which is calculated as:

$$CC^{R} = (1-\delta).C^{R} + \delta.CF^{R} \tag{3.4.19}$$

where δ is a controlling parameter of the confidence and consistency weights. Then, on the basis of these confidence-consistency index values, the end to end satisfaction of experts are calculated with the weighting vector connected to CC-IOWA operator:

$$w_{h} = Q\left(\frac{\sum_{k=1}^{h} CC^{\sigma(k)}}{\sum_{R=1}^{k} CC^{R}}\right) - Q\left(\frac{\sum_{k=1}^{h-1} CC^{\sigma(k)}}{\sum_{R=1}^{k} CC^{R}}\right) \tag{3.4.20}$$

where $\sigma(k)$ is the gradation of the CC^R values. "Most of", which is a type of the linguistic quantifier, can be used to form the weighting vector with $Q(f) = f^{1/2}$. Then, the RIFP relation $\mathrm{r}_{\mathrm{ij}}^{cc} = \left(\mu_{\mathrm{ij}}^{cc}, v_{\mathrm{ij}}^{cc}\right)$ is as follows:

$$\mu_{\mathrm{ij}}^{cc} = \sum_{h=1}^{k} w_h . \mu_{\mathrm{ij}}^{h} \tag{3.4.21}$$

$$v_{\mathrm{ij}}^{cc} = \sum_{h=1}^{k} w_h . v_{\mathrm{ij}}^{h} \tag{3.4.22}$$

Here while formula (3.4.20) gives the weights of experts, formulas (3.4.21) and (3.4.22) help the aggregation of experts' evaluations.

Step 3.5: In this final part of Step 4, the importance levels based on quantifiers are determined. To evaluate whether a factor is considered the optimal choice by most experts, the IF quantifier guided dominance degree (IFQGDD) can be employed. This measure indicates how much a particular factor dominates the fuzzy majority of other factors and is calculated as follows:

$$IFQGDD_i = \phi_Q(r_{\mathrm{ij}}^{cc}, j = 1, \ldots, n) \tag{3.4.23}$$

using r_{ij}^{cc} to denote the μ_{ij}^{cc} subvariety of RIFPs, while ϕ_Q represents an OWA operator lead with linguistic quantifier "most of". When this degree is normalized, the weights of factors can be calculated through it.

Step 4: Here, the construction of a super-matrix is performed. ANP uses a super-matrix formation to assist in the analysis of the effects of interdependency that exists among clusters in the decision network. This is a partitioned matrix and each of the submatrices within is a composition of relationship among two components in the graphical model.

By placing the weights computed in Step 3 in the necessary columns, preliminary super-matrix can be formed.

Step 5: The super-matrix is solved in the last step of the proposed approach. First, each of the columns can be normalized by dividing each weight in the column by the sum of that column. Next, priorities are found for each factor. In order to calculate the final priority weights of the factors, the normalized super-matrix should be increased to the limiting powers. By this end, the cumulative effect of each factor in the matrix on every other factor it interacts with are reached.

This IIFP extended ANP method is applied in success and risk factor evaluation that is proposed in Section 4. The calculation steps and detailed application can be seen there.

3.4.3. Steps for IIFP extended ANP-HoQ

The second proposed evaluation approach of the study includes eight steps which can be seen in Figure 3.2 in a HoQ structure. In HoQ, DRs are accepted as independent and have no correlation with each other.

Step 1: In the HoQ model, the left-box represents CNs and the upper-box represents DRs, which can be identified through a variety of methods such as literature reviews, questionnaires, or expert opinions. This section of the approach focuses on describing and positioning these CNs, and then identifying DRs with the ultimate goal of transforming CNs into design parameters. The key aspect of this process is to provide clear and direct responses to the identified requirements.

Step 2: In this step, the interrelations are determined between CNs. The procedure used here is the same that is given in section 3.4.2 – step 1.

Step 3: In this step, comparative evaluation matrices for the relevant needs are determined. The computational procedure used here is the same that is given in section 3.4.2 – step 2.

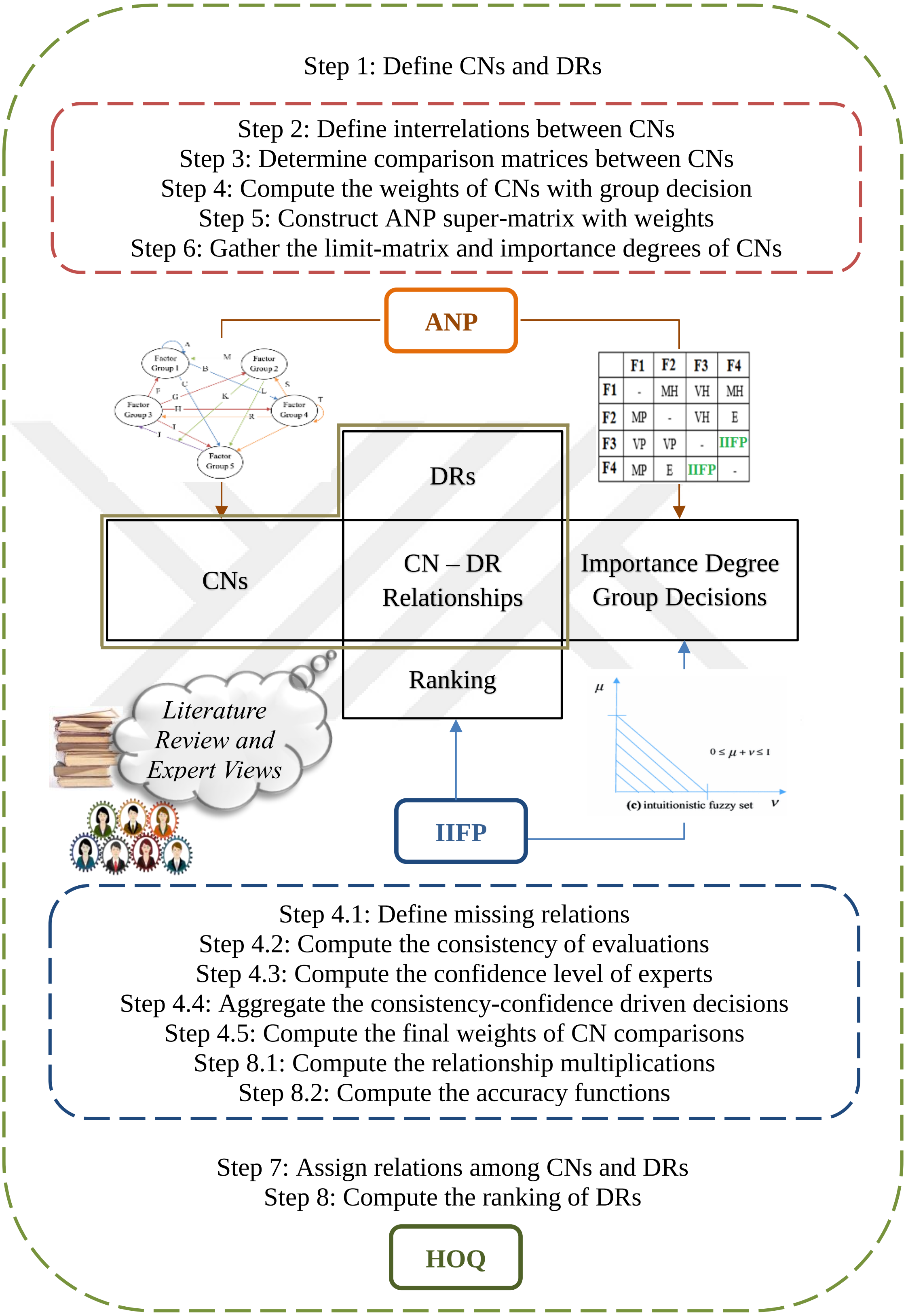


Figure 3.2: Steps of the proposed IIFP-ANP based HoQ evaluation approach

Step 5: This step is the construction of a super-matrix which is given as section 3.4.2 – step 4.

Step 6: This step is for solving the super-matrix and gathering the importance values, which is given as section 3.4.2 – step 5. The calculated importance values $IFQGDD_i$ are placed at the right side of the HoQ matrix.

Step 7: The experts in this part of the process formulate a relationship matrix that incorporates CNs and DRs, based on their expert judgements. By employing the values indicated in Table 3.4, relationships between the DRs and their influence on fulfilling the CNs are assigned as r_{ij}^{rm}. Since the evaluators possess comprehensive technical expertise at this step, there is no need for an incomplete approach in this case.

Step 8: In this final stage, the importance of each DR is calculated and ranked. Initially, the importance rate for each requirement $IFQGDD_i$ is multiplied by the relation matrix values $\mathrm{r}_{\mathrm{ij}}^{rm}$ to achieve the weighted values of DR assessments r_{ij}^{p} using:

$$r_{\mathrm{ij}}^{p} = p_i . r_{\mathrm{ij}}^{rm} = \left(1 - \left(1 - \mu\left(r_{\mathrm{ij}}^{rm}\right)\right)^{p_i}, v\left(r_{\mathrm{ij}}^{rm}\right)^{p_i}\right). \tag{3.4.24}$$

Afterwards, the collected values are added up in their respective columns to determine the total importance value r_{j}^{p} for each design parameter using:

$$r_{\mathrm{j}}^{p} = \sum_{i=1}^{n} r_{\mathrm{ij}}^{p} = \left(\mu_i\left(r_{\mathrm{ij}}^{p}\right) + \mu_n\left(r_{\mathrm{nj}}^{p}\right) - \mu_i\left(r_{\mathrm{ij}}^{p}\right)\mu_n\left(r_{\mathrm{nj}}^{p}\right),\ v_i\left(r_{\mathrm{ij}}^{p}\right) v_n\left(r_{\mathrm{nj}}^{p}\right)\right). \tag{3.4.25}$$

Lastly, the DRs can be ranked according to the score (S) and accuracy (H) formulations (Hong and Choi 2000):

$$S_j = \mu_{\mathrm{j}}^{p} - v_{\mathrm{j}}^{p} \tag{3.4.26}$$

$$H_j = \mu_{\mathrm{j}}^{p} + v_{\mathrm{j}}^{p} \tag{3.4.27}$$

Here, S_j values can be arranged in descending order. In case of a tie among these DR scores, the same process is applied to H_j values. DRs with higher H_j values are are ranked higher. When there is still a tie on top of it, then these DRs are considered equal.

4. SUCCESS AND RISK FACTORS FOR BLOCKCHAIN AND AI IN SC

The main motivation behind examining and prioritizing the success and risk factors of Blockchain and AI applications in SC is bringing practitioners a guidance and roadmap of these technologies in SCs. By doing that, this study intends to create a decision making environment where multiple stakeholders collectively create a feasible, efficient Blockchain and AI based SC environment for practitioners. BC and AI are proven technologies, and there have been Blockchain applications in SCM for some time, and more recently AI applications. However, at the same time, industrial implementations are not easy and there are challenges for successful implementation. Therefore, the aim of this chapter is to identify success and risk factors to provide a roadmap and support to practitioners for successful implementation. The objective of the study for offering a new success and risk evaluation framework is achieved with the ANP method in a fuzzy environment. This is a unique approach to the decision problem. So far, success and risk factors of Blockchain and AI in SC have not been addressed by a combination of ANP and IIFPs. All these motivations defined three interlocking RQs to study:
(RQ4.1): What are the success factors in Blockchain and AI based SCs in order to provide successful performance, and what are their importance degrees?
(RQ4.2): What are the risk factors in Blockchain and AI based SCs in order to provide successful performance, and what are their importance degrees?
(RQ4.3): Is IIFP extended ANP method capable of addressing the first question and provide a flexible environment for decision making?

Theoretical and practical contributions of this section can be summarized as the following: (1) Identifying success and risk factors for Blockchain and AI in SCs, investigating the priorities of these factors, and confirming these models with expert views, (2) Extending the ANP methodology with GDM to form an unbiased evaluation environment, (3) Combining incomplete preferences and intuitionistic fuzzy relations into the ANP method to cope with uncertainty in the linguistic evaluations for the first time, (4) Validating the proposed approach with a case in industry that includes the support of experts who work in industry and academia.

The rest of this chapter continues with Section 4.1, which gives a theoretical background for Blockchain and AI in SC and with literature survey. Then, Section 4.2 reviews the evaluation frameworks. Section 4.3 demonstrates an application of the approach, and Section 4.4 presents its results and discussions.

4.1. Literature of Success and Risk for Blockchain and AI

The introduction of Blockchain and AI into the SC has the potential to revolutionize the way goods and services are tracked and monitored throughout the entire chain from the time of product pickup to the time it reaches the consumers. They have the ability to introduce autonomous and decentralized business models, which improve SCs' adaptability, efficiency, and affordability (Kumar et al., 2023).

These two technologies, when combined and implemented in a SC, can offer a strong foundation for safe communication amongst system users. Each technology benefits from the other (Kumar et al., 2024). Blockchain contributes to AI's increased credibility, integrity, and user trust since its digital record provides information about the AI's foundation and the source of the data it uses. AI models have historically faced the challenge of gathering data, requiring connections to various datasets from various sources. Blockchain technology can assist in resolving this issue by offering a transparent and safe database for information storage, and AI can simulate how the human mind solves problems. AI provides the necessary intelligence to Blockchain as it can read, comprehend, and correlate data at incredible speed, thoroughly and rapidly. An audit trail may be produced by storing and distributing AI models on Blockchain, and combining Blockchain and AI can improve data security (Sodhi et al., 2022). AI models integrated into smart contracts on a Blockchain system may select the most environmentally friendly shipping option, execute transactions as stock purchases, payments, and reorders depending on predetermined criteria and events, and recommend expired products to return. When you combine AI and Blockchain technologies, decentralized AI apps and algorithms are created with access to an identical vision of a reliable and shared data platform for storing records, knowledge, and decisions. When accurate records of every AI algorithm before are maintained, during and after the process of learning and making decisions, this platform can be quite helpful (Ressi et al., 2024).

Blockchain and AI based systems are multi-process and multi-agent complex structures. Besides the potential benefits, this implies that it may also contain some risk factors that can damage or threaten the SC, and its actors. These can be, for example, cyberattacks, adoption problems, costs, and scalability problems, beside others (Karaşan et al., 2021). A careful examination of such success and risk factors in advance is therefore a must when considering a Blockchain and AI based application. As Table 4.1 shows, there are some publications in the literature dealing with this examination.

There is extensive research on the critical factors which investigated risk (challenge, barrier) or success (benefit, trend) points in Blockchain and AI. However, our review here suggests that only a few of them examined the SC area and analyzed the factors with computational approach. On Blockchain side, Hastig and Sodhi (2019) investigated business requirements and critical success factors of Blockchain for SC traceability. They conducted a thematic analysis about what different stakeholders involved in a SC need. Lohmer et al. (2020) also analyzed the factors for the resilience of Blockchain-coordinated SCs. They developed certain potential risk scenarios for Blockchain implementation and examined with the help of an agent-based simulation model how the SC resilience strategies respond to changes. Orji et al. (2020) evaluated critical parameters that affects Blockchain applications in the freight logistics industry. They proposed a theoretical concept consisting of critical factors affecting the successful adoption of Blockchain technology and prioritize them using ANP method with views based on technology, environment and organization. Shoaib et al. (2020) proposed a framework to evaluate Blockchain-based SC success factors. They identified 11 categories for success factors and evaluated them with AHP. Budak and Çoban (2021) aimed to reveal causality among factors to assess the impact of Blockchain on the SC using three CM methodologies: hesitant fuzzy CM, probabilistic linguistic fuzzy CM, and rough set CM. Huang et al. (2022) investigated critical success factors for Blockchain implementation for circular SC management, and they used a combined method of AHP and DEMATEL.

Table 4.1: Several literature for success or risk factors of Blockchain and AI

Reference	**Object**	**Methodology**
Prasad et al. (2018)	To examine critical success factors for Blockchain-based cloud services	Total interpretive structural modelling (TISM)
Fernando et al. (2019)	To analyze success factors of Blockchain technology in pharmaceutical industry	Literature review
Abdel-Monem et al. (2020)	To evaluate Blockchain risk on enterprise systems	Single valued neutrosophic sets, AHP, DEMATEL
Zhou et al. (2020)	To investigate the key challenges and critical success factors of Blockchain in maritime industry	AHP , PESTEL analysis
Erol et al. (2021)	To examine critical success factors for the performance of a Blockchain-based solar photovoltaic energy ecosystem	IF-DEMATEL
Karaşan et al. (2021)	To propose Blockchain risk framework	Hesitant Z-Fuzzy DEMATEL, CM
Ngyen et al. (2021)	To identify risks for Blockchain enable container shipping	Directed acyclic graph network analysis
Habbal et al. (2024)	To examine AI challenges and applications for risk and security management	Trust, Risk and Security Management (TRiSM) framework
Kaladharan et al. (2024)	To examine the barriers to implement Blockchain enabled drug recycling	TSIM, Cross-Impact Matrix Multiplication Applied to Classification (MICMAC)
Ressi et al. (2024)	To review opportunities and advancements of AI enhanced Blockchain	Literature review

Table 4.1: Several literature for success or risk factors of Blockchain and AI (continued)

Reference	**Object**	**Methodology**
Ressi et al. (2024)	To review opportunities and advancements of AI enhanced Blockchain	Literature review
Singh and Kumar (2024)	To integrate Blockchain success factors in the SC of circular economy-driven construction materials	PESTEL, Fuzzy DEMATEL
Sruthy (2024)	To understand challenges faced by Indian SC executives on AI-driven solutions adoption for resilience	ANOVA, t-tests
Younis et al. (2024)	To highlight the complexities and opportunities involved in adopting Blockchain in SC	Literature review

On AI side, Dora et al. (2022) studied on critical success factors for AI adoption in food SCs and they used Step-Wise-Assessment and Ratio-Analysis (SWARA) methodology to analyse these factors. Mishra et al. (2023) investigated the challenges in AI adoption in Agri-Food SC during COVID-19, and Kumar et al. (2023) examined critical success factors for managing healthcare SC with AI used the same SWARA approach. Literature shows that there are not enough research to guide SC practitioners for both the successful implementation and risks of Blockchain and AI as a hybrid investigation. Only Sodhi et al. (2022) analyzed how professionals perceive technology (Blockchain, AI, and IoT) in SCs, and performed a affordance theory to investigate the importance values of their criteria for adoption. For gaining a more comprehensive knowledge of the concept, it is crucial to assess the factors utilizing an analytical tool. Here, IIFP extended ANP based approach is seen as a working, powerful methodology to define and evaluate the possible options according to the literature, and its computational steps have already been explained in Section 3.4.1.

4.2. Identification of Success and Risk Factors

A comprehensive literature review is carried out to determine the decision parameters used in various frameworks which is Step 1. The data collection methodology in this paper is based on search with well-defined keywords (Wang et al., 2020) in articles related to Blockchain, AI, and SCs. The following keywords are searched within abstracts: Factors, Aspects, Elements, Enablers, Barriers, Risks, Challenges, Benefits, and Drivers. Following the examination of the publications, the most analyzed success and risk factors in the literature are determined. Then, an expert group (Expert group 1 – explained in Section 4.3) consisting of SC and IT professionals is consulted to investigate how the sector perceives the Blockchain and AI in SC and progress on it. Details of the expert group are provided in Section 4.3, where the application is described. The checklist questions for developing and finalizing the frameworks are given in Table 4.2.

Table 4.2: Checklist for development of the frameworks

Checklist	**Result**
Are the research keywords for success and risk factors adequate?	Justified by expert group and authors.
Are there any reported risk factors for Blockchain or AI or Blockchain based SC or AI based SC?	Justified by the literature review in Section 4.1.
Are there any reported success factors for Blockchain or AI or Blockchain based SC or AI based SC?	Justified by the literature review in Section 4.1.
Are the gathered data associated with Blockchain and AI in SC and are they relevant?	Justified by the literature review, expert group, and authors.

Obtaining the experts' feedback and validation contributed to the structure of the frameworks and helped clarify the success and risk factors to be evaluated. Many meetings are held until the proposed frameworks became mature (i.e. all experts agreed that no further additions are needed). The risk factors are given in Table 4.3, and the success factors of are given in Table 4.4.

Table 4.3: Blockchain and AI risk factors in SCs

Clusters	Factors	Details	References
Shortcomings	Lack of infrastructure	Deficiency of necessary software, equipment, and tools in these technologies	Abdel-Monem et al. (2020), Karaşan et al. (2021), Mishra et al (2023), Painuly et al. (2023)
	Lack of knowledge and skills	Deficiency of workforce proficient, expertise, knowledge, and skills in this technology	Abdel-Monem et al. (2020), Ahl et al. (2020), Budak and Çoban (2021), Sodhi et al. (2022), Velev and Zlateva (2023)
	Lack of staff	Deficiency of talented and trained developers, job losses and lack of human interaction as AI automates	Ahl et al. (2020), Budak and Çoban (2021), Karaşan et al. (2021), Shatat and Shatat (2022), Mishra et al (2023), Velev and Zlateva (2023)
	Lack of management support	Deficiency of top management contribution, lack of manager capabilities to identify the impacts	Abdel-Monem et al. (2020), Budak and Çoban (2021), Karaşan et al. (2021), Kouhizadeh et al. (2021), Fosso Wamba et al. (2022), Sodhi et al. (2022)
	Lack of customer awareness	Deficiency of understanding by customers and SC stakeholders	Karaşan et al. (2021), Kouhizadeh et al. (2021), Mishra et al (2023), Sodhi et al. (2022)

Table 4.3: Blockchain and AI risk factors in SCs (continued)

Clusters	Factors	Details	References
Technical and Operational Challenges	Inefficient Data Management	Failure of shared data management and modelling, inefficient deep learning models and collection of inputs, inappropriate (quality & quantity) data sets	Abdel-Monem et al. (2020), Mosakheil (2018), Mishra et al (2023), Shatat and Shatat (2022), Painuly et al. (2023), Kumar et al. (2024)
	Differences in infrastructures among SC actors	Differences and lacking of innovation in infrastructures and techniques among organizations	Karaşan et al. (2021), Ozdemir et al. (2021), Shatat and Shatat (2022), Painuly et al. (2023)
	Enforcing organizational culture	Missing a technological culture and resistance to the organizational change	Moretto and Macchion (2022), Kouhizadeh et al. (2021), Shatat and Shatat (2022), Sodhi et al. (2022)
	Insufficient standards and operating rules	Missing shared vision, standards and procedures in organization and industry	Budak and Çoban (2021), Ozdemir et al. (2021), Moretto and Macchion (2022), Kouhizadeh et al. (2021), Sodhi et al. (2022)
	Response time and efficiency	Network and Inter-node Latency of Blockchain, the amount of waiting time of for the transaction to appear on the Blockchain, lack of AI system that operates quickly and with less effort	Abdel-Monem et al. (2020), Nguyen et al. (2021), Ressi et al. (2024), Mishra et al. (2023), Painuly et al. (2023), Kumar et al. (2024)

Table 4.3: Blockchain and AI risk factors in SCs (continued)

Clusters	**Factors**	**Details**	**References**
Adoption Barriers	User antitrust	Missing trust of users and customers because of benefits being ambiguous	Abdel-Monem et al. (2020), Karaşan et al. (2021), Kouhizadeh et al. (2021), Sodhi et al. (2022)
	Technology complexity	Difficulty of understanding how the technology works, complexity of the techniques	Abdel-Monem et al. (2020), Ozdemir et al. (2021), Moretto and Macchion (2022), Shatat and Shatat (2022), Ressi et al. (2024), Kumar et al. (2024)
	Legal and regulatory risk	Existence of regulations that prevent Blockchain and AI from paving the way	Abdel-Monem et al. (2020), Erol et al. (2021), Karaşan et al. (2021), Prasad et al. (2018), Sodhi et al. (2022), Ressi et al. (2024), Kumar et al. (2024)
	Low technological maturity	A low level of digitalization in SC and immature technology in general to implement Blockchain and AI	Prasad et al. (2018), Erol et al. (2021), Kouhizadeh et al. (2021), Moretto and Macchion (2022), Mishra et al. (2023), Dora et al. (2022), Sodhi et al. (2022)
	Low usability	Low amount of technology usage, need for more insight and industry case	Abdel-Monem et al. (2020), Ozdemir et al. (2021), Fosso Wamba et al. (2022)

Table 4.3: Blockchain and AI risk factors in SCs (continued)

Clusters	**Factors**	**Details**	**References**
Infrastructural Issues	Scale issues	Scalability challenges in Blockchain, requirement of AI on massive amount of existing data	Abdel-Monem et al. (2020), Nguyen et al. (2021), Sodhi et al. (2022), Mishra et al. (2023), Kumar et al. (2024)
	Interoperability deficiencies	Problems in the ability of different networks and systems to communicate, exchange and leverage data between one another	Karaşan et al. (2021), Ozdemir et al. (2021), Shatat and Shatat (2022)
	Inability for technology compliance	Lack of integrated systems, inability to replace or comply with the existing technology	Karaşan et al. (2021), Ozdemir et al. (2021), Shatat and Shatat (2022), Mishra et al. (2023), Sodhi et al. (2022)
	Storage and capacity problems	Lowering throughput and limited transaction capacity	Abdel-Monem et al. (2020), Karaşan et al. (2021), Nguyen et al. (2021), Kumar et al. (2024), Painuly et al. (2023), Ressi et al. (2024)
	Flaws in protocols and design	Malfunctions and faults in the program design, deficiencies in AI models and decisions	Karaşan et al. (2021), Mosakheil (2018), Shatat and Shatat (2022)

Table 4.3: Blockchain and AI risk factors in SCs (continued)

Clusters	**Factors**	**Details**	**References**
Security and Privacy	Data safety	Data leak and deficiency of preventing data manipulation, Data theft and challenges on maintaining data accuracy	Abdel-Monem et al. (2020), Nguyen et al. (2021), Shatat and Shatat (2022), Painuly et al. (2023), Mishra et al. (2023), Habbal et al. (2024)
	Cyberattacks	Network and Sybil attacks that bypass the Blockchain's security protocols, Adversarial Attacks utilizing manipulated training data to deceive AI systems	Abdel-Monem et al. (2020), Karaşan et al. (2021), Mosakheil (2018), Nguyen et al. (2021), Habbal et al. (2024), Kumar et al. (2024)
	Verification vulnerabilities	Blockchain consensus and transaction verification challenges between all the participants, AI potential for wrong decisions, perpetuate biases and unfairness	Mosakheil (2018), Nguyen et al. (2021), Mishra et al. (2023), Velev and Zlateva (2023)
	System threats	Threats on the smart contract scripts, exploiting vulnerabilities in AI systems	Mosakheil (2018), Nguyen et al. (2021), Habbal et al. (2024)
	Privacy	Authentication-authorization problems on protecting identities and private keys, mistreatment of weak authentication, encryption, and access control in AI	Abdel-Monem et al. (2020), Karaşan et al. (2021), Nguyen et al. (2021), Shatat and Shatat (2022), Painuly et al. (2023), Habbal et al. (2024), Ressi et al. (2024)

Table 4.3: Blockchain and AI risk factors in SCs (continued)

Clusters	Factors	Details	References
SC Stability	Customer dissatisfaction	Failure of meeting CNs at the right amount at the right time, delayed supplies	Budak and Çoban (2021), Karaşan et al. (2021), Painuly et al. (2023)
	Contract /partner inefficiency	Support and coordination problems among actors	Kouhizadeh et al. (2021), Ozdemir et al. (2021), Moretto and Macchion (2022), Shatat and Shatat (2022)
	Governance difficulties	Difficulties for managing and implementing changes, lack of standardization	Karaşan et al. (2021), Nguyen et al. (2021), Mishra et al. (2023), Shatat and Shatat (2022)
	Inefficient processes through the chain	Effort-consuming processes, lack of automation	Budak and Çoban (2021), Ozdemir et al. (2021), Painuly et al. (2023)
	Financial instability and costs	Weakness due to Blockchain & AI operation costs (such as design, development, migration, maintenance costs), big data integration and scaling costs	Abdel-Monem et al. (2020), Karaşan et al. (2021), Moretto and Macchion (2022), Mishra et al. (2023), Velev and Zlateva (2023), Ressi et al. (2024), Kumar et al. (2024)

Table 4.4: Blockchain and AI success factors in SCs

Clusters	**Factors**	**Details**	**References**
Technical Skills	Enhanced scalability and latency	A higher transaction processing speed and performance, having scale-out capabilities	Ar et al. (2020), Erol et al. (2021), Ozdemir et al. (2021), Kumar et al. (2023), Pang et al. (2024)
	Integration with other tech. and apps	Compatibility and being interoperable within each stakeholder and with other applications	Prasad et al. (2018), Ar et al. (2020), Erol et al. (2021), Dora et al. (2022), Kumar et al. (2023), Pang et al. (2024)
	Improved security and privacy	Becoming more aware of cyber-threats, reducing counterfeit, limiting privacy, ensuring user control and data safety	Ar et al. (2020), Shoaib et al. (2020), Ozdemir et al. (2021), Moretto and Macchion (2022), Dora et al. (2022), Kumar et al. (2023), Kumar et al. (2024)
	Better architecture and design	Having a modular architecture, operational model, and design of SC technology based on AI and Blockchain	Lohmer et al. (2020), Huang et al. (2022), Painuly et al. (2023)
	Better throughput and storage	Having capacity on demand and a good rate of valid transactions	Prasad et al. (2018), Erol et al. (2021), Mishra et al. (2023), Kumar et al. (2024)

Table 4.4: Blockchain and AI success factors in SCs (continued)

Clusters	Factors	Details	References
Digital Trust	Transparency	Making data visible to stakeholders	Shoaib et al. (2020), Ozdemir et al. (2021), Yousefi and Tosarkani (2022), Painuly et al. (2023), Kumar et al. (2024)
	Traceability	Better trackability of transactions	Erol et al. (2021), Ozdemir et al. (2021), Painuly et al. (2023), Pang et al. (2024)
	IT resilience and robustness	Having the capability to resist or even avoid the impact of disruptions, and the flexibility to quickly recover	Lohmer et al. (2020), Erol et al. (2021), Yousefi and Tosarkani (2022), Painuly et al. (2023)
	User desirability and acceptance	Stakeholder intention and pressure, acceptance, and loyalty for adaption and usage of Blockchain and AI	Erol et al. (2021), Ozdemir et al. (2021), Kumar et al. (2023), Dora et al. (2022)
	Audit / accountability	Accountability of what is reported by different actors, providing data towards customers and legal institutions, change management initiatives	Ozdemir et al. (2021), Moretto and Macchion (2022), Yousefi and Tosarkani (2022), Dora et al. (2022), Fosso Wamba et al. (2022)

Table 4.4: Blockchain and AI success factors in SCs (continued)

Clusters	**Factors**	**Details**	**References**
Organizational Readiness	Top management commitment	Leadership readiness and support to embrace a novel technology	Prasad et al. (2018), Zhou et al. (2020), Erol et al. (2021), Dora et al. (2022), Kumar et al. (2023)
	Staff training and consultation	Sufficient knowledge and expertise of human resources about Blockchain and AI	Prasad et al. (2018), Zhou et al. (2020), Erol et al. (2021), Dora et al. (2022), Kumar et al. (2023)
	Transformed technology culture	Technological readiness, and ability to adopt a novel technology by the organization	Orji et al. (2020), Huang et al. (2022), Dora et al. (2022), Kumar et al. (2023)
	Sufficient financial capital	Financial readiness for the costs of Blockchain and AI implementation and maintenance	Orji et al. (2020), Zhou et al. (2020), Kumar et al. (2023), Pang et al. (2024)
	Trust and vision	Visibility and trust among the actors in a reliable way, a clear link between strategy and vision, alignment between business goals	Ar et al. (2020), Orji et al. (2020), Moretto and Macchion (2022), Dora et al. (2022), Kumar et al. (2023), Kumar et al. (2024)

Table 4.4: Blockchain and AI success factors in SCs (continued)

Clusters	Factors	Details	References
Operational Effectiveness	Reduce intermediaries and human labour	Disintermediation in the SC network, reduction of human tasks and errors	Erol et al. (2021), Ozdemir et al. (2021), Moretto and Macchion (2022), Fosso Wamba et al. (2022)
	Reduced operational cost	Reduction of the costs of operations	Moretto and Macchion (2022), Yousefi and Tosarkani (2022), Fosso Wamba et al. (2022), Kumar et al. (2024)
	Resource efficiency and sharing	Efficient use of resources, optimization, reducing waste in the system	Prasad et al. (2018), Shoaib et al. (2020), Erol et al. (2021), Fosso Wamba et al. (2022), Kumar et al. (2024)
	Legal regulations and compliance	The existence of new regulations, government support and incentive programs for Blockchain and AI based SCs	Prasad et al. (2018), Zhou et al. (2020), Erol et al. (2021), Dora et al. (2022), Pang et al. (2024)
	Support for SC Automation and Smart Contracts	Automation of manual processes including transactions with smart contracts and AI-ML models	Ozdemir et al. (2021), Moretto and Macchion (2022), Yousefi and Tosarkani (2022), Shatat and Shatat (2022), Fosso Wamba et al. (2022), Kumar et al. (2024)

Table 4.4: Blockchain and AI success factors in SCs (continued)

Clusters	Factors	Details	References
Data Efficiency	Accuracy	Keeping the data accurate and free from human error, more accurate production policies in SC	Yadav and Singh (2020), Fosso Wamba et al. (2022), Painuly et al. (2023)
	Consistency/ Immutability	Guaranteeing the immutability of the data, having the same data by all the nodes at the same time	Prasad et al. (2018), Erol et al. (2021), Ozdemir et al. (2021), Yousefi and Tosarkani (2022), Ressi et al. (2024)
	Provenance of data	Assuring the history, authenticity, and ownership of products, advancing from historical data in AI operations	Yousefi and Tosarkani (2022), Painuly et al. (2023)
	Integrity	Trustworthy internal processes and data that include relationships with other communication service providers and suppliers	Shoaib et al. (2020), Yousefi and Tosarkani (2022), Kumar et al. (2023), Pang et al. (2024)
	Reliability	All the transactions records and data flow information are authenticated and protected	Shoaib et al. (2020), Yadav and Singh (2020), Kumar et al. (2023), Kumar et al. (2024)

Table 4.4: Blockchain and AI success factors in SCs (continued)

Clusters	Factors	Details	References
SC Performance	Efficient partner collaboration and coordination	Collaboration, communication, and information sharing between SC actors for increased SC performance	Prasad et al. (2018), Erol et al. (2021), Huang et al. (2022), Dora et al. (2022), Fosso Wamba et al. (2022), Kumar et al. (2023), Pang et al. (2024)
	Availability and Responsiveness	Keeping transactions and data available all the time even after crashing of any node or quit of the node, downtime minimization	Shoaib et al. (2020), Yadav and Singh (2020), Moretto and Macchion (2022), Fosso Wamba et al. (2022)
	Efficient Inventory and Order Management	Facilitating management throughout SCs by recording orders, improving order-picking, and making information available to the stockholders	Shoaib et al. (2020), Yadav and Singh (2020), Yousefi and Tosarkani (2022), Fosso Wamba et al. (2022)
	Quality and Customer Satisfaction	Making the businesses easier and taking necessary steps for the smooth flow of high-quality products, customer centricity and customization	Shoaib et al. (2020), Yadav and Singh (2020), Yousefi and Tosarkani (2022), Dora et al. (2022), Sodhi et al. (2022)
	Enhanced/ effective logistics capabilities	Business and logistics efficiency (e.g., reduction of logistics risks, reduction of and bureaucracy and insurance costs)	Lohmer et al. (2020), Moretto and Macchion (2022), Painuly et al. (2023)

4.3. Application of the Proposed IIFP extended ANP Approach

As Wang (2019a) noted, it is not necessary for all experts to be Blockchain specialists given the progressive state of technologies. However, they must be able to comprehend the technological aspects and relate its use in SCs. Similar issue is also valid for AI. To ensure a comprehensive evaluation, a decision maker group consisting of ten experts is formed, all of which are highly specialized in SC and Information Technology (IT) who emphasize digital and sustainable improvements in the field. This group consists of three logistics professionals, three specialists who give consulting service and/or are technology service providers, and four researchers who has academic experience, conducting industrial studies and applications, and/or also contributors to associations. Additionally, they possess AI and/or Blockchain expertise and understand their application in SC. All have some level of familiarity with these technologies, i.e. an understanding of their use in SC practices and the dimensions to correlate their use in SCs. The experts are therefore able to understand the technological dimensions and can relate the use of Blockchain and AI in SCs. Moreover, one of the experts is a Blockchain technical expert at The Scientific and Technological Research Council of Turkey (TUBITAK).

The application in this chapter has two main parts and two sub-groups of the experts accordingly. The first part involves determining the Blockchain and AI success and risk factor frameworks which are given in Section 4.2, with the help of expert group-1 (all ten experts). The second part entail decision making and computational implementation of the recommended Blockchain and AI success and risk models which are given in Section 4.3, with expert group-2 (consists of five individuals from group-1 who possess the most knowledge, expertise, and experience in Blockchain and AI technologies). This focus group helped for more effective evaluations due to their deeper knowledge on the technologies. In expert group 2, Expert-1 and Expert-2 are academicians and at the same time consultants with at least eighteen years of work experience in logistics and SC. Expert-3 is a manager from a logistics company with more than twelve years of experience. Expert-4 is a technology service provider, has its own technology that is suggested to the logistics companies in the sector, working for almost ten years. Expert-

5 is founder of an R&D company who has IT background, has realized many projects on digital transformation in the logistics and SC sector, with fifteen years of experience. Each expert is treated based on weightings explained in 3.4.2, step 3.4, also considering the confidence and consistency of their linguistic evaluations.

Step 1. Success and risk factors are described in Section 4.2. The relations are established between elements, as shown in Figure 4.1. Each relation is represented with a capital letter.

Step 2. Here, experts construct sets of the pairwise comparisons based on direction and influence within necessary factors. Here, numerical calculation steps are exemplified only for risk factors of Blockchain. For success factor evaluations, the computational processes are done by following the same steps. In addition, all these same steps are conducted for AI success and risk factor evaluations in the similar way. Table 4.5 presents a sample evaluation of Expert-1 with the goal of measuring the weights in relation C which is between S and TO. If we consider both S and TO clusters have 5 factors, this sample will show the evaluation of all the TO factors according to first S1 factor. There is no relationship between TO3 and the remaining factors according to Expert-1.

Table 4.5: Incomplete evaluation of Expert-1 for relation S1 – TO

	Linguistic Assessment				IIFPs			
S1	TO1	TO2	TO4	TO5	TO1	TO2	TO4	TO5
TO1	-	H	H	E	-	(0.60,0.30)	(0.60,0.30)	(0.50,0.50)
TO2	P	-	E	E	(0.30,0.60)	-	(0.50,0.50)	(0.50,0.50)
TO4	P	E	-	**?**	(0.30,0.60)	(0.50,0.50)	-	**?**
TO5	E	E	**?**	-	(0.50,0.50)	(0.50,0.50)	**?**	-

Step 3.1. To describe these steps in detail, the calculations of Expert-1 are illustrated. The ungiven values in Table 4.5 are computed via an intermediate preference value. The estimated values are given in Table 4.6.

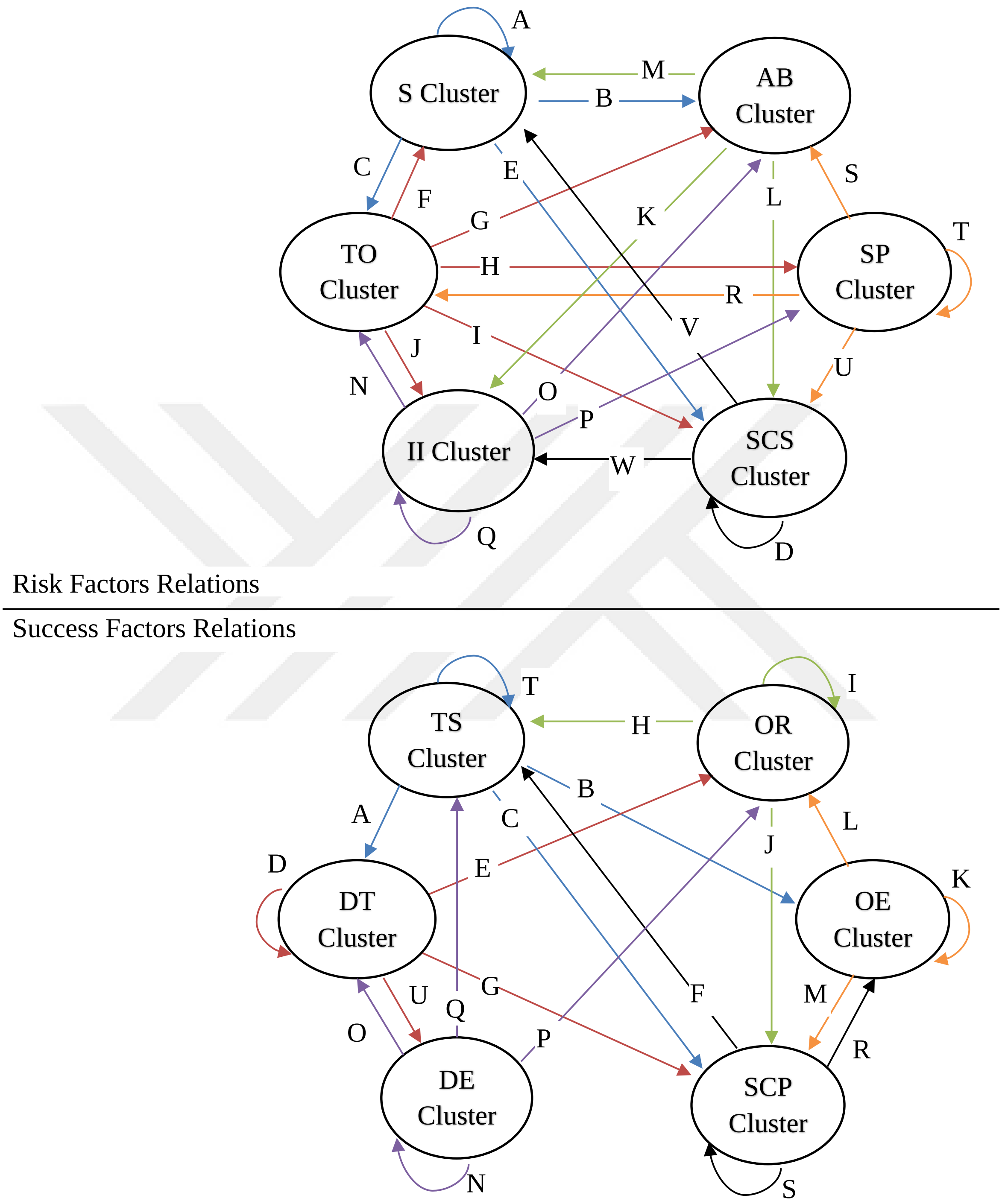


Figure 4.1: Relations within success and risk frameworks for Blockchain

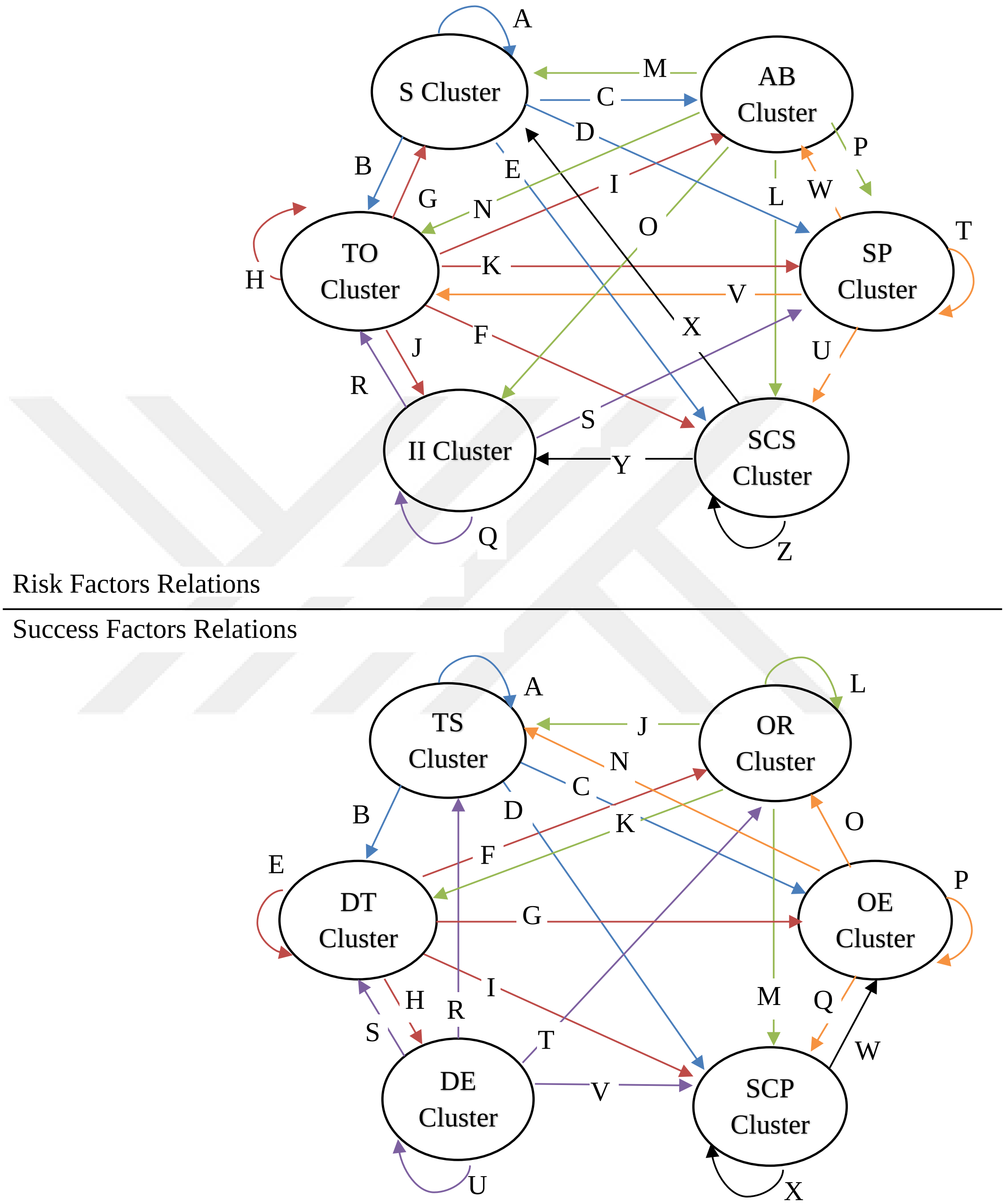


Figure 4.2: Relations within success and risk frameworks for AI

Table 4.6: Complete evaluation of Expert-1 for relation S1 – TO

S1	TO1	TO2	TO4	TO5
TO1	-	(0.60,0.30)	(0.60,0.30)	(0.50,0.50)
TO2	(0.30,0.60)	-	(0.50,0.50)	(0.50,0.50)
TO4	(0.30,0.60)	(0.50,0.50)	-	(0.40,0.55)
TO5	(0.50,0.50)	(0.50,0.50)	(0.55,0.40)	-

$er_{34}^{1} = \frac{r_{31}.r_{14}}{r_{31}.r_{14}+(1-r_{31}).(1-r_{14})} = \frac{0.30\times0.50}{0.30\times0.50+(1-0.30)\times(1-0.50)} = 0.30$ and

$er_{34}^{2} = \frac{r_{32}.r_{24}}{r_{32}.r_{24}+(1-r_{32}).(1-r_{24})} = 0.50$, therefore $er_{34} = \frac{0.30+0.50}{2} = 0.40$.

$er_{43}^{1} = \frac{r_{41}.r_{13}}{r_{41}.r_{13}+(1-r_{41}).(1-r_{13})} = 0.60$ and $er_{43}^{2} = \frac{r_{32}.r_{24}}{r_{32}.r_{24}+(1-r_{32}).(1-r_{24})} = 0.50$,

therefore, $er_{34} = 0.55$.

Step 3.2. Consistency level is calculated and shown in Table 4.7. The consistency for Expert-1 is finalized as $C^1 = \sum_{i=1}^{n} C_{\mathrm{i}} / n = 0.85$ from the average of Ci values in Table 9, which is bigger than 0.50 (i.e. consistent). The consistencies of remaining expert evaluation matrices are calculated as $C^2 = 0.98$, $C^3 = 0.84$, $C^4 = 0.86$, $C^5 = 0.88$.

Table 4.7: Levels of consistency of Expert-1 for relation S1 – TO

S1	TO1	TO2	TO4	TO5
TO1	-	0.85	0.91	0.64
TO2	0.85	-	0.91	0.81
TO4	0.93	0.93	-	0.99
TO5	0.80	0.66	0.95	-
Ci	0.80	0.86	0.95	0.80

Step 3.3. Here, the confidence degrees of experts are calculated. The confidence degrees for Expert-1 is shown in Table 4.8. For instance, $CF_{12} = 1 - \tau_{12} = 1 - 0.10 = 0.90$. Expert 1's confidence degree is found as $CF^1 = \sum_{i=1}^{n} CF_{\mathrm{i}} / n = 0.96$ from Table 8. The remaining degrees are $CF^2 = 0.96$, $CF^3 = 0.86$, $CF^4 = 0.90$, $CF^5 = 0.89$.

Table 4.8: Degrees of confidence of Expert-1 for relation S1 – TO

S1	TO1	TO2	TO4	TO5
TO1	-	0.90	0.90	1.00
TO2	0.90	-	1.00	1.00
TO4	0.90	1.00	-	0.95
TO5	1.00	1.00	0.95	-
CF_i	0.93	0.97	0.95	0.98

Step 3.4. In order to compute the consistency-confidence guided aggregation, δ is accepted as 0.3 as per the recommendation of the experts. This choice was made because the expert group wanted most of the weight to be placed on consistency rather than trust. The set of consistency/confidence index values CC^R are computed as $CC^1 = (1 - 0.3) \times 0.85 + 0.3 \times 0.96 = 0.88, CC^2 = 0.97, CC^3 = 0.85, CC^4 = 0.87, CC^5 = 0.88.$ To evaluate the overall satisfaction of experts, the weighting vector associated to the CC-IOWA operator is found as $w_1 = 0.18, w_2 = 0.47, w_3 = 0.10, w_4 = 0.12, w_5 = 0.13.$ Afterwards, the evaluation matrices of experts are aggregated. The group importance relation matrix obtained is given in Table 4.9.

Table 4.9: Aggregated evaluation of experts for relation S1 – TO

S1	TO1	TO2	TO4	TO5
TO1	-	(0.29,0.68)	(0.23,0.70)	(0.28,0.68)
TO2	(0.68,0.29)	-	(0.56,0.38)	(0.63,0.33)
TO4	(0.70,0.23)	(0.38,0.56)	-	(0.52,0.42)
TO5	(0.68,0.28)	(0.33,0.63)	(0.42,0.52)	-

Step 3.5. The quantifier-guided importance degrees are calculated in this step. For exploitation, the weighting vector (0.58, 0.24, 0.18) is used, corresponding to the quantifier "at most". These values indicate the dominance that one element has over the "most'' elements, according to "most'' of the experts. Group aggregated importance degrees are then calculated based on Table 8 as $IFQGDD_{TO1} = 0.274, IFQGDD_{TO2} = 0.649, IFQGDD_{TO4} = 0.598, IFQGDD_{TO5} = 0.555$. Finally, the normalized weights are found as $W_{TO1} = 0.13, W_{TO2} = 0.31, W_{TO4} = 0.29, W_{TO5} = 0.27$.

Step 4: A super matrix is constructed at this step as presented in Table 4.10. The weights found in Step 3.5 is placed in the first column of relation C, which is shown in detail in Table 4.11. All the weights found are put like that in the necessary columns in the success and risk super-matrices. These four computational steps explained are performed also for the same success and risk factors for the evaluation on AI point of view (computation example is not given to avoıd repetition of same procedures). Super matrix formation and detail view for AI are also given in Tables 4.12 and 4.13.

Table 4.10: ANP super matrix formations of success and risk factors for Blockchain

Risk Clusters

	S	*TO*	*AB*	*II*	*SP*	*SCS*
S	**A**	**F**	**M**			**V**
TO	**C**			**N**	**R**	
AB	**B**	**G**		**O**	**S**	
II		**J**	**K**	**Q**		**W**
SP		**H**		**P**	**T**	
SCS	**E**	**I**	**L**		**U**	**D**

Success Clusters

	TS	*DT*	*OR*	*OE*	*DE*	*SCP*
TS	**T**		**H**		**Q**	**F**
DT	**A**	**D**			**O**	
OR		**E**	**I**	**L**	**P**	
OE	**B**			**K**		**R**
DE		**U**			**N**	
SCP	**C**	**G**	**J**	**M**		**S**

Step 5: In this last step, the super matrices in Step 4 is solved by raising the super matrix to limit matrix. The importance values of each factor that are found from limit-matrix calculation can be seen from Tables 4.14 and 4.15.

Table 4.11: Detailed view of super matrix values for Blockchain risk relation C

	S	*TO*	…	…
S	**A**	**F**	…	…
TO	**C**			
AB	**B**			
…				
…				

C	*S1*	*S2*	*S3*	*S4*	*S5*
TO1	**0.13**				
TO2	**0.31**				
TO3	**0**				
TO4	**0.29**				
TO5	**0.27**				

According to the evaluations on Blockchain point of view, while top five risk factors are found as SCS5: Financial instability for expected costs, SCS2: Contract and partner inefficiency, S3: Lack of experienced staff, II2: Interoperability deficiencies, and II3: Inability to comply with existing technology, top five success factors are found as OR1: Top management commitment, TS3: Improved security and privacy, SCP2: Availability and Responsiveness, OR3: Transformed organizational culture, and OR4: Sufficient financial capital.

Table 4.12: ANP super matrix formations of success and risk factors for AI

Risk Clusters

	S	*TO*	*AB*	*II*	*SP*	*SCS*
S	**A**	**G**	**M**			**X**
TO	**B**	**H**	**N**	**R**	**V**	
AB	**C**	**I**			**W**	
II		**J**	**O**	**Q**		**Y**
SP	**D**	**K**	**P**	**S**	**T**	
SCS	**E**	**F**	**L**		**U**	**Z**

Success Clusters

	TS	*DT*	*OR*	*OE*	*DE*	*SCP*
TS	**A**		**J**	**N**	**R**	
DT	**B**	**E**	**K**		**S**	
OR		**F**	**L**	**O**	**T**	
OE	**C**	**G**		**P**		**W**
DE		**H**			**U**	
SCP	**D**	**I**	**M**	**Q**	**V**	**X**

Table 4.13: Detailed view of super matrix values for AI risk relation B

	S	*TO*	…	…
S	**A**	**G**	…	…
TO	**B**			
AB	**C**			
…				
…				

B	*S1*	*S2*	*S3*	*S4*	*S5*
TO1	**0.38**				
TO2	**0**				
TO3	**0.23**				
TO4	**0.15**				
TO5	**0.24**				

On AI point of view, results are also given similarly in Tables 4.14 and 4.15. According to the evaluations, while top five AI risk factors are found as SCS5: Financial instability and costs, TO1: Inefficient data management, SP2: Cyberattacks, S3: Lack of experienced staff, and SP1: Data safety, top five AI success factors are found as OR3: Transformed technology culture, TS3: Improved security and privacy, OE4: Legal regulations and compliance, TS2: Integration with other tech. and apps, and DT4: User desirability and acceptance.

4.4. Results and Discussions

4.4.1. Results on Risk Factors

The evaluation of risk factors framework addresses the RQ4.1. Based on the risk factor evaluations, the global values of cluster evaluations are shown in Figure 4.3. While inner circle shows the cluster weights of Blockchain, outer circle shows the weights for AI. As the focus is on SC area, the most critical risk cluster is found as the stability of SC in both technologies. However, when the factors within the clusters are examined, it is seen that many technical and operational factors also come to the fore.

Table 4.14: Application results for risk factors

Cluster		**Risk Factors**	**Blockchain**	**AI**
S	S1	Lack of infrastructure	0.0280	0.0184
	S2	Lack of knowledge and skills	0.0207	0.0193
	S3	Lack of staff	**0.0811**	**0.0556**
	S4	Lack of management support	0.0316	0.0397
	S5	Lack of customer awareness	0.0289	0.0436
TO	TO1	Inefficient Data Management	0.0095	**0.0876**
	TO2	Different infrastructures of SC actors	0.0410	0.0222
	TO3	Enforcing organizational culture	0.0117	0.0147
	TO4	Insufficient standards and operating rules	0.0164	0.0185
	TO5	Response time and efficiency	0.0173	0.0279
AB	AB1	User antitrust	0.0359	0.0494
	AB2	Technology complexity	0.0094	0.0073
	AB3	Legal and regulatory risk	0.0167	0.0406
	AB4	Low technological maturity	0.0552	0.0253
	AB5	Low usability	0.0257	0.0458
II	II1	Scale issues	0.0127	0.0182
	II2	Interoperability deficiencies	**0.0752**	0.0450
	II3	Inability for technology compliance	**0.0667**	0.0406
	II4	Storage and transaction capacity problems	0.0025	0.0050
	II5	Flaws in protocols and program design	0.0074	0.0158
SP	SP1	Data safety	0.0039	**0.0523**
	SP2	Cyberattacks	0.0049	**0.0568**
	SP3	Verification vulnerabilities	0.0056	0.0104
	SP4	System threats	0.0361	0.0018
	SP5	Privacy	0.0130	0.0135
SCS	SCS1	Customer dissatisfaction	0.0655	0.0333
	SCS2	Contract and partner inefficiency	**0.0905**	0.0451
	SCS3	Governance difficulties	0.0649	0.0338
	SCS4	Inefficient processes through the chain	0.0281	0.0231
	SCS5	Financial instability for expected costs	**0.0942**	**0.0894**

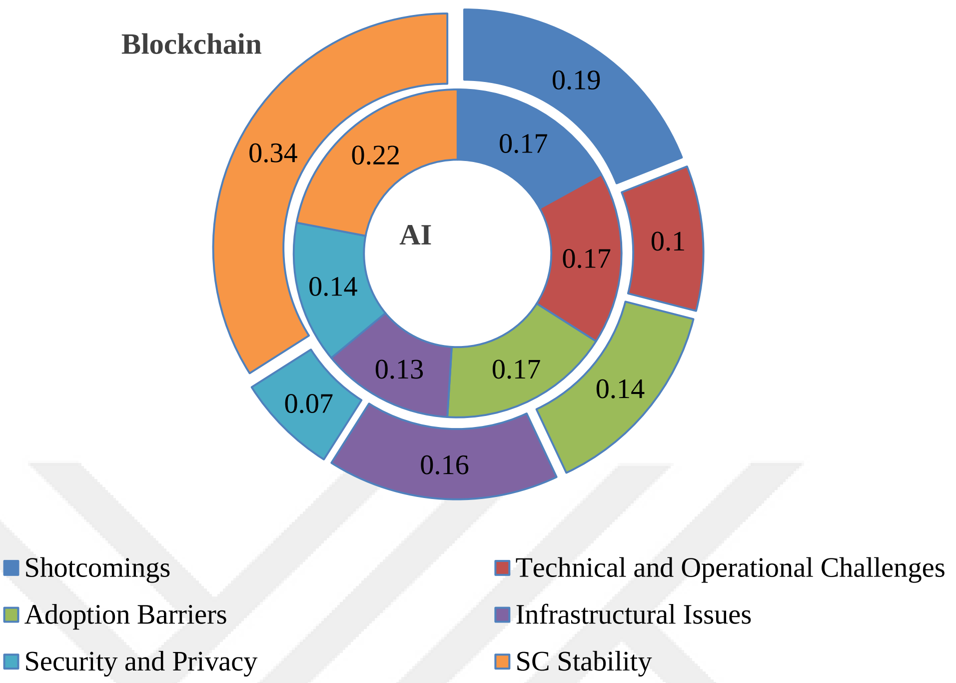


Figure 4.3: Evaluation of risk factor clusters

The findings in Blockchain show similarities to the literature when top five risk factors are examined. In their evaluation model, Karaşan et al. (2021) found interoperability with systems and compatibility with existing technology as two of their top risk factors. Trained staff to Blockchain technology, and good proficiency of developers in this technology are indicated as critical factors by Ahl. et al (2020) and Budak and Çoban (2021). Therefore, a lack of talented staff is one of the critical risks and a major barrier for Blockchain technology implementation in SCs. Another important risk is the cost and financial instability. Blockchain operation costs for the design, development, deployment, migration, maintenance, and other elements must be taken into account in the decision (Abdel-Monem et al., 2020, Moretto and Macchion, 2022, Ressi et al., 2024).

According to Moretto and Macchion (2022), to use the Blockchain, it is necessary to have strong collaboration among the SC partners. The actual level of collaboration in the SC can be weak, though, as also highlighted by the experts. This may create support and coordination inefficiencies with partners, presenting another risk factor standing before the adoption of such technologies in the SC.

The findings in AI also show similarities to the literature when top five success factors are examined. Financial instability and lack of staff factors come to fore in AI also as in Blockchain risk. These two factors can be counted in the implementation of any technology that will be integrated in SC system. Mishra et al. (2023) and Sodhi et al. (2022) both found cost as the top factor in their challenge assessments. The types of costs they investigate includes big data, cost of technical setup, training, and support. In a similar evaluation point of view, Sodhi et al. (2022) and Habbal et al. (2024) listed lacking of experienced staff in their top five risk factors in AI implementation and adoption.

The rest of the risk factors imply that, as AI is heavily rely on huge amount of data, collection of appropriate inputs and safety and maintenance of the data are two crucial implementation issues for AI (Mishra et al., 2023). Attacks are also seen as important security concern and stays in front in the risk factors in many researches (Sodhi et al., 2022; Habbal et al., 2024). According to Ressi et. al. (2024), even though with a sufficient amount of data, the performance of AI can quickly decline if the input's nature changes or new detection challenges arise. For instance, if the programming language used is updated or a new type of attack or vulnerability emerges, a new model must be trained from scratch. However, this process can be lengthy and may require multiple retraining, especially in the early stages when there is limited data available for the model to learn from.

4.4.2. Results on Success Factors

The evaluation of success factors framework presents also the answer for RQ4.2. Risk factors must be considered together with success factors for a more complete understanding. Based on the success factor evaluations, the global values of cluster evaluations are shown in Figure 4.4. Here, the emphasis is more on the organizational readiness cluster considering the successful adoption of Blockchain and AI technologies in SC. However, other technical and operational factors also emerge similar to the case with the risk factors.

Table 4.15: Application results for success factors

Cluster		**Success Factors**	**Blockchain**	**AI**
TS	TS1	Enhanced scalability and latency	0.0237	0.0112
	TS2	Integration with other tech. and apps	0.0343	**0.0574**
	TS3	Improved security and privacy	**0.0850**	**0.0755**
	TS4	Better architecture and design	0.0309	0.0163
	TS5	Better transaction throughput and storage	0.0194	0.0092
DT	DT1	Transparency	0.0025	0.0020
	DT2	Traceability	0.0092	0.0114
	DT3	IT resilience and robustness	0.0508	0.0562
	DT4	User desirability and acceptance	0.0095	**0.0565**
	DT5	Audit / accountability	0.0293	0.0304
OR	OR1	Top management commitment	**0.1068**	0.0545
	OR2	Staff training and consultation	0.0600	0.0478
	OR3	Transformed technology culture	**0.0741**	**0.0832**
	OR4	Sufficient financial capital	**0.0671**	0.0334
	OR5	Trust and vision	0.0609	0.0497
OE	OE1	Reduce intermediaries and human labour	0.0344	0.0400
	OE2	Reduced operational cost	0.0451	0.0467
	OE3	Resource efficiency and sharing	0.0331	0.0432
	OE4	Legal regulations and compliance	0.0265	**0.0654**
	OE5	Support for automation and smart contracts	0.0076	0.0120
TE	TE1	Accuracy	0.0010	0.0014
	TE2	Consistency/ Immutability	0.0011	0.0048
	TE3	Provenance of data	0.0008	0.0136
	TE4	Integrity	0.0017	0.0230
	TE5	Reliability	0.0124	0.0346
SCP	SCP1	Efficient collaboration and coordination	0.0503	0.0444
	SCP2	Availability and Responsiveness	**0.0775**	0.0271
	SCP3	Efficient inventory and order management	0.0095	0.0072
	SCP4	Quality and customer satisfaction	0.0154	0.0155
	SCP5	Enhanced/effective logistics capabilities	0.0201	0.0264

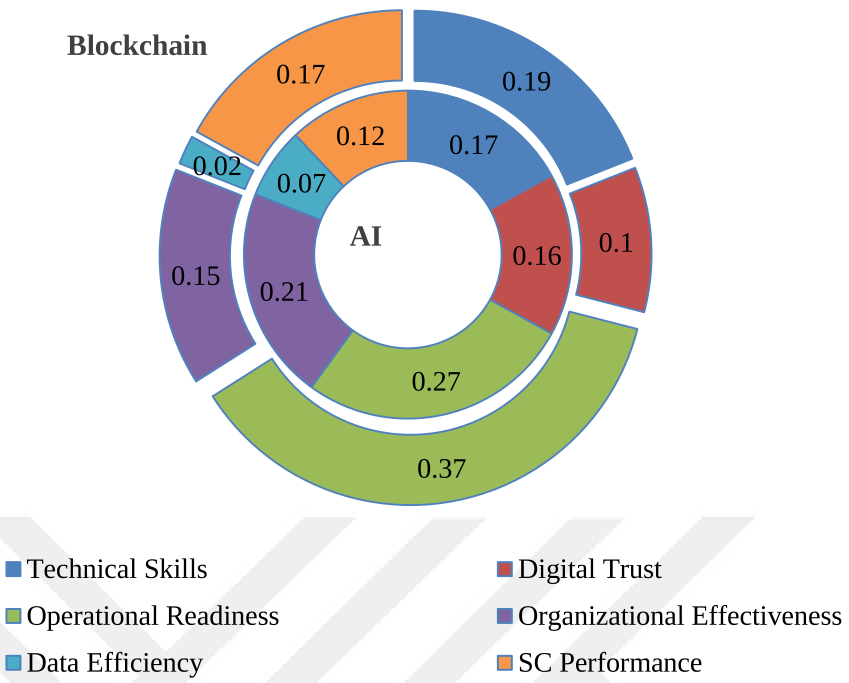


Figure 4.4: Evaluation of success factor clusters

The findings in Blockchain show similarities to the literature when top five success factors are examined. For instance, Zhou et al. (2020) found in their study the support from senior management as the most important success factor. Also Erol et al. (2021) found the top management commitment factor as one of the top influencing factors for success and effectiveness of Blockchain. Leadership readiness and support to embrace a novel technology is also one of the biggest steps to transformed organizational culture. In other papers, the acceptance and support of the technology by the organization is identified for the success of Blockchain-based SCs (Orji et al. 2020; Huang et al., 2022).

Economic aspects also have both success and risk impacts, and take one of the top places in both frameworks. If financial readiness and growth is backed by adequate capital, further investment in Blockchain can be supported in the SC, making the technology's implementation, transition, and maintenance more practical and economical (Orji et al. 2020; Zhou et al., 2020). Another critical success factor is the improved security and privacy of the chain. This factor includes actions such as becoming more aware of cyber-threats, reducing counterfeit, limiting privacy, ensuring user control and data safety (Ar et al. 2020; Shoaib et al., 2020; Ozdemir et al., 2021; Moretto and Macchion, 2022). It is critical to ensure that the information shared is essentially secure to avoid manipulation. Even after a node crashes or exits, keeping transactions and data accessible at all times will support the SC system to be responsive and available, which is one of the most important factors in the literature (Yadav and Singh, 2020b; Moretto and Macchion, 2022).

The findings in AI also show similarities to the literature when top five success factors are examined. Transformed technology culture and Improved security and privacy factors come to fore in AI also as in Blockchain success Technological readiness and a well-established infrastructure are crucial for the successful incorporation of AI (Dora et al., 2022; Kumar et al., 2023). In their study, Dora et al. (2022) also defined these factors as the top two critical success factors. To assure the effectiveness of AI adoption and integration in a SC, it is crucial for service providers to ensure confidentiality measures for data protection, security, and access control. This way, unauthorized use of information by service providers can will be prevented, and the integrity of the system will be maintained.

The results also emphasizes the importance of compliance with regulations and government support, which has been determined as one of the key factors for technology adoption also by Dora et al. (2022) and Kumar et al. (2023). Another highly important factor in the results is seen as the integration with other technologies and applications for successful implementation of AI in SCs. The literature supports this factor as Sodhi et al. (2022) proposes end-to-end integration, and Kumar et al. (2023) proposes interoperability in their critical success factors. User desirability and acceptance, involving stakeholder acceptance, intention, loyalty, and competitive pressure, is also seen as highly important in SCs as it can promote the adoption of cutting-edge technologies such as AI, ML, and Blockchain to achieve the objective of a resilient SC (Dora et al., 2022; Kumar et al., 2023). Due to this precedent and competitive pressure, SC actors and SCs as a whole may compete with other actors and SCs to demonstrate their technological capabilities.

4.4.3. Directions on IIFP-ANP Methodology

This research emphasizes the significance of the success and risk factors highlighted. The decision-makers involved in this study concurred with the findings and verified that they are consistent with the literature and the SC industry on a global scale. Additionally, the ANP method appears to be adept at fulfilling the assessment requirements for the success and risk factors. In response to RQ4.3, the IIFPs have fostered a versatile environment for decision-making.

The ANP method is known to be able to capture and model the interrelationships among clusters and the elements within clusters. Thus, this proposed hybrid method is advantageous for this decision problem. Furthermore, decision-makers can articulate their preferences without knowledge deficits, given their diverse professions and areas of expertise. There may be several points during these processes where the competence of decision-makers is uncertain, complicating the decision making process. Therefore, IIFPs offer comprehensive knowledge integration for practitioners. The primary advantage of IIFPs is that their integrated methods do not require absolute data or complete evaluations from deciders. Here, imprecise inputs can be estimated and subjective information is handled, including the hesitancies and uncertainties of experts. The proposed hybrid method offers a novel approach to effectively solve decision making problems involving hesitancy.

In order to estimate the true potential of any disruptive technology, it is first necessary to understand and examine the success and risk factors (Erol et al., 2021; Karaşan et al. 2021). Therefore, this section investigates these factors and answer the RQs. Literature review in Section 2 indicated that BC and AI are popularly analyzed technologies in SC studies, but industrial implementations are not easy and there are challenges for successful implementation. Therefore, the study continued for further investigation to provide a roadmap and support to practitioners by evaluating success and risk factors. These factors also formed the basis of CNs and key designing system requirements of these technologies in SCs that are investigated in the next chapter.

4.4.4. Sensitivity Analysis

This section contains a sensitivity calculation for consistency-confidence based aggregation parameter. When combining the individual preferences of experts, the parameter δ is used for controlling the weight of both confidence and consistency degrees of expert assessments. By the suggestion of experts, δ was selected as 0.3 in this research. Experts preferred the results to be dependent more on consistency levels of evaluations than confidence levels of individuals. Here, an analysis for sensitivity can be conducted on behalf of this parameter to assess the results considering the alteration in the confidence and consistency weights. This step is performed by appointing 5 different sample δ values. With the control of the changes in aggregation for the weighting vectors of experts that are seen in Table 4.16, an example outcome for the relation between S1 and TO was achieved, as shown in Figure 4.5.

According to the analysis, the effect of δ parameter can be seen in both tables that it changes the priority of experts and therefore affecting factor priorities. Based on this evaluation, the most consistent and confident decision maker was Expert-2, as it is with the highest priority even the δ changes. When experts' CF and CN levels are similar or close valued, the results seems stable and not much sensitive to the changes in δ. If the weights are too close, then the ranking of the factors might change.

Table 4.16: Sensitivity results of expert weights for S1 – TO

δ \ $W_{experts}$	W_{E1}	W_{E2}	W_{E3}	W_{E4}	W_{E5}	W
0.1	0.11	0.47	0.10	0.14	0.18	$W_{E2}>W_{E5}>W_{E4}>W_{E1}>W_{E3}$
0.3	0.18	0.47	0.10	0.12	0.13	$W_{E2}>W_{E1}>W_{E5}>W_{E4}>W_{E3}$
0.5	0.18	0.47	0.10	0.11	0.14	$W_{E2}>W_{E1}>W_{E5}>W_{E4}>W_{E3}$
0.7	0.19	0.46	0.10	0.14	0.11	$W_{E2}>W_{E1}>W_{E4}>W_{E5}>W_{E3}$
0.9	0.19	0.46	0.10	0.14	0.11	$W_{E2}>W_{E1}>W_{E4}>W_{E5}>W_{E3}$

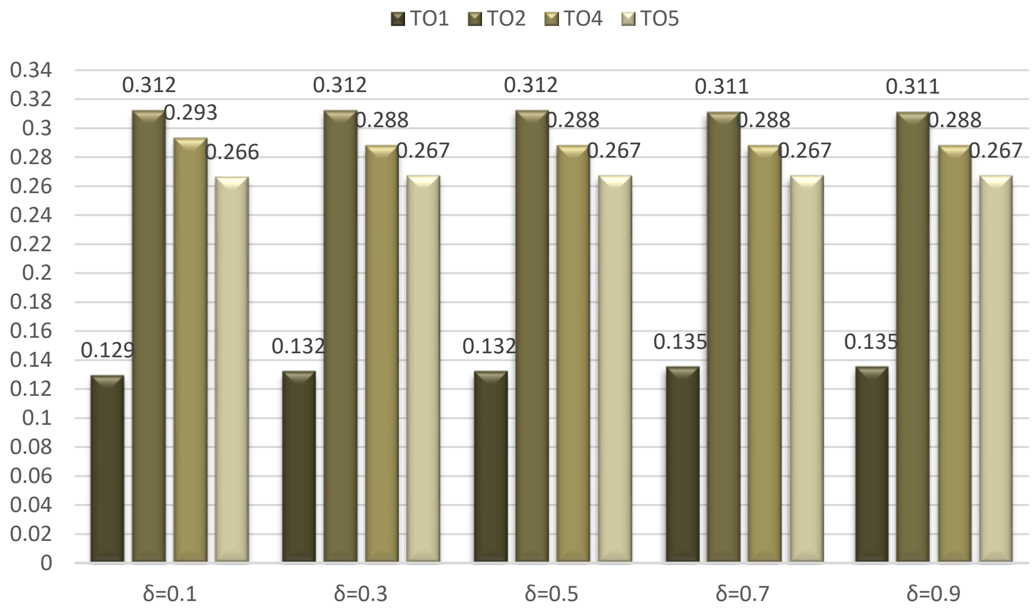


Figure 4.5: Sensitivity results for S1 – TO

4.4.5. Comparative Analysis

Several researchers have investigated various decision aggregation operators for problems involving intuitionistic fuzzy numbers. In light of the extensive research on these diverse weighted operators, it is determined that conducting a comparative study to confirm the viability of the proposed decision making method is necessary. For the purpose of comparison, the intuitionistic fuzzy weighted aggregation (IFWA) operator (Xu, 2007) was chosen for analysis. Further information can be found in the original article.

In this thesis, for aggregation, CC-IOWA operator is used to take into account the consistency and confidences of the experts while generating weights to unite their preferences. The comparison is made with IFWA operator which does not take those values into account. The results show that, priorities can differ based on operator. Figure 4.6 includes the results of sample evaluation. As an example, while the evaluation weights of TO via CC-IOWA operator are TO2 > TO5 > TO4 > TO3 > TO1, the weights via IFWA are TO2 > TO5 > TO4 > TO3 = TO1. Similar changing effect can be recognized in the weighs of S also.

Figure 4.6: Comparison results for Blockchain risk factors

As most of the criteria weights and rankings are close to each other, it shows that the proposed approach can procure and manage consistent results as others. According to the consistency/confidency based formula, it can be affirmed that the CC-IOWA operator is significantly more sensitive to the inputs offered than the other one. Hence, the utilization of CC-IOWA is recommended as an aggregation strategy.

5. BLOCKCHAIN AND AI SYSTEM REQUIREMENTS FOR AN EFFECTIVE SC STRUCTURE

The main motivation behind investigating CNs and DRs of a Blockchain and AI enabled SC is to create a resilient and digitalized SC structure. Despite Blockchain and AI in SC is an emerging field, there is a clear gap in the literature regarding assessment models to guide practitioners. To fill this gap, this chapter mainly aims on investigation of CNs and DRs to apply these technologies effectively to SCs. This chapter suggests that a QFD methodology should be used to design this integration, and therefore a HoQ is recommended to build an effective SC structure. As mentioned above, the inclusion of these technologies in existing systems is still an emerging area, and guideline for practitioners seems missing. HoQ, a powerful tool, has a crucial role in transmitting customer requests into critical operations (Akao, 1990). However, in the HoQ process, when each expert provides different data based on personal opinion, reaching objective results is only possible with GDM. In this context, aggregating uncertain and even missing data can be a difficult task. Accordingly, based on the experiences and knowledge, experts may not have detailed point of views. Therefore, they may attach importance to diverse or complementary aspects for evaluation (e.g. while one expert puts emphasis on technical dimensions, the other one can interest in organizational aspects), and some aspects may be missing.

The HoQ tool is thus suggested with IIFPs to handle the complexity throughout this operation. Integration of IIFPs enhance flexibility and facilitate improved management and aggregation of evaluations. This is again a unique approach to the decision problem. So far, CNs and design reqirements of Blockchain in SC have not been addressed by a combination of HoQ and IIFPs. These motivations defined three RQs to study:

(RQ5.1): What are the CNs for Blockchain and AI in order to integrate such technologies into SCs, and what are their importance degrees?
(RQ5.2): What are the system requirements for Blockchain and AI in order to design an effective SC structure, and what are their importance degrees?
(RQ5.3): Is IIFP extended HoQ method capable of addressing the first two questions and provide a flexible environment for decision-making?

Theoretical and practical contributions of this study can be summarized as follows: (1) Identifying customer requirements and design specifications for Blockchain in SC, exploring the interconnections between these elements, and confirming the model with expert feedback, (2) Employing HoQ in the design of a Blockchain-based SC system for the first time, (3) Enhancing HoQ with GDM to establish a fair decision-making atmosphere, (4) Incorporating IIFPs into the HoQ framework for the first time to address the uncertainty resulting from linguistic evaluations.

The rest of this chapter continues with Section 5.1, which gives a theoretical background for for related fields. Then, Section 5.2 reviews the evaluation framework. Section 5.3 demonstrates a case application of the approach, and Section 5.4 presents its managerial implications and discussions.

5.1. Literature for Blockchain Requirements in SC

Recently, there has been an increase in the number of studies and applications of Blockchain in the SC literature. Researchers employ a variety of methods and concentrate on different aspects or components of Blockchain. However, fewer articles focus on the use of Blockchain structure in SC. In 2018, Perboli et al. (2018) proposed a lean approach to logistics SC. In this article, the authors identified gaps in the Blockchain literature and developed a standard methodology for designing Blockchain technology implementations that are not related to financial cases. Khatter and Relan (2022) introduced a study on Blockchain-enabled medical SC and focused on the determination of non-functional requirements for Blockchain based systems which enables a smoother process for the engineers on the specification of requirements and design of the system.

According to their study, these NFRs includes traceability, scalability, interoperability, latency, integrity, confidentiality, security, availability, performance, throughput, and trust needs to be there at every stage of the medical SC to properly benefit from Blockchain. Gölcük (2022) studied an axiomatic design method under fuzzy environment and proposed an application in evaluating Blockchain deployment projects in SCs. In this study, six criteria was determined as alignment to digitalization strategies, fulfillment of sectoral expectations, operational efficiency, IT infrastructure, top management involvement, and customer satisfaction. Another study is proposed by Li et al. (2023) including a scheme for Blockchain based SC storage and access control for ecological business data in automotive industry. Their focus is authorization and security, and based on their security analysis, requirements are included as confidentiality, integrity and tamper resistance, eliminating single points of failure, resilience against attacks, auditability, and legal constraints.

Recently, Riaz et al. (2024) explored cubic picture fuzzy sets for developing Blockchain-based solutions to fulfill uncertain SCM and contemporary urban transportation challenges. They analyzed strategy alternatives based on eight criteria: the decreased need for infrastructure, increased traffic congestion, enhancing interoperability, addressing privacy concerns, enabling smart city integration, skilled labor requirements, facilitating the payment, need for rules, regulations, and standards. Çıkmak et al. (2024) also proposed a fuzzy MCDM approach for evaluating the effects of Blockchain characteristics on SC performance measurement attributes. They identified the characteristics of Blockchain technology and used eight criteria in their evaluation as decentralization, consensus, immutability, transparency, traceability, autonomy, security, and accountability.

Many studies have found that the primary reasons for implementing Blockchain technology in SC management are traceability/trackability and information security. However, several challenges have also been identified, such as storage capacity and scalability, privacy problems, regulatory issues, throughput and latency, and a lack of skilled workers. Although various articles have explored the implications of Blockchain in recent years, there is still a lack of clarity in the process of adopting or designing a

Blockchain-based structure for SC. It is important to note that the above information is based on a review of several studies conducted in the past. Most of these studies focus on one specific point or area, and generally introduces only one-way set of needs as criteria of their evaluations. In order for this technology to provide the expected benefits, both CNs and critical DRs that answers these CNs must be ensured in SC integration. Therefore, the present chapter aims to fulfill this necessity and provide valuable guidance for practitioners when applying this technology in SC.

Table 5.1: Literature for Recent Blockchain –SC Integrated Studies

Author	**Object**	**Methodology**
Afrianto et al. (2025)	To present the implementation of security systems in blockchain-based supply chains	Review and framework design
Aggarwal et al. (2024)	To propose a layered architecture for an efficient Blockchain-based agri-food traceability system	Remix IDE, MetaMask wallet, Sepolia test network, JMeter simulation toolkit
Ali et al. (2024)	To investigate the application of Blockchain in optimizing warehouse management and to identify and evaluate critical blockchain practices	Best-Worst method, Fuzzy-Delphi, Combined Compromise Solution (CoCoSo)
Grünewald et al. (2024)	To examine Blockchain-based business models and present their taxonomy	Cluster analysis with Ward algorithm
Pang et al. (2024)	To present a comprehensive evaluation framework for Blockchain-based Agricultural SC Traceability	Review and framework design

5.2. Literature for AI Requirements in SC

AI encompasses logic-based techniques, advanced analytics, and applications that enable improved learning, problem-solving, and decision making capabilities. AI can strengthen a company’s adaptability by providing enhanced forecasting abilities, data-driven decision making, continuous learning, and automated process optimization (Senapati et al., 2024). Recently, there has been an increase in the number of studies and applications of AI in the SC literature. Researchers employ a variety of methods and concentrate on different aspects or components. These studies generally focuses on barriers or advantages of the AI usage in SCs. Dora et al. (2022) studied the factors of the adoption of AI in food SCs. According to their study based on Technology–Organization–Environment–Human (TOEH) dimensions, technological readiness, customer satisfaction, security and privacy, demand volatility, competitor pressure, regulatory compliance, and information sharing among actors are the leading requirements of AI in food SCs. To study the advantages of AI adoption in healthcare SCs, Kumar et al. (2023) proposed a hierarchical analysis similarly with TOEH theory. The findings in their study indicate that technologic feasibility, competitive pressure, integrity, and sustainable quality of data are the most significant dimensions to facilitate AI implementation in healthcare SCs.

Recently, Wang et al. (2024) similarly reported barriers and benefits of AI for food SC resilience, and investigated the role of AI benefits in mitigating the barriers for building a resilient food SC. While agile ability shortage and inadequate response to SC disruption were the top barriers, information sharing and improvement of effective response to demand fluctuations were the top AI benefits. Another study is proposed by Hao and Demir (2024) for AI assisted decision making in SCs. They studied the environmental, social, and governance (ESG) triggers and technologic barriers affecting AI adoption.

Fewer of the literature focus on understanding the concept or usage of AI structure in SC. Helo and Hao (2022) studied an overview of AI and SC concepts and focused on analysis of AI-driven SC research and applications. Singh et al. (2024) investigated how AI is used to enable resilience among SCs and identified the compelling and interdependent attributes that AI facilitates. They state that the interruption effect of an event depends on transparency, and the impact of transparency lightens the procurement strategy for mass customization and reduces the effect of interruption. Table 1 lists several more studies for the latest literature.

Table 5.2: Literature for Recent AI –SC Integrated Studies

Author	Object	Methodology
Ahmad et al. (2024)	To present the integration of generative AI in a risk framework to enhance SC resilience	Review
Li et al. (2024a)	To examine the role of dynamism and coordination in generative AI enabled SC management	Relational view and hypothesis testing
Li et al. (2024b)	To investigate generative AI usage and sustainable SC performance	Practice-based view and hypothesis testing
Ruan (2024)	To study the potential and challenges of combining multimodal AI in green SC	Multimodel fusion strategy and network structure design
Wang and Zang (2024)	To examine how generative AI works for sustainable development goals in the digital SC	Resource-based view and dynamic capabilities theory

Although various articles have explored the implications of AI in recent years, there is still lack of clarity in the area of adopting or designing an AI-based structure for SC. It is critical to note that the above information is based upon a review of several studies conducted in the past. Most of these studies focus on one specific point or area, and generally introduces only one-way set of needs as criteria of their evaluations. In order for this technology to ensure the expected advantages, both CNs and DRs that answers these CNs must be ensured in SC integration. Therefore, the present study aims to fulfill this necessity and provide valuable guidance for practitioners when applying AI in SC.

5.3. CNs and DRs

In this research, the examined success and risk factors of previous chapter provide a basis of critaria for the model. Subsequently a comprehensive literature review was conducted again, and finally, the opinions of SC professionals were received (expert group 1) to investigate the topic deeply, and explore how practitioners are advancing in Blockchain technology and how they perceive it. By incorporating their insights and validation, a Blockchain-based SC structure was developed and the evaluation model was refined.

5.3.1. CNs for Blockchain

For contructing the Blockchain model, criteria in next two Sections (5.3.1 and 5.3.2) are firstly determined based on a literature survey that incorporates studies related to Blockchain and SC (Kamble et al., 2019; Moin et al., 2019; Saberi et al., 2019; Wang et al., 2019a; Zhang et al., 2019; Çolak et.al, 2020; Erol et al., 2021; Çıkmak et al., 2024; Pang et al. (2024); Riaz et al., 2024; Singh and Kumar, 2024). This is then followed by a review and critique by expert group 1, which involved several meetings until the proposed model reached maturity and all experts agreed that no further additions were necessary. Based on these expert-supported reviews and verification results, five main dimensions - namely, economic, informational, processual, technical, and organizational - are defined as CNs from a digital SC perspective.

Economical Performance (CN1): The economic needs of a firm from Blockchain-based structure for an effective SC management includes cost reduction (CN11), time reduction (CN12), service improvement (CN13), and inventory management (CN14). It is undeniable that cost and time reduction, along with ongoing financial benefits, are essential for SC sustainability. Several studies have found that Blockchain can positively impact cost by reducing process times, transaction costs, and the need for intermediaries. Blockchain can generate activity records which can also decrease inventory costs and address inventory management needs of companies. Enhancing service levels is crucial as quality is a vital factor for sustainable growth. This is a widely recognized indicator of performance for SCs and serves as a key driver for technological progress.

Informational Standards (CN2): The informational needs from Blockchain can encompass reliability (CN21), integrity (CN22), consistency (CN23), and accuracy (CN24). Reliability is the basic requirement for building trust. It is typically anticipated that Blockchain technology will provide assurance of the reliability and authenticity of individual network nodes. In particular, financial transactions involving Blockchain often involve the management of assets by various intermediaries. The adoption of Blockchain technology by firms entails the risk of forged certificates or fraudulent activities, which necessitates the need for a system that ensures the integrity of the process and prevents any form of manipulation or falsification. In the process of reconciling differences between different institutions, inconsistencies and errors in ledger records may arise due to differences in their architectural and business processes, making consistency a critical requirement for a Blockchain-based SC. Accurate data quality is also expected from Blockchain to ensure that transactions are recorded in a verified manner.

Processual Needs (CN3): The primary processual needs of companies in the usage Blockchain can involve SC monitoring and traceability (CN31), transparency (CN32), security (CN33), and privacy (CN34). Previous research has pinpointed various SC barriers, such as the absence of information and traceability systems and a scarcity of transparency and trust. It has been proposed that Blockchain technology could help tackle these issues. Although it is conceivable to overcome these obstacles without Blockchain technology, this cutting-edge innovation offers several significant benefits, such as the inability to manipulate data and real-time access to verified information regarding the status of any specific product in the SC flow. This ensures transparency and traceability for all stakeholders. In an Industry 4.0 environment, security is a crucial aspect, and Blockchain technology stands out from most existing information systems in this regard. By addressing security needs, Blockchain technology can enhance system suitability and prevent data breaches and cyber-attacks through malevolent software. The privacy of Blockchain satisfies the need for discretion in transactions, the privacy of all data, or the protection of sensitive data stored on the system. In Blockchain, the level of privacy can be determined by system participants, and trust can be established in cost-effective IT solutions.

Technical Skills (CN4): The four main technical characteristics are availability (CN41), upgrade maturity (CN42), interoperability (CN43), and responsiveness (CN44). Availability pertains to the promptness of responses to inquiries. Integration of transactions in the ledger is crucial. Upgradation readiness entails adapting to changes in the Blockchain protocol or diverging from the prior versi on of the Blockchain. Interoperability refers to the capability to execute operations in different environments, including machines, equipment, and manufacturers. It facilitates expansion of multiple networks in a manufacturing system. Blockchain-based SCs are expected to collaborate effectively across various networks, and multiple chains are anticipated to produce unforeseeable outcomes, particularly in smart contracts. Responsiveness, a consequence of service orientation, allows organizations to respond to market changes more swiftly. The capability to promptly adapt to events or issues and run a variety of scenarios without significantly increasing operational costs is anticipated from a Blockchain-based SC.

Organizational Needs (CN5): Institutional requirements comprise four primary dimensions, including stakeholder management (CN51), standardization and compliance (CN52), reduced impact on community and environment (CN53), and civil society accountability (CN54). Effective stakeholder management, which enables communication, reduces risk, and fosters trust between the involved parties or partners, is a crucial element to consider. Compliance with legal requirements, standardization, and the establishment of a systematic management system have been identified as significant motivators for firms to implement activities in their SCs. Blockchain technology can guarantee standards and controls to provide proof that regulatory conditions have been fulfilled. Due to regulations of government, increase of public awareness, and pressure of customers for sustainable industries, companies are striving to fulfill their environmental and social responsibilities in their SC processes. Consequently, businesses aim to guarantee both corporate responsibility and sustainable and digital development. Blockchain technology has the potential to minimize environmental impact by reducing waste, overproduction, and energy consumption with intelligent systems and devices, thereby reducing the need for the movement of goods. Additionally, it is crucial to ensure civil society accountability in order to bolster citizen engagement and strengthen civil society.

5.3.2. DRs for Blockchain

Transparent and real-time bookkeeping (DR1): The refers to the transparent and simultaneous process of transactions that is facilitated by the verification of multiple consensuses in the Blockchain system. This feature allows participants to have a better understanding of the transactions.

The absence of intermediaries and central governing authority (DR2): This aspect eliminates the need for intermediaries in transactions, leading to the disintermediation of SCs and a reduction in bureaucracy.

Modular Architecture (DR3): This DR indicates modular architecture with layers of programmability and custom izability of the Blockchain technology. It is desirable to have a universal Blockchain architecture that any company can adopt.

Immutable and Tamper-resistant data records (DR4): It serves the purpose of verifying the integrity of goods by creating a time-stamped copy of a file in the event of any modifications to the original file.

User Anonymity/Pseudonimity (DR5): This requirement refers to a concealed identity status that aims to protect users' real names by keeping real-world entities from being directly involved in the Blockchain.

Resistance to attacks (DR6): It ensures the security of the Blockchain system by safeguarding it from Distributed Denial of Service (DDoS) attacks that attempt to overwhelm the system with unnecessary requests, thereby disrupting the functioning of legitimate services.

Consensus Protocols (DR7): This indicates the presence and capacity for consensus services. Consensus is necessary for individual decisions and updates to ensure a majority confirmation in a Blockchain network.

Transaction and Data Confidentiality (DR8): This is a crucial aspect that ensures the privacy, and security of data during transactions. This feature specifically safeguards sensitive information such as personal data, trade secrets, and bank account details from unauthorized disclosure. Only authorized users are granted access to this protected data.

Transaction Speed (DR9): This requirement is designed to enhance speed by digitizing physical processes and reducing the necessity for interactions and communications to a minimum.

Network Latency (DR10): This requirement pertains to the flow of data in the Blockchain. The term "block time" refers to the amount of time it takes to produce the next block of transactions in the chain. In simpler terms words, it means the amount of time that a user waits to see his transaction appear on the Blockchain.

Clear Communication (DR11): It focuses on ensuring clear communication and information sharing. It enables users to comprehend the process flow and share common values.

Process Capability (DR12): As the Blockchain ledger expands over time, this requirement of scalability aims to maintain performance levels and capabilities while handling an increasing number of requests.

Automation (DR13): This refers to automated processes in the Blockchain that can trigger actions between nodes (such as payments or other events) once certain conditions are met. The ultimate goal is to achieve digital process management and continuous efficiency through automation and stabilization.

Trust (DR14): It is a critical reliability consequence of decentralization. This requirement aims to regulate and control the behaviors of network members based on legal agreements.

Effective Coordination (DR15): This enables various stakeholders within organizations to collaborate and develop value for consumers. Its goal is to facilitate cooperation among the different parties involved in SC.

Conformity (DR16): This requirement establishes a framework that each user or participant agrees to follow. Maintaining the relevancy and applicability of the Blockchain during changing times and requirements is a vital aspect of this aspect. It aims to provide the same services as the state and corresponding public authorities in a decentralized and efficient manner while preserving the same level of validity.

5.3.3. CNs for AI

For constructing the AI model, criteria in next two Sections (5.3.3 and 5.3.4) are firstly determined based on a literature survey that incorporates studies related to AI and SC (Dora et al., 2022; Shatat and Shatat, 2022; Sodhi et al., 2022; Kumar et al. 2023; Ressi et al., 2024; Liang et al., 2024; Senapati et al., 2024; Singh et al., 2024). For CNs, it was seen that AI criteria are similar to Blockchain criteria. The reasons behind of this result are firstly they both are latest emerging technologies, and secondly these CNs are generalized based on digitalization of a SC. Therefore, the same CN dimensions are also used here. However, as the technology differs in structure and features, the DRs are different and are defined based upon a survey of literature that incorporates studies related to AI and SC. After this step, the opinions of expert group 1 were again received to investigate the topic deeply, and explore how practitioners are advancing in AI technology and how they perceive it. This is finally followed by a review and critique by the expert group 1, which involved several meetings until the proposed model reached maturity and all experts agreed that no further additions were necessary. In summary, by incorporating their insights and validation, an AI-based SC structure was developed and the evaluation model was refined. According to these reviews and verification results based on expert support, same five essential dimensions are defined as CNs from a digital SC perspective. The detail definitions given here are now on the AI point of view of those same CNs.

Economical Performance (CN1): By focusing on cost efficiency (CN11), time efficiency (CN12), enhancement of service (CN13), and effective management of inventory (CN14), businesses can better meet customer expectations that leads to increased satisfaction, loyalty, and ultimately, profitability. AI can play a transformative role in SC management for those CNs. Analysis of historical data to estimate demand trends for future, allowing companies to optimize the levels of inventory and reduce holding costs are expected from AI. AI algorithms can calculate the efficient transportation routes, reduce time and improve speed which is another CN for time efficiency. Accurate predictions of demand are also needed from AI to allow companies to meet CNs promptly, thereby improving service levels.

Informational Standards (CN2): When considering the informational needs, it needs to be reliable (CN21), integrate (CN22), consistent (CN23), and accurate (CN24) for effective decision making and operational efficiency. Reliability refers to the ability of the information systems to consistently perform their intended functions without failure. Integrity ensures that the data used within the AI is trustworthy, and protected from unauthorized alterations. Consistency refers to the uniformity of data across different systems and stages of the SC. Accuracy refers to the correctness of the information being used by AI in the SC operations.

Processual Needs (CN3): The four primary processual needs of companies in the usage AI for their SC can be counted as: SC should be monitorable and traceable (CN31), transparent (CN32), secure (CN33), and private (CN34). Constantly monitoring SC activities helps in identifying and resolving issues before they escalate. AI-powered tools can provide real-time visibility into the SC, enabling quicker response times to disruptions and better coordination across different stakeholders. Stakeholders, including consumers, should also have transparency and access to information about how decisions are made, particularly regarding sourcing and labor practices. Implementing robust security and privacy measures to prevent unauthorized access and ensuring that only validated data is utilized in AI decision making processes are also critical and required.

Technical Skills (CN4): Considering technical performance characteristics, to ensure the system functions effectively when implementing AI in SC, it should be available (CN41), technologically mature (CN42), interoperable (CN43), and responsive (CN44). AI systems should have high availability to support decision making and real-time processing. AI models should be designed for continuous learning and improvement. Also organizations need a structured approach to manage and implement model upgrades without disrupting SC operations. AI solutions must seamlessly integrate with existing SC management systems, ERP software, and other operational tools, and need to support interoperability between the entities in the SC. AI systems should be capable of adjusting algorithms and strategies based on real-time data and changing market conditions to provide responsiveness.

Organizational Needs (CN5): Implementing AI in SC requires addressing various organizational needs including management of stakeholders (CN51), compliance and standardization (CN52), reducing environment and community impact (CN53), and accountability of civil society (CN54). SC often include various stakeholders as suppliers, retailers, manufacturers, and logistics providers. AI systems need to support them for better data sharing and collaboration. Developing industry-specific standards and ensuring AI implementations comply with local, national, and international regulations governing data privacy, cybersecurity, and SC operations is critical. Adopting AI technologies that promote sustainability in SC operations which contributes to reduced environmental footprints and resource conservation is found as a must have. Lastly, integration of AI initiatives with corporate social responsibility efforts to demonstrate accountability toward communities and society is also one of the important requirements.

5.3.4. DRs for AI

Sensing and interacting (DR1): This aims to enable computers to analyze and interpret meaningful information using data collected from sensors, to develop systems that will perform tasks in line with human language instructions, and perform vision based methods. AI-powered chatbots can also offer immediate assistance to customers for customer support, addressing inquiries and issues efficiently without human intervention.

Learning and decision making (DR2): It refers to AI's ability to learn from data, implement automated analysis, and provide decisions to react to the events in the SC. AI systems need mechanisms for continuous learning and improvement, allowing them to adapt and refine their outputs based on real-world performance and feedback. AI applications in SC decision making can also be listed as optimization, expert systems, planning and scheduling methods, simulations and modelling.

Precise and adaptive programming (DR3): This requirement is to detect and handle errors in software and accomplish test requirements, decrease error percentage, and for accurate prediction of AI. Organizations need a structured approach to manage and implement model upgrades without disrupting SC operations. This includes testing new models in a staging environment before full deployment. AI systems should also be capable of adjusting algorithms and strategies based on real-time data and changing market conditions. AI models should be regularly updated with new data to enhance their predictive capabilities. This ensures that SC operations remain efficient and competitive.

Advanced computing and backup system (DR4): The quality and flexibility of the infrastructure considerably affects the upcoming operational performance of AI services. The ability to adapt AI applications to different technologies and platforms is vital. This ensures that organizations can leverage their existing infrastructure while adopting new AI innovations. AI systems should have high availability to support real-time processing and decision making. This requires robust infrastructure and redundancy measures to minimize downtime. Implementing disaster recovery plans is essential to quickly restore functionality in case of system failures or breaches. Backup systems must be in place to ensure data continuity, mitigating the risk of downtime impacting operations.

Impediment diagnosis and proactivity (DR5): This requirement of AI brings support to SC detection of anomalies, bugs, inaccuracies, fraud, and vulnerabilities. For instance, AI can streamline inventory audits by identifying discrepancies and inaccuracies, leading to more precise inventory management. Implementing AI also allows for the anticipation of disruptions or demand changes. The system should have the capability to trigger alerts and suggest corrective actions before issues escalate.

Collecting data sources (DR6): This refers to collection of different types of data sources (structured data, unstructured data, sensor data, and new data types). It brings advantages as detailed observations, objective metrics, real-time data, and distinctive information. Here, source data needs to be gathered from reliable suppliers and validated to avoid introducing errors into the AI models. Also implementing reconciliation processes to periodically verify and align data from different sources to maintain consistency is crutial.

Data structure (DR7): It indicates the basic conditions of data, including data availability, auditing, cleaning, and management. Consistent data formats should be used to ensure that information from various sources can be easily integrated and compared. Developing industry-specific standards and protocols for data formats facilitates interoperability and consistency across the SC. Implementing quality assurance processes to maintain data standards in AI applications, ensures accuracy and reliability in data handling, decision making, and reporting.

Legal instruments (DR8): It refers to a well-defined AI guidance policy for establishing a governance mechanism. AI guidelines should help to evaluate the coherence of policies and regulations that govern data and AI. It should be ensured that AI implementations comply with local, national, and international regulations governing data privacy, cybersecurity, and SC operations. This involves continuous monitoring of regulatory changes and adjusting practices accordingly. Maintaining logs of data changes and transactions to provide audit trails is also needed for tracking and verifying data integrity over time.

Ecosystem management (DR9): This requirement is to measure the degree of collaboration, information sharing (real-time), and communication between all systems and parties in the AI enabled chain. Establishing regular communication channels, feedback loops and mechanisms for stakeholders to provide feedback about data quality can lead to improvements in data collection and processing methods for AI, fostering collaboration and trust.

Securing data and privacy (DR10): This describes the capacity of an AI system to protect sensitive SC information, maintain adherence to privacy laws and regulations, and reduce the likelihood of unauthorized data access. Addressing ethical concerns related to AI deployments is important, such as bias in decision making, surveillance, and data privacy. Organizations should adopt ethical frameworks to guide AI development and use.

Scalability (DR11): This aspect indicates that the AI application should be accessible and easily scalable, adaptable to changing requirements. This will accommodate the growth of the network and ensure long-term effectiveness and value. As business needs evolve, the AI system must support easier upgrades and scaling. This may involve modular architectures that allow for specific components of the system to be enhanced or replaced independently.

Intelligent Automation (DR12): This refers to automated processes through AI. The ultimate goal is to achieve digital process management and continuous efficiency through automation and stabilization. The fusion of AI with process automation (intelligent automation) allows companies to automate increasingly sophisticated, comprehensive processes. This integration incorporates predictive analytics and insights into workflows, empowering employees to work more efficiently and effectively through enhanced automation technologies. For instance, AI can calculate the most efficient delivery routes, which can lead to reduce transit time and improve overall delivery speed. It can adjust inventory levels dynamically based upon real-time sales data and trigger automatic reordering of stock, ensuring optimal inventory levels are maintained. Utilizing AI for logistics and operations can help streamline processes, reduce wastage, and identify cost-saving opportunities in transportation and warehousing.

Descriptive and predictive analytics (DR13): It is a process to utilize historical data, advanced ML algorithms, and external factors for identifying trends and patterns in operations and customer behavior. The AI system should provide insights and analytics, enabling quick decision making. This involves processing large volumes of data and presenting actionable information. It also then uses these insights for demand planning and forecasting. By analyzing trends and demand patterns, AI algorithms can make accurate predictions of demand. For instance, a retailer might use predictive analytics to foresee inventory needs based on previous sales data and upcoming trends.

End-to-end integration (DR14): It indicates the approach toward complicated integration and interaction between several participants and domains, and between AI and existing systems and solutions. Interconnected systems should be employed that enable seamless data exchange to avoid discrepancies across different functional areas (e.g., procurement, inventory management, and logistics).

Customization (DR15): It refers data gathering on requirements of the customers by using AI's analytical capability to support the SC to generate personalized solutions and products to the specific needs of the individual users. AI can analyze data to offer personalized services and recommendations, enhancing the overall customer experience.

Human intervention (DR16): Human oversight and expertise is important in understanding the outcomes generated by AI/ML models. Although these technologies are highly sophisticated, they may not adequately capture the nuances and context of SC operations. Simply put, the objective findings derived from AI models do not always align perfectly with the knowledge of domain experts. Domain specialists can assess the results of these models by taking into account broader industry standards, regulatory guidelines, and unique business practices.

5.4. Application of the Proposed IIFP extended ANP-HoQ Approach for Blockchain Model

The application of this chapter involves an integrated logistics company which provides warehousing, domestic distribution, foreign trade, and SC management services. The company's business model is bolstered by technological inspiration. It is constantly offering customers integrated, interconnected, and innovative solutions, and always tries to be one-step ahead. This boosts its customers' accomplishments and creates environmental, financial, and social benefits.

The company's belief in continuous and dynamic transformation guided the application in this chapter. This belief also guides the company to growth and development every day, and being aware of the fact that any other means cannot lead to success. The company wants to inspire logistics industry and bring new perspectives to it by engaging cutting-edge technology to offer advanced solutions to its customers alongside the understanding of excellent service. It is also always trying to explore better ways to increase efficiency and automation, to reduce costs and minimize errors, to enhance its system supporting the coordination of information, processes, and stakeholders. All those motivations of the company and its technology based manifest, brought the focus on technological alternatives, and Blockchain and AI are among the options. The company thinks that technical and structural innovations, particularly the integration of Blockchain and AI into their structure will enhance the company in competition towards digitization.

The application in this chapter has again two main parts and two sub-groups of the experts similarly to the previous chapter. The first part involves determining the CNs and DRs which are given in Section 5.3.1 and 5.3.2, with the help of expert group-1 again. The second part entail decision making and computational implementation of the recommended HoQ models which are given in Section 5.4, with expert group-2 for Blockchain (consist of three individuals from group-1 who possess the most knowledge, expertise, and experience in Blockchain and AI technologies (Expert-1, Expert-2, and Expert-4), plus two professionals from case company). This focus group helped for more effective evaluations due to their deeper knowledge on the technologies.

In expert group-2, one of the additional expert is an IT product manager from the case company who has eleven years of experience in this area, works on new technologies and knowledgeable on Blockchain. The second additional expert is a system architech from the company who has extensive knowledge about IT systems, Blockchain and AI with twenty years of experience in IT. Each expert is again treated based on weightings explained in 3.4.2, step 3.4, also considering the confidence and consistency of their linguistic evaluations.

Step 1: The CNs and DRs for Blockchain based SC have already been described in Sections 5.3.1 and 5.3.2.

Step 2: The interrelations of CNs are demonstrated in Figure 5.1.

Step 3: A comparison of the related needs is conducted by five experts to determine their respective importance.

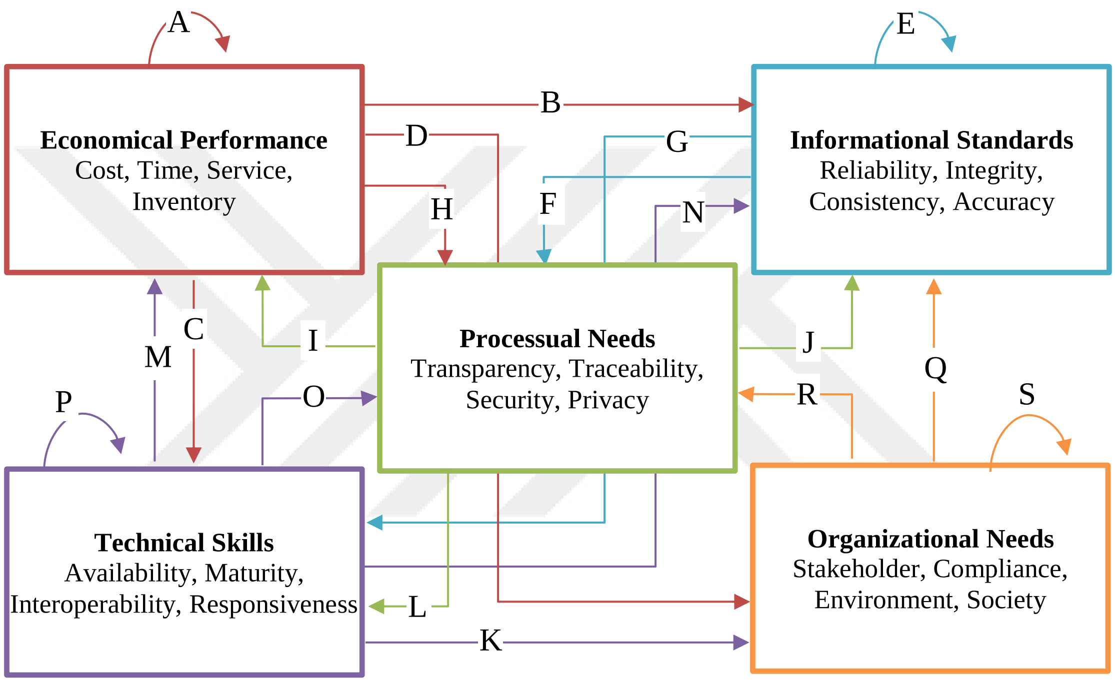


Figure 5.1: CN relations for Blockchain

Table 5.3: Incomplete evaluation of Expert-1 for relation CN33 – CN2

	Linguistic Assessment				IIFPs			
CN33	CN21	CN22	CN23	CN24	CN21	CN22	CN23	CN24
CN21	-	H	VH	VH	-	(0.60,0.30)	(0.85,0.10)	(0.85,0.10)
CN22	P	-	FH	FH	(0.30,0.60)	-	(0.70,0.20)	(0.70,0.20)
CN23	VP	FP	-	**?**	(0.10,0.85)	(0.20,0.70)	-	**?**
CN24	VP	FP	**?**	-	(0.10,0.85)	(0.20,0.70)	**?**	-

Step 4: Table 5.3 provides an instance of an assessment conducted by Expert-1, with the intention of determining the significance between second-level needs of CN1. Additional evaluations can be found in Table 5.4.

Table 5.4: Remaining expert evaluations for relation CN33 – CN2

	Expert-2				Expert-3			
CN33	CN21	CN22	CN23	CN24	CN21	CN22	CN23	CN24
CN21	-	**?**	VH	FH	-	**?**	**?**	FH
CN22	**?**	-	VH	H	**?**	-	FH	FH
CN23	VP	VP	-	FP	**?**	FP	-	P
CN24	FP	P	FH	-	FP	FP	H	-
	Expert-4				Expert-5			
CN33	CN21	CN22	CN23	CN24	CN21	CN22	CN23	CN24
CN21	-	H	VH	FH	-	**?**	VH	FH
CN22	P	-	FH	MH	**?**	-	FH	H
CN23	VP	FP	-	**?**	VP	FP	-	P
CN24	FP	MP	**?**	-	FP	P	H	-

Step 4.1: To offer a clearer description of these processes, the calculations performed by Expert-1 will be demonstrated. The absent values in Table 5.3 are estimated through an alternative value. In Table 5.5, the estimated preferences for Expert-1 are displayed. The remaining incomplete data for other experts are calculated in the same manner and presented in Table 5.6.

$er_{34}^{1} = \frac{r_{31}.r_{14}}{r_{31}.r_{14}+(1-r_{31}).(1-r_{14})} = \frac{0.10\times0.85}{0.10\times0.85+(1-0.10)\times(1-0.85)} = 0.39$ and

$er_{34}^{2} = \frac{r_{32}.r_{24}}{r_{32}.r_{24}+(1-r_{32}).(1-r_{24})} = 0.37$, therefore $er_{34} = \frac{0.39+0.37}{2} = 0.38$.

$er_{43}^{1} = \frac{r_{41}.r_{13}}{r_{41}.r_{13}+(1-r_{41}).(1-r_{13})} = 0.39$ and $er_{43}^{2} = \frac{r_{32}.r_{24}}{r_{32}.r_{24}+(1-r_{32}).(1-r_{24})} = 0.37$,

therefore, $er_{34} = 0.38$.

Table 5.5: Complete evaluation of Expert-1 for relation CN33 – CN2

CN33	CN21	CN22	CN23	CN24
CN21	-	(0.60,0.30)	(0.85,0.10)	(0.85,0.10)
CN22	(0.30,0.60)	-	(0.70,0.20)	(0.70,0.20)
CN23	(0.10,0.85)	(0.20,0.70)	-	(0.38,0.38)
CN24	(0.10,0.85)	(0.20,0.70)	(0.38,0.38)	-

Table 5.6: Remaining complete expert evaluations for relation CN33 – CN2

	Expert-2			
CN33	CN21	CN22	CN23	CN24
CN21	-	(0.50,0.27)	(0.85,0.10)	(0.70,0.20)
CN22	(0.27,0.50)	-	(0.85,0.10)	(0.60,0.30)
CN23	(0.10,0.85)	(0.10,0.85)	-	(0.20,0.70)
CN24	(0.20,0.70)	(0.30,0.60)	(0.70,0.20)	-
	Expert-3			
CN21	-	(0.37,0.37)	(0.78,0.10)	(0.70,0.20)
CN22	(0.37,0.37)	-	(0.70,0.20)	(0.70,0.20)
CN23	(0.10,0.78)	(0.20,0.70)	-	(0.30,0.60)
CN24	(0.20,0.70)	(0.20,0.70)	(0.60,0.30)	-
	Expert-4			
CN21	-	(0.60,0.30)	(0.85,0.10)	(0.70,0.20)
CN22	(0.30,0.60)	-	(0.70,0.20)	(0.55,0.40)
CN23	(0.10,0.85)	(0.20,0.70)	-	(0.22,0.60)
CN24	(0.20,0.70)	(0.40,0.55)	(0.60,0.22)	-
	Expert-5			
CN21	-	(0.50,0.27)	(0.85,0.10)	(0.70,0.20)
CN22	(0.27,0.50)	-	(0.70,0.20)	(0.60,0.30)
CN23	(0.10,0.85)	(0.20,0.70)	-	(0.30,0.60)
CN24	(0.20,0.70)	(0.30,0.60)	(0.60,0.30)	-

Step 4.2: The level of consistency is calculated and given in Table 5.7. Final consistency for the relation matrix of Expert 1 is found as $C^1 = \sum_{i=1}^{n} C_\mathrm{i} / n = 0.96$ from the average of Ci values in Table 5.5 which is bigger than 0.50. The remaining consistencies for experts' evaluation matrices are found as $C^2 = 0.88$, $C^3 = 0.82$, $C^4 = 0.94$, $C^5 = 0.94$.

Table 5.7: Levels of consistency of Expert-1 for relation CN33 – CN2

CN33	CN21	CN22	CN23	CN24
CN21	-	0.87	0.93	0.93
CN22	0.95	-	0.93	0.93
CN23	0.99	0.98	-	1.00
CN24	0.99	0.98	1.00	-
C_i	0.91	0.94	0.99	0.99

$mr_{12}^3 = \frac{r_{13}.r_{32}.r_{21}}{r_{23}.r_{31}} = \frac{0.85\times0.20\times0.30}{0.70\times0.10} = 0.73$ and $mr_{12}^4 = 0.73$, therefore $mr_{12} = 0.73$.

$C_{12} = 1 - d(r_{12}, mr_{12}) = 1 - d(0.60, 0.73) = 0.87$.

Step 4.3: In this step, the confidence degrees of experts are calculated. The confidence degrees for the relation matrix of Expert 1 is given in Table 5.8. For instance, $CF_{12} = 1 - \tau_{12} = 1 - 0.10 = 0.90$. While the confidence degree of Expert 1 is found as $CF^1 = \sum_{i=1}^{n} CF_\mathrm{i} / n = 0.89$ from Table 5.8, remaining degrees are $CF^2 = 0.89$, $CF^3 = 0.87$, $CF^4 = 0.90$, $CF^5 = 0.88$.

Table 5.8: Degrees of confidence of Expert-1 for relation CN33 – CN2

CN33	CN21	CN22	CN23	CN24
CN21	-	0.90	0.95	0.95
CN22	0.90	-	0.90	0.90
CN23	0.95	0.90	-	0.75
CN24	0.95	0.90	0.75	-
CF_i	0.93	0.90	0.87	0.87

Step 4.4: In the process of calculating confidence-consistency guided aggregation, experts recommend setting δ to 0.3 to prioritize consistency over confidence. The set of consistency/confidence index values CC^R are computed as $CC^1 = (1 - 0.3) \times 0.96 + 0.3 \times 0.89 = 0.94, CC^2 = 0.88, CC^3 = 0.84, CC^4 = 0.93, CC^5 = 0.92$. To assess the level of contentment among experts, the CC-IOWA operator's associated weighting vector is calculated as $w_1 = 0.46, w_2 = 0.11, w_3 = 0.10, w_4 = 0.18, w_5 = 0.15$. Subsequently, the evaluation matrices from the specialists are combined. With regards to the evaluations in Tables 5.5 and 5.6, the group importance relation matrix is gathered and presented in Table 5.9.

Table 5.9: Aggregated evaluation of experts for relation CN33 – CN2

CN33	CN21	CN22	CN23	CN24
CN21	-	(0.55,0.30)	(0.84,0.10)	(0.77,0.15)
CN22	(0.30,0.55)	-	(0.70,0.20)	(0.66,0.24)
CN23	(0.10,0.84)	(0.20,0.70)	-	(0.32,0.49)
CN24	(0.15,0.77)	(0.24,0.66)	(0.49,0.32)	-

Step 4.5: In the final stage of Step 4, the computation of quantifier-guided importance degrees takes place. To carry out exploitation, a weighting vector (0.58, 0.24, 0.18) is applied, which corresponds to the quantifier "at most." These values indicate the dominance that one alternative has over "most" of the alternatives, as determined by "most" of the experts. The group-aggregated importance degrees are then calculated using the values in Table 5.9, resulting in a total of$IFQGDD_{CR11} = 0.747, IFQGDD_{CR12} = 0.617, IFQGDD_{CR13} = 0.254, IFQGDD_{CR14} = 0.369$. Finally, the normalized weights are found as $W_{CR11} = 0.38, W_{CR12} = 0.31, W_{CR13} = 0.12, W_{CR14} = 0.19$.

Step 5: A super-matrix is constructed at this step as presented in Table 5.10. The weights found in Step 4.5 are placed in the necessary column of relation J. All the weights calculated are put like that in the necessary columns in the super-matrix.

Table 5.10: Detailed view of super matrix values for relation J

	EP	*IS*	*PN*	*TS*	*ON*
EP(CN1)	**A**		**I**	**M**	
IS(CN2)	**B**	**E**	**J**	**N**	**Q**
PN(CN3)	**H**	**F**		**O**	**R**
TS(CN4)	**C**	**G**	**L**	**P**	
ON(CN5)	**D**			**K**	**S**

J	*CN31*	*CN32*	*CN33*	*CN34*
CN21			**0.38**	
CN22			**0.31**	
CN23			**0.12**	
CN24			**0.19**	

Step 6: In this last step of IIFP extended ANP steps, the super-matrix in Step 5 is solved by raising the super matrix to limit matrix. The importance values of each factor that are found from limit-matrix calculation can be seen in the last column of Table 5.11.

Step 4: Based on the agreement (consensus) of experts, a relationship matrix is established and can be viewed in the final HoQ scheme presented in Table 5.11 again. This matrix serves as the foundation for understanding the connections among various elements.

Step 5: After computing the CN weighted DR values, the collected values are then added up in their respective columns displayed as DR values. Subsequently, these values can be sorted based on the score (S) and accuracy (H) functions as in Table 5.11.

5.5. Results and Discussions for Blockchain Model

5.5.1. Results on Blockchain Model

This chapter addresses the lack of research on the evaluation of SC based on Blockchain technology. By presenting the Blockchain based SC model, which has been evaluated by experts, this study aims to offer unique theoretical contributions as it reflects the prominent SC needs that are expected from Blockchain, as well as the design attributes for a Blockchain-based structure.

Table 5.11: HoQ sheme for Blockchain in SC

		DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	Weights
CN1	CN11		MH		E		E	MH						EH		FH		0.08
	CN12		MP		E			FH	E	VH		MH	H	EH		FH		0.07
	CN13	E			P				P			P		MH		H		0.04
	CN14	MH			MP				MP			P		FH		E		0.05
CN2	CN21				VH	E	FH		VH					MH	VH			0.06
	CN22		P	E	MH									E				0.06
	CN23	MP			H				E					E				0.06
	CN24				VH	H		E	H				MH		MH			0.04
CN3	CN31	FH				H		E				MP		E				0.06
	CN32	MH			H				H					H				0.05
	CN33				FH	FH	VH	FH	H				H		E			0.05
	CN34				P	FH	FH	E	VH									0.06
CN4	CN41			FH							FH		VH	MH				0.03
	CN42			VH			MH										FH	0.04
	CN43			FH				E				H				VH		0.05
	CN44			VH			MH			VH	VH			H				0.04
CN5	CN51		P					MP	E			VH			VH	VH		0.06
	CN52																H	0.03
	CN53													MH				0.03
	CN54	FH			E										E			0.04
S Function		-0.50	-0.71	-0.44	-0.50	-0.48	-0.34	-0.32	-0.12	-0.59	-0.72	-0.47	-0.59	0.66	-0.39	0.44	0.09	
H Function		0.97	0.97	0.95	1.39	0.94	0.95	0.95	0.94	0.96	0.96	0.94	0.95	0.66	0.99	1.56	1.89	
Ranking		12	15	8	11	10	6	5	4	13	16	9	14	1	7	2	3	

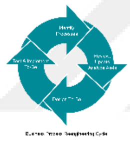
Furthermore, the quantitative application of this model provides a means to manage the information and knowledge uncertainty caused by the digitalization of SCs. This research can also provide practical contributions to SC practitioners, equipping them with the knowledge to implement this technology. Understanding the SC needs that Blockchains can meet and the design attributes that are necessary to have can help organizations to develop their digitalization strategies. The findings of this study can assist senior executives in proactively perceiving and managing the transformation processes.

The present chapter proposes a literature-based evaluation model for Blockchain based SC, taking into consideration the relevant criteria. The proposed model is subsequently refined through the application of expert knowledge and experience. Ultimately, two expert groups contribute to the development of an effective evaluation model. To ensure the conceptual validity of our model, we sought the input of these expert groups during the construction and analysis of the data. Author continuously presented the model's structure to the experts, and each time confirmed its theoretical accuracy and relevance. Similarly, the compensation of dimensions and evaluations was validated through expert consultation, and the model's application received enthusiastic endorsement from both scientific and potential users. The consulted experts for this case validated these results and confirmed that they are globally compatible with the literature and SC industry.

To gain an understanding of an effective Blockchain based SC structure, it is important to initially recognize the expected outcomes. Consequently, the construction of CNs is a response to RQ5.1. Based on experts' feedback regarding the needs of a Blockchain based SC, the primary conclusion is that economic, informational, and processual aspects come to fore as more important dimensions.The whole view of evaluations are given in Table 5.12.

Based on the evaluations, the top five crucial CNs are cost and time reduction, SC monitoring – traceability, stakeholder management, and reliability. This suggests that a significant financial advantage, efficient time management, and tracking support are highly anticipated from a Blockchain-driven SC for better management of activities, operations, data, and products throughout the SC and among different actors. These attributes are also considered the most critical in the literature; thus, this study reinforces their importance (Babich and Hilary, 2020; Lohmer et al., 2020; Wang et al., 2019a). Furthermore, the experts who were consulted for this study confirmed that these results are globally applicable to the SC sector and align with the literature.

Table 5.12: Output of CNs for Blockchain in SC

Dimensions	**Criteria**	**Final Weights**
Economic 	*Cost Reduction* *Time Reduction* *Service Improvement* *Inventory Management*	0.08 0.07 0.04 0.05
Informational 	*Reliability* *Integrity* *Consistency* *Accuracy*	0.06 0.06 0.06 0.04
Processual 	*SC Monitoring- Traceability* *Transparency* *Security* *Privacy*	0.06 0.05 0.05 0.06
Technical 	*Availability* *Upgrade Maturity* *Interoperability* *Responsiveness*	0.03 0.04 0.05 0.04
Organizational 	*Stakeholder Management* *Standardization* *Reduced Impact* *Accountability*	0.06 0.03 0.03 0.04

Lohmer et al. (2020) investigated the use of Blockchain-coordinated SC management and discovered that it can significantly reduce overall costs by facilitating efficient collaboration, leading to enhanced service levels and decreased maintenance expenses (Cole et al., 2019). According to Giovanni De (2020), Blockchain technology can overcome the limitations of traditional information systems in SCM by enabling all Industry 4.0 applications, such as ensuring visibility and transparency among all SC members and recording and presenting transaction details to interested parties. For instance, manufacturing companies can use Blockchain to quickly trace the origin of specific products, components, or manufacturers (Angrish et al., 2018). Therefore, the findings of the study align with previous research, as traceability is a top-level criterion in the critical success factors of SC networks (Llopis, 2021). Moreover, the experts consulted for this study also validated the findings and confirmed that they are globally compatible with the SC sector and the literature.

When analyzing the data from Table 5.11, it becomes clear that automation, effective coordination, conformity, transaction and data confidentiality, and consensus protocols are the five most important requirements. These findings provide crucial information for answering RQ5.2. Several studies, such as those by Cole et al. (2019), Babich and Hilary (2020), and Lohmer et al. (2020), have also emphasized the significance of these factors. Choi et al. (2020) argue that there may be cases where all stakeholders in a SC can benefit from product information disclosure, depending on the dynamics of the SC. However, transaction or personal data disclosure is a distinct aspect, and Blockchain-based systems should ensure the secure storage of data and prevent unauthorized access. Lohmer et al. (2020) identified long-term partnership opportunities and collaboration among Blockchain adoption possibilities in operation management and manufacturing. In a trusted business network where all relevant participants are known, a transaction must be considered valid, and the same information and values must be shared. In private Blockchains, this is achieved through consensus mechanisms such as proof of authority (PoA), multi-signature, and practical byzantine fault tolerance (PBFT) (Zhang et al., 2019). These mechanisms validate information and authorize transactions, making the Blockchain network verifiable. Automation is also crucial for effective and digital management of processes. Connecting factories and machines to blockchain platforms can facilitate automated value-added processes (Lohmer et al., 2020). This connectivity can provide valuable feedback on various SC operations and processes, such as production and logistics. In this context, smart contracts are the recommended practices (Cole et al., 2019; Giovanni De 2020). SCs especially tend to practice private Blockchain systems, and it would be beneficial to implement private Blockchain designs that incorporate these five essential features.

5.5.2. Directions on IIFP-ANP-HoQ Methodology

It has been identified in this study that the HoQ method is effective in meeting the requirements of a Blockchain-based SC design, and that the use of IIFPs creates a flexible environment for the GDM, in response to RQ5.3. To explain the reasons for the analytical techniques used in this study, we can start by outlining the benefits of the hybrid approach and its suitability for the problem being addressed. The HoQ method is a systematic approach to gathering and presenting information that assists in designing and developing processes for Blockchain-based SC to fulfill CNs, determine necessary design practices, and prioritize them.

During these processes, experts can express their preferences through their lack of information or knowledge gaps, given their diverse professions and areas of expertise. There may be several points at which the proficiency of experts is unclear, making GDM challenging. Therefore, IIFPs provide comprehensive information integration for practitioners. The main advantage of this approach is that it does not require complete data and absolute evaluations from decision-makers. It can predict imprecise inputs and handle subjective information shaped by the opinions and feelings of experts. With this proposed hybrid approach, issues involving hesitancy can be effectively resolved.

This approach also allows for the levels of consistency and confidence (based on hesitancy) of the experts while weighing their CN evaluations. It is furthermore observed that the ANP methodology is quite capable to address the evaluation requirements of the CNs. The ANP method is known to be able to capture and model the interrelationships among clusters and the elements within clusters. Thus, this proposed hybrid method is advantageous for this decision problem. The proposed hybrid method offers a novel approach to effectively solve decision problems involving uncertainty.

One potential limitation of the calculations involved in controlling the weights of both experts' consistency and confidence is the number of parameters involved. To address this, a sensitivity analysis is performed in Section 5.5.3 to evaluate the overall satisfaction of experts based on the consistency-confidence index values. Additionally, weighting and aggregation operators can effectively prioritize decisions using a fuzzy majority concept. The advantage of these operators is that they can not only weight experts' decisions but also combine subjective ideas into the GDM process. The decision alternatives are then ranked through the GDM process, resulting in a more comprehensive evaluation of the total weights. However, a limitation of this approach is the absence of other aggregation types. To address this, a comparative analysis is performed in Section 5.5.4 for benchmarking performances against alternative methods.

5.5.3. Sensitivity Analysis

As a reminder, in section 3.4.2, step 3.4, the calculation of confidence-consistency guided aggregation is conducted. The δ parameter is used to control the weight of both consistency and confidence degrees of the expert evaluations when fusing individual preferences. In this study, the recommendation of experts resulted in δ being chosen as 0.3. However, a sensitivity analysis can be performed to evaluate the results when changes in the consistency and confidence weights are considered.

By assigning diverse values to δ ranging from 0 to 1, the step is conducted by controlling the changes in the weighting vectors w_h of experts in aggregation. An example outcome for the sub-criteria of CN33 – CN2 is displayed in Table 5.13. The sensitivity analysis demonstrates that the weighting vectors have the same ranks until δ=0.7, due to consistencies (CC values) between expert evaluations. However, as the δ value approaches 0.7, according to the varying confidence levels of experts (with CF now having a mode weight), the orders and even the weighting vectors are modified for experts. The adjustments to the δ parameter can also impact the final weights of CNs as shown in Figure 5.2, and, consequently, the rankings of DRs when the evaluations of experts are comparable (i.e., when the IFQGDD values are approximately equal).

Table 5.13: Sensitivity results of expert weights for CN33 – CN2

δ \ $W_{experts}$	W_{E1}	W_{E2}	W_{E3}	W_{E4}	W_{E5}	W
0.1	0.46	0.12	0.09	0.19	0.14	$W_{E1}>W_{E4}>W_{E5}>W_{E2}>W_{E3}$
0.3	0.46	0.11	0.10	0.18	0.15	$W_{E1}>W_{E4}>W_{E5}>W_{E2}>W_{E3}$
0.5	0.46	0.12	0.10	0.18	0.14	$W_{E1}>W_{E4}>W_{E5}>W_{E2}>W_{E3}$
0.7	0.19	0.12	0.10	0.45	0.14	$W_{E4}>W_{E1}>W_{E5}>W_{E2}>W_{E3}$
0.9	0.19	0.14	0.11	0.45	0.11	$W_{E4}>W_{E1}>W_{E2}>W_{E5}=W_{E3}$

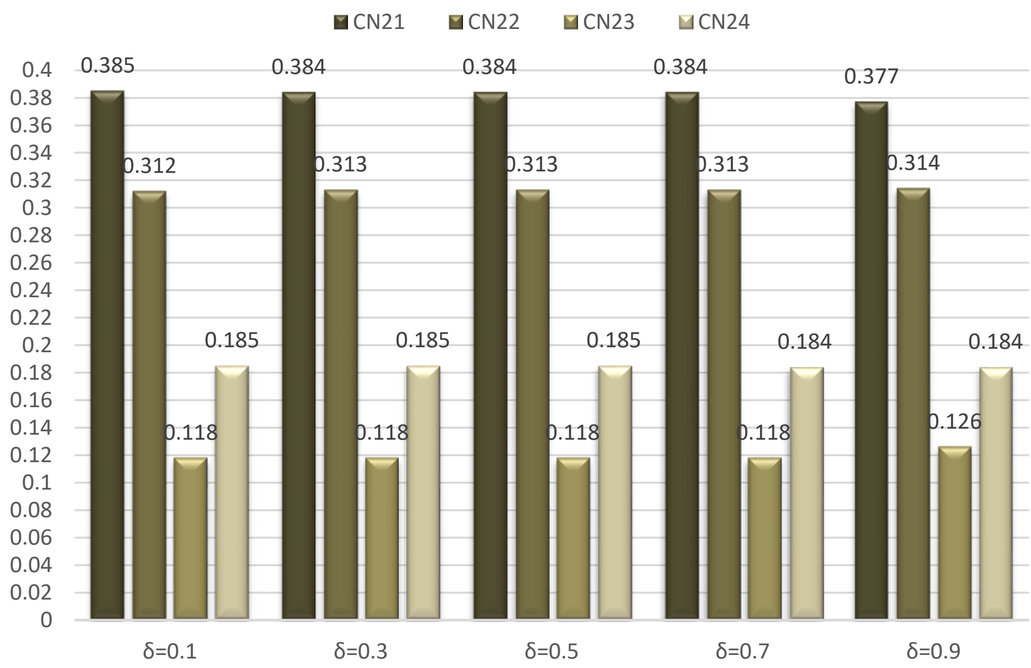


Figure 5.2: Sensitivity results for CN33 – CN2

5.5.4. Comparative Analysis

For verification of the effectiveness and applicability of the proposed IIFP based decision making process, IFWA operator is used again for comparative analysis. The results of the examination are depicted in Figure 5.3.

Figure 5.3: Comparison results for Blockchain CNs

According to the findings, both operators supplied similar sub-criteria rankings with varying weights most of the time. This indicates that both of these operators are effective in resolving aggregation concerns. However, in C2 and C5, it can be seen that sub-criteria rankings are also changing due to the changes in the weights. When it is compared in overall primary criteria, the CC-IOWA operator assigns rankings of Economic = Processual > Informational > Organizational > Technical, while the IFWA operator assigns rankings of Economic > Processual > Informational > Organizational > Technical. The discrepancy in these results is due to the sensitivity of the CC-IOWA formula. From this comparative analysis, it can be inferred that these operators assign different weights, which affect the final results.

5.6. Application of the Proposed IIFP extended ANP based HoQ Approach for AI Model

The application in this chapter continues two main parts and two sub-groups of the experts similarly to the previous chapter. The first part involves determining the CNs and DRs which are given in Section 5.3.3 and 5.3.4, with the help of expert group-1 again. The second part entail decision making and computational implementation of the recommended HoQ models which are given in Section 5.6, with expert group-3 for AI (consist of three individuals from group-1 who possess the most knowledge, expertise, and experience in Blockchain and AI technologies (Expert-1, Expert-2, and Expert-4), plus two professionals from case company).

This focus group helped for more effective evaluations due to their deeper knowledge on the technologies. In expert group-3, one of the additional expert is a team lead of the robotics and AI department from the case company who has ten years of experience in this area. The second additional expert is the system architech from expert group-2 as he is knowledgeable for both Blockchain and AI technologies. Each expert is again treated based on weightings explained in 3.4.2, step 3.4, also considering the confidence and consistency of their linguistic evaluations.

Step 1: CNs and DRs are explained in previous sections 5.3.3 and 5.3.4.

Step 2: The relations are defined among CNs, as shown in Figure 5.4. Each relation is represented with an arrow that shows the direction of the effect.

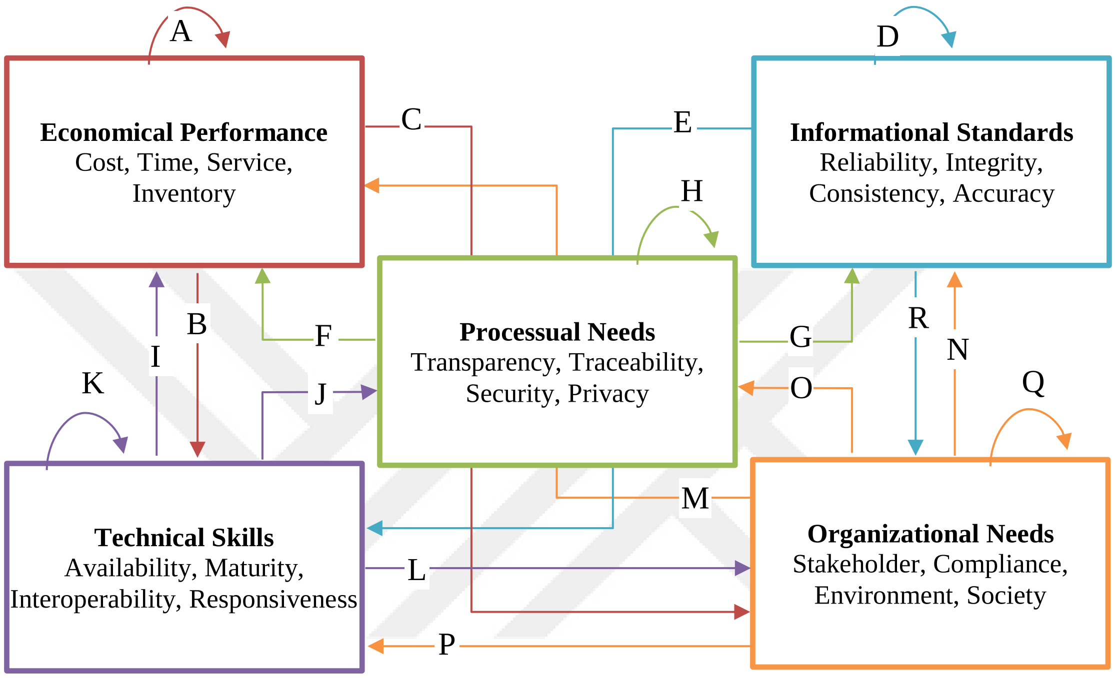


Figure 5.4: CN relations for AI

Step 3: In this context, experts construct comparison sets based on direction and influence within required CNs. To illustrate the calculations, the relationship between CN31 and CN1 is used as an example. For all the evaluations, same computational processes are followed. Table 5.14 presents a sample evaluation of first expert.

Step 4: To describe the computational steps, sample evaluation and computations of Expert-1 are explained with more details.

Step 4.1: The ungiven values in Table 5.14 are calculated with the help of an intermediate preference value. Table 5.15 contains the estimated values.

Table 5.14: Incomplete evaluation of Expert-1 for relation CN31 – CN1

	Linguistic Assessment				IIFPs			
CN31	CN11	CN12	CN13	CN14	CN11	CN12	CN13	CN14
CN11	-	S	S	S	-	(0.60,0.30)	(0.60,0.30)	(0.60,0.30)
CN12	W	-	S	E	(0.30,0.60)	-	(0.60,0.30)	(0.50,0.50)
CN13	W	W	-	**?**	(0.30,0.60)	(0.30,0.60)	-	**?**
CN14	W	E	**?**	-	(0.30,0.60)	(0.50,0.50)	**?**	-

Table 5.15: Complete evaluation of Expert-1 for relation CN31 – CN1

CN31	CN11	CN12	CN13	CN14
CN11	-	(0.60,0.30)	(0.60,0.30)	(0.60,0.30)
CN12	(0.30,0.60)	-	(0.60,0.30)	(0.50,0.50)
CN13	(0.30,0.60)	(0.30,0.60)	-	(0.35,0.50)
CN14	(0.30,0.60)	(0.50,0.50)	(0.50,0.35)	-

$er_{34}^{1} = \frac{r_{31}.r_{14}}{r_{31}.r_{14}+(1-r_{31}).(1-r_{14})} = \frac{0.30\times 0.60}{0.30\times 0.60+(1-0.30)\times(1-0.60)} = 0.39$ and

$er_{34}^{2} = \frac{r_{32}.r_{24}}{r_{32}.r_{24}+(1-r_{32}).(1-r_{24})} = 0.30$, therefore $er_{34} = \frac{0.30+0.50}{2} = 0.35.$

$er_{43}^{1} = \frac{r_{41}.r_{13}}{r_{41}.r_{13}+(1-r_{41}).(1-r_{13})} = 0.39$ and $er_{43}^{2} = \frac{r_{42}.r_{23}}{r_{42}.r_{23}+(1-r_{42}).(1-r_{23})} = 0.60,$

therefore, $er_{43} = 0.50.$

Step 4.2: Consistency level is calculated and shown in Table 5.16. The consistency degree on the relationship matrix of Expert-1 is finalized as $C^1 = \sum_{i=1}^{n} C_{\mathrm{i}} / n = 0.86$ from the mean of C_i values in Table 5.16. It is accepted as consistent as it is greater than 0.50. The consistencies of remaining expert assessment matrices are calculated as $C^2 = 0.83$, $C^3 = 0.98$, $C^4 = 0.84$, $C^5 = 0.70$.

Table 5.16: Levels of consistency of Expert-1 for relation CN31 – CN1

C31	C11	C12	C13	C14	C_i
C11	-	0.85	0.57	0.91	C_{11}= 0.78
C12	0,85	-	0,.77	0.90	C_{12}= 0.84
C13	0.88	0,79	-	0.97	C_{13}= 0.88
C14	0.93	0.93	0.98	-	C_{14}= 0.95

Step 4.3: This step includes the calculation of the vales of confidence degrees that experts have. The confidence values of Expert-1 evaluation is shown in Table 5.17. For instance, $CF_{12} = 1 - \tau_{12} = 1 - 0.10 = 0.90$. Expert 1's confidence value is calculated as $CF^1 = \sum_{i=1}^{n} CF_{\mathrm{i}} / n = 0.91$. The remaining degrees are $CF^2 = 0.98$, $CF^3 = 0.91$, $CF^4 = 0.90$, $CF^5 = 0.91$.

Table 5.17 Degrees of confidence of Expert-1 for relation CN31 – CN1

C31	CF11	CF12	CF13	CF14	CF_i
CF11	-	0.90	0.90	0.90	CF_{11}= 0.90
CF12	0.90	-	0.90	1.00	CF_{12}= 0.93
CF13	0.90	0.90	-	0.84	CF_{13}= 0.88
CF14	0.90	1.00	0.84	-	CF_{14}= 0.91

Step 4.4: In order to compute the consistency-confidence guided aggregation, δ is accepted as 0.3 as per the recommendation of the experts. This choice was made because the expert group wanted greater part of the weight to be placed on consistency rather than trust. The index values related to confidence-consistency CC^R are found as $CC^1 = (1 - 0.3) \times 0.86 + 0.3 \times 0.91 = 0.88, CC^2 = 0.93, CC^3 = 0.85, CC^4 = 0.87, CC^5 = 0.88$. To evaluate the end to end reassurance of experts, the weighting vector related to the CC-IOWA is found as $w_1 = 0.12, w_2 = 0.18, w_3 = 0.47, w_4 = 0.12, w_5 = 0.11$. Afterwards, the assessments of experts are combined. The importance relation matrix of the expert group is obtained as in Table 5.18.

Table 5.18 Aggregated evaluation of experts for relation CN31 – CN1

CN31	CN11	CN12	CN13	CN14
CN11	-	(0.58,0.32)	(0.68,0.20)	(0.62,0.30)
CN12	(0.32,0.58)	-	(0.58,0.35)	(0.52,0.45)
CN13	(0.20,0.68)	(0.35,0.58)	-	(0.32,0.59)
CN14	(0.30,0.62)	(0.45,0.52)	(0.59,0.32)	-

Step 4.5: The quantifier-guided importance degrees are calculated in this step which gives the final weights for CNs. For exploitation, the weight vector (0.58, 0.24, 0.18) is utilized, corresponding to the quantifier "at most". This vector value indicates the dominance that one element has over the "most'' elements, based on the "most'' of the experts. Aggregation of group importance values are accordingly computed based upon Table 5.18 as $IFQGDD_{CN11} = 0.649$, $IFQGDD_{CN12} = 0.519$, $IFQGDD_{CN13} = 0.304$, $IFQGDD_{CN14} = 0.503$. Eventually after normalization, the final weights are obtained as $W_{CN11} = 0.33, W_{CN12} = 0.26, W_{CN13} = 0.15, W_{CN14} = 0.26$.

Step 5: A super-matrix is constructed at this step as given in Table 5.19. The priorities obtained in Step 4.5 are put in the first column of relation CN31 and CN1. All the priorities obtained are put as such in the appropriate columns in the super-matrix.

Table 5.19: Detailed view of super matrix values for relation F

	EP	*IS*	*PN*	*TS*	*ON*
EP(CN1)	**A**		**F**	**I**	**M**
IS(CN2)		**D**	**G**		**N**
PN(CN3)			**H**	**J**	**O**
TS(CN4)	**B**	**E**		**K**	**P**
ON(CN5)	**C**	**R**		**L**	**Q**

F	*CN31*	*CN32*	*CN33*	*CN34*
CN11	**0.33**			
CN12	**0.26**			
CN13	**0.15**			
CN14	**0.26**			

Step 6: Here, the super-matrix in Step 5 is solved by raising the super matrix to limit matrix. The final importance degrees of each CN are computed and can be seen on the right W column in Table 5.20 in the form of QFD. According to the evaluations on AI

and SC points of view, while top five CNs are found from economic performance and data quality dimensions which are CN51: Stakeholder management, CN21: Reliability, CN24: Accuracy, CN52: Standardization and compliance, and CN11: Cost reduction.

Step 7: Based on the agreement (consensus) of experts, relations are assigned between CNs and DRs which can be viewed in Table 5.20. This matrix serves as the foundation for understanding the connections among various elements.

Step 8: After computing the DR values with respect to CN weights, the accumulative values are summed up in their individual columns displayed as DR values. Subsequently, these values can be ranked according to score (S) and accuracy (H) formulas as in Table 8. According to rank computation, top five DRs are found as DR5: Impediment diagnosis, DR3: Precise programming, DR12: Intelligent automation, DR10: Securing sensitive data, DR2: Learning and decision making.

5.7. Results and Discussions for AI Model

5.7.1. Results on AI Model

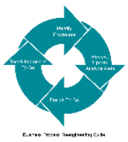
This chapter aims to address the lack of research on CNs and DRs for an AI-based SC model. First of all, an evaluation model is developed, based on the factors gathered from the literature. It is then adapted to the case study under favor of the experts. Throughout the creation and analysis of the data, authors repeatedly consulted with these experts for conceptual validity of the factors and concepts. The results of this chapter are also approved at the scientific and user levels.

Table 5.20: HoQ Sheme for AI in SC

		DR1	DR2	DR3	DR4	DR5	DR6	DR7	DR8	DR9	DR10	DR11	DR12	DR13	DR14	DR15	DR16	Weights
CN1	CN11	H	H										H					0.07
	CN12	H	H										H					0.04
	CN13	MP	MP										H	MP		FH		0.05
	CN14	P	P				P						P	H				0.02
CN2	CN21			FH		FH					E			FP		FP		0.12
	CN22						E								FH		E	0.02
	CN23				E		E								E			0.06
	CN24			FH			P							FP				0.10
CN3	CN31			P			P						MP		MP			0.02
	CN32								FP				MP					0.02
	CN33					FH					P							0.03
	CN34					P					FH							0.02
CN4	CN41			E	E										FP			0.02
	CN42			E	E							P						0.03
	CN43			E	E							FH						0.02
	CN44			P	P	FH						FP	MP					0.03
CN5	CN51					P		P	P	FH	FP				P			0.13
	CN52					P		P	P		FP						P	0.09
	CN53		P			E			P				MP					0.06
	CN54						FP	E	FH								P	0.05
S Function		-0.71	-0.66	-0.38	-0.82	-0.34	-0.75	-0.73	-0.77	-0.67	-0.65	-0.93	-0.50	-0.78	-0.74	-0.80	-0.86	
H Function		0.97	0.96	0.92	0.99	0.93	0.98	0.97	0.96	0.95	0.96	0.95	0.91	0.97	0.97	0.97	0.98	
Ranking		7	5	2	14	1	10	8	11	6	4	16	3	12	9	13	15	

First step of the HoQ approach addresses the “what” question for CNs and DRs in RQ1 and RQ5.2. Accordingly, step 2 to 8 addresses the “what” question for importance degrees of these factors. Overall application shows the capability of this extended MCDM-QFD methodology to support decision making which answers RQ5.3. According to the study, the five most important CNs in an AI-based SC are (Table 5.21): Stakeholder management, Reliability, Accuracy, Standardization and compliance, and Cost reduction. These factors are also widely discussed in the literature.

Table 5.21: Output of CNs for AI in SC

Dimensions	Criteria	Final Weights
Economic 	*Cost Reduction*	0.07
	Time Reduction	0.04
	Service Improvement	0.05
	Inventory Management	0.02
Informational 	*Reliability*	0.12
	Integrity	0.02
	Consistency	0.06
	Accuracy	0.10
Processual 	*Traceability*	0.02
	Transparency	0.02
	Security	0.03
	Privacy	0.02
Technical 	*Availability*	0.02
	Upgrade Maturity	0.03
	Interoperability	0.02
	Responsiveness	0.03
Organizational 	*Stakeholder Management*	0.13
	Standardization	0.09
	Reduced Impact	0.06
	Accountability	0.05

Sodhi et al. (2022) found cost as the top factor in their assessments. The types of costs they investigate includes big data, cost of technical setup, training, and support. Reliability and Accuracy factors are also highly needed as AI is heavily rely on huge amount of data, collection of appropriate inputs (Senapati et al., 2024). Data quality and governance were also considered as main criteria in the investigation of Liang et al. (2024) for AI service supplier selection in SC.The significance of compliance with regulations, government support, and regulatory framework have also been identified as a key factor for adoption by Dora et al. (2022) and Kumar et al. (2023). For stakeholder management, Li et al. (2024a) examined the relationships between supplier and buyer in AI based SC and emphasized the importance of coordination.

Based on these CNs, top five DRs are found as: Impediment diagnosis, Precise programming, Intelligent automation, Securing sensitive data, and Learning and decision making. Liang et al. (2024) considered anomaly detection, security structure as evaluation criteria of an AI supplier. Senapati et al. (2024), and Helo and Hao (2022) stated automation and learning factors as important AI methods in SC applications. They indicated that the techniques infuse intelligence in systems to make them gain the ability to automatically learn and adapt to a changing environment using past experiences through training. Also a well-established infrastructure are critic for the successful AI incorporation (Dora et al., 2022; Kumar et al., 2023). In their research, Dora et al. (2022) also ranked this factor in one of the first two positions among their critical factors.

5.7.2. Sensitivity Analysis

This section contains a sensitivity calculation for consistency-confidence based aggregation parameter. When combining the individual preferences of experts, the parameter δ is used for controlling the weight of both confidence and consistency degrees of expert assessments. By the suggestion of experts, δ was selected as 0.3 in this research. Experts preferred the results to be dependent more on consistency levels of evaluations than confidence levels of individuals. Here, an analysis for sensitivity can be conducted on behalf of this parameter to assess the results considering the alteration in the confidence and consistency weights. This step is performed by appointing 5 different sample δ values. With the control of the changes in aggregation for the weighting vectors of experts which are seen in Table 5.22, an example outcome for the relation between CN31 and CN1 was achieved, as shown in Figure 5.5.

Table 5.22: Sensitivity results of expert weights for CN31-CN1

δ \ $W_{experts}$	W_{E1}	W_{E2}	W_{E3}	W_{E4}	W_{E5}	W
0.1	0.13	0.48	0.12	0.18	0.09	$W_{E2}>W_{E4}>W_{E1}>W_{E3}>W_{E5}$
0.3	0.12	0.18	0.47	0.12	0.11	$W_{E3}>W_{E2}>W_{E1}=W_{E4}>W_{E5}$
0.5	0.14	0.18	0.47	0.12	0.09	$W_{E3}>W_{E2}>W_{E1}>W_{E4}>W_{E5}$
0.7	0.13	0.46	0.19	0.12	0.10	$W_{E2}>W_{E3}>W_{E1}>W_{E4}>W_{E5}$
0.9	0.14	0.46	0.18	0.12	0.10	$W_{E2}>W_{E3}>W_{E1}>W_{E4}>W_{E5}$

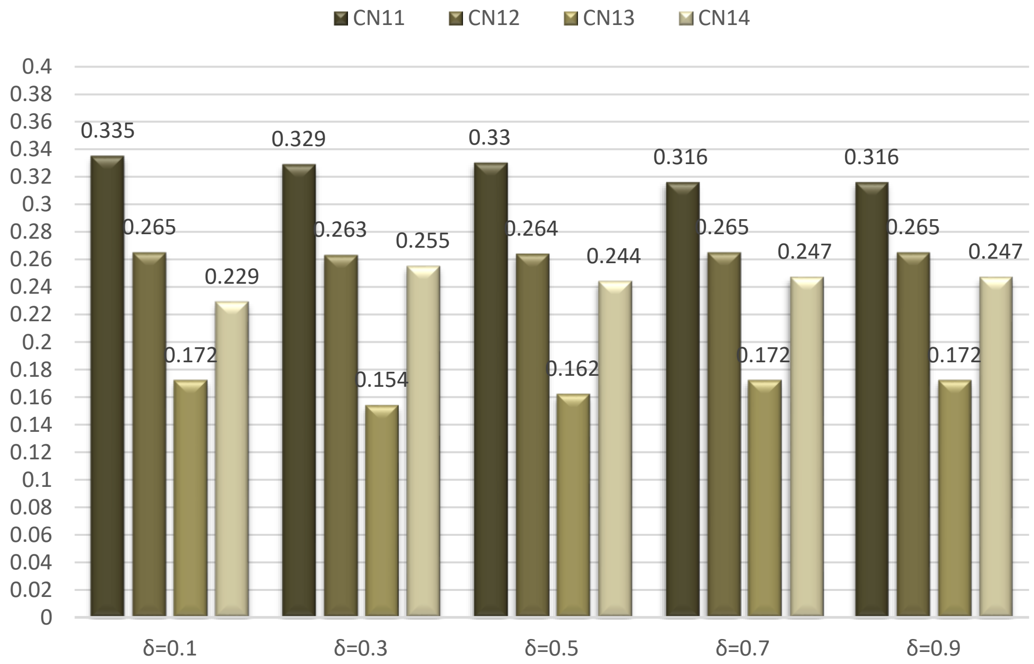


Figure 5.5: Sensitivity results for CN31-CN1

According to the analysis, the effect of δ parameter seems varying which results on different expert weights and orderings in decision making. In previous sensitivity analyzes, CC and CF of the experts were similar. Therefore the change in weights were not visible. Here as these values highly vary between experts, it reflected to the orderings and significant changes in CN1 weights. Even though the ranking of CN1 is same in all δ values, as the weights are considerably changing (e.g. CN11 moves from 0.335 to 0.316), it had effect on DR ranking. The more incomplete evaluations experts have, the less CF they have. This leads to more significant changes in CN priorities also which can be seen in Figure 5.4. When CN weights starts to change and this might affect the DRs ranking also if the change is too high.

5.7.3. Comparative Analysis

For the purpose of comparison, IFWA operator used again to see here the effects on AI based CNs. The comparison analysis in this section resulted in the same rankings and highly similar weights. This indicates that both of these operators are effective in resolving aggregation concerns. However, in previous chapter's analysis, the changes were seen on the close valued weights. The results of the examination are depicted in Figure 5.6. Here for AI point of view, the rankings in the primary criteria comparison are found as Organizational > Informational> Economic > Processual >Technical with both CC-IOWA and IFWA operators. From this comparative analysis, it can be inferred that these operators assign different weights, which can affect the final results. Although the rankings do not change significantly in this analysis, the impact of the operators can be more clearly observed as the rankings fluctuate with different expert evaluations.

Figure 5.6: Comparison results for AI CNs

6. MANAGERIAL IMPLICATIONS

In this chapter, the motivation is to analyze the results of previous chapters, and give insights about the common and diverse points of these two technologies, as this will direct the literature and enable practitioners to form proper strategies. This motivation defined four interlocking research questions (RQs) to study:

(RQ6.1) What are the diverse or common dimensions, themes, focus areas associated with Blockchain and AI in SC (based on results of Section 2)?

(RQ6.2) What are the diverse or common top risk factors associated with Blockchain and AI in SC (based on results of Section 4)?

(RQ6.3) What are the diverse or common top success factors associated with Blockchain and AI in SC (based on results of Section 4)?

(RQ6.4) What are the diverse or common CNs and DRs associated with Blockchain and AI in SC (based on results of Section 5)?

(RQ6.5) What are the diverse or common technical results associated with sensitivity analysis and comparisons (based on results of Sections 4 and 5)?

6.1. Implications on Literature Review

With the conclusion of Section 2, several points can be discussed and conclusions can be drawn as the answer of RQ6.1. Table 6.1 summarizes the most used types of attributes in the subjected literatures based on the science mapping analysis outputs. The outputs have consistency among attributes. Healthcare and agriculture resulted as the area that investigates or makes use of these technologies at most. This is relevant with the cybersecurity, traceability, and big data aspects as these sectors have higher counterfeit ratios and backtracking needs than others. It is seen that IoT is the most studies technology with Blockchain and AI in the literature. While in Blockchain-SC and AI-SC fields have mostly research and decision application studies, the combined Blockchain-AI-SC literature has mostly research and literature review yet. The introduction of Blockchain and AI into the SC has the high potential to reform and innovate the way goods and services are tracked and monitored throughout the entire chain from the time of product pickup to the time it reaches the consumers. They have the ability to introduce autonomous and decentralized business models, which improve SCs' transparency and efficiency (Kumar et al. 2023). They can offer added value by ensuring that data is resistant to manipulation, access to verified information on the state of any product in SC stream is real-time. These two technologies, when combined and implemented in a SC, can offer a strong foundation for safe communication amongst system users. Each technology benefits from the other (Kumar et al. 2024).

Table 6.1: Publication Analysis for Blockchain, AI, and SC

	Blockchain Studies	***AI Studies***	***Blockchain + AI Studies***
Area	Healthcare, Food, Agriculture	Healthcare, Logistics	Healthcare, Smart Systems
Focus	Digitalization, Sustainability, Cost - Finance	Information Management, Risk Management, Operations Management	Sustainability, Circular Economy
Integration	IoT	IoT, Blockchain, ML	IoT
Article Type	Research, Decision Applications	Research, Decision Applications	Research, Literature Survey
Aspect	Traceability, Security, Digital Storage	Big Data Analytics, Automation	Traceability, Security, Big Data, Digital Storage

Blockchain technology can assist in resolving this issue by offering a transparent and safe database for information storage, and AI can simulate how the human mind solves problems. AI provides the necessary intelligence to Blockchain as it can read, comprehend, and correlate data at incredible speed, thoroughly and rapidly (Sodhi et al.

2022). When Blockchain and AI are combined together, decentralized AI apps and algorithms are created with reliable and shared data platform for storage, learning, and decisions. This platform can be quite helpful (Ressi et al. 2024). AI models integrated into smart contracts on a Blockchain system may select the most environmentally friendly shipping option, execute transactions as stock purchases, payments, and reorders depending on predetermined criteria and events, and recommend expired products to return. Therefore, sustainability and circular economy focuses in SCs can be achieved more effectively. However, as this integration of Blockchain and AI is rather new in SC, to maximize the benefit of this interaction there are several research and application directions that can be performed.

6.2. Implications on Risk Factors

With the conclusion of Section 4, several points can be discussed and conclusions can be drawn as the answer of RQ6.2. When comparing these evaluations, in the top five, it can be seen that Blockchain and AI have common cost and knowledge concerns which are shown in Figure 6.1. Differently from each other, while interoperability, compliance and coordination issues are seen as more risky in Blockchain implementation, data management and safety issues are seen as more risky in AI. Here, Blockchain can bring several valuable contributions to the world of AI. Therefore, the integration of Blockchain and AI in a SC system, can enhance AI's capabilities and also will help to cope with data risk that is seen in literature and also in this study. Blockchain's primary advantage for AI is the security and integrity of data. The immutable nature of the ledger prevents any unauthorized changes, ensuring the data's reliability and safety. This is essential for AI, which requires dependable data sources to make precise predictions. By keeping data in blocks that cannot be altered, Blockchain improves the accuracy of the information fed into AI algorithms.

Additionally, cryptographic techniques employed in Blockchain guarantee the protection of sensitive information, enhancing the dependability of AI-driven decision-making processes in SCs. However it's important to acknowledge that both Blockchain and AI are relatively new technologies with a complex nature, and integrating them with traditional information systems in any organization can be challenging (Kumar et al., 2024). As a result, AI may exacerbate the risks associated with interoperability and compliance with existing technology in Blockchain. Nevertheless, it's crucial to find ways to align these systems to take advantage of the benefits that Blockchain and AI offer.

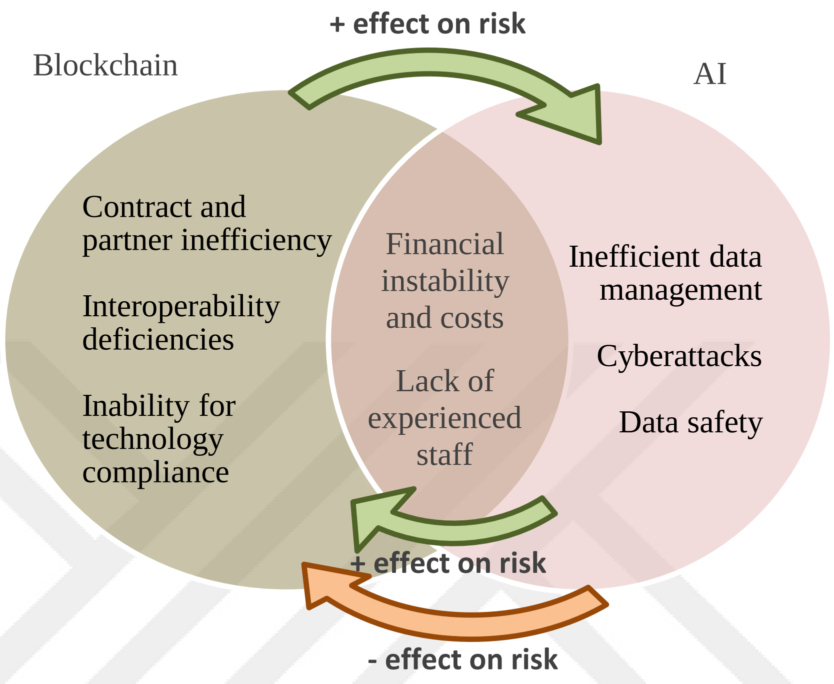


Figure 6.1: Top risk factors for Blockchain and AI

6.3. Implications on Success Factors

When comparing these evaluations, in the top five, it can be seen that Blockchain and AI have two common factors to be successful as ensuring security and privacy, and transforming culture for technological readiness and maturity which are shown in Figure 6.2. Differently from each other, while management commitment, financial capital, availability and responsiveness issues are seen as top keys in Blockchain implementation, regulatory compliance, acceptance, and compatibility issues are seen as important success factors for AI.

Here, incorporating AI and Blockchain can significantly enhance the SC security. AI-driven algorithms are highly proficient in the realm of security monitoring and threat detection. AI is capable of constantly analyzing network traffic to detect patterns and anomalies that could show potential cyber threats. This proactive approach to security is essential in today's globalized era, given the high stakes involved in safeguarding sensitive data and valuable digital assets stored on the Blockchain. Collaboration between Blockchain and AI can lead to innovation and higher technological maturity as these technologies converge and enhance each other. By mutually reinforcing each other in the two key factors as illustrated in Figure 4.5, they can also positively impact both management and user acceptance, as well as government regulator support and pressure on firms to incorporate these technologies in their SC operations and the development of appropriate regulations.

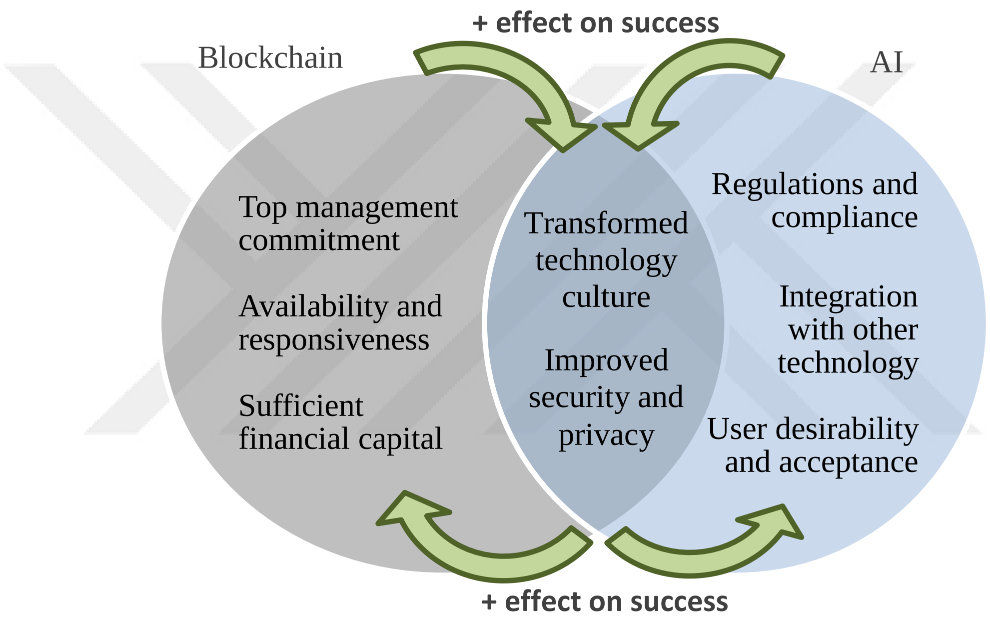


Figure 6.2: Top success factors for Blockchain and AI

6.4. Implications on CNs and DRs

With the conclusion of Section 4, several points can be discussed and conclusions can be drawn as the answer of RQ6.3. Based on the CNs and DRs of this study, the proposed model can be seen that supports the SC with different tasks in Figure 6.3. It also demonstrates where the different focus points of the DRs lie in this AI implementation model.

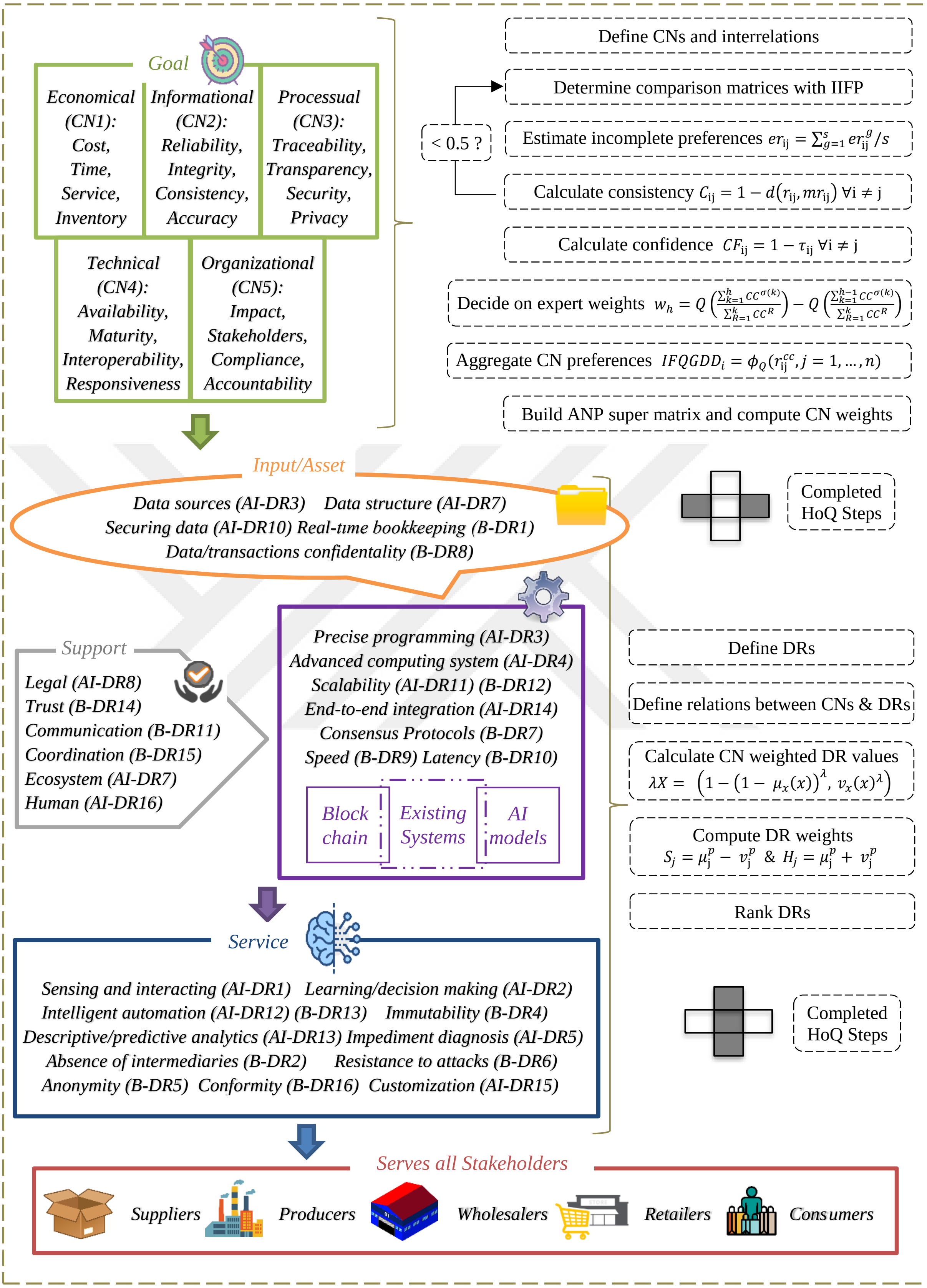


Figure 6.3: Proposed model for Blockchain and AI based SC design

When top five CNs are checked, it can be seen from Figure 6.4 that for both technology integration in SC, customers/users/organizations expect effects on cost reduction and financial efficiency, and also expect these technologies to help on better stakeholder management and make the chain more reliable. Differently from each other, while time reduction and traceability dimensions are seen as more desired CNs in Blockchain implementation, data accuracy and standardization issues are expected more in AI. Here, the integrated usage of Blockchain and AI can support some customer expectations for an effective SC structure. Blockchain's immutable records can help on accuracy of the data for AI. The decentralized nature of Blockchain reduces risks of data tampering and fraud, ensuring that all participants in the SC can trust the information. In addition, with more accurate analyzes and insights of AI, reliability of the system will increase. ML algorithms can provide accurate forecasts for demand, enabling better inventory management and reducing excess stock or shortages, which will support reliability and time reduction. AI tools can optimize routes for delivery, reducing transportation costs and time, and improving efficiency.

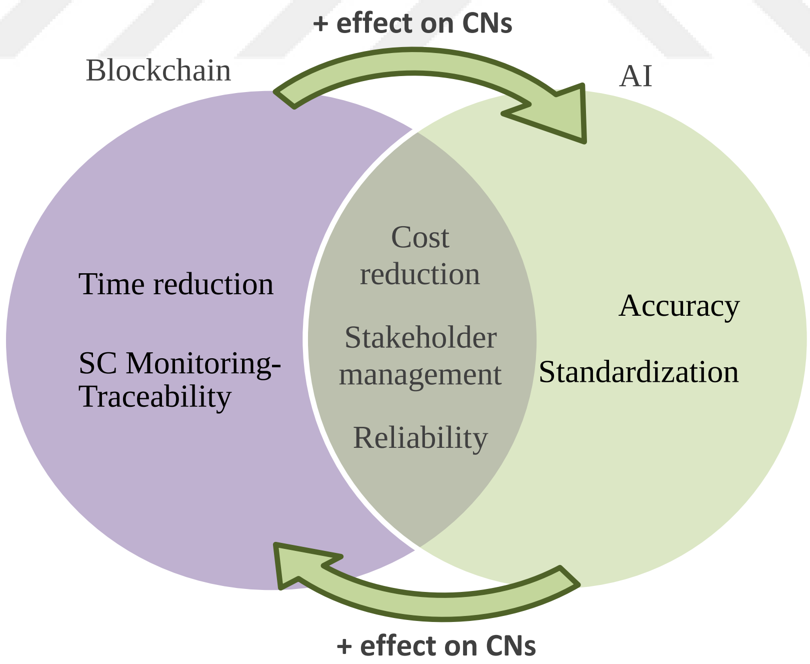


Figure 6.4: Top CNs for Blockchain and AI

When top five DRs are checked, it can be seen from Figure 6.5 that while automation, effective coordination, conformity, transaction and data confidentiality, and consensus protocols are the five most important requirements for Blockchain implementation, intelligent process automation, impediment diagnosis, precise programming, securing data, and learning & decision making are the five most important requirements for AI implementation. From those DRs automation and securing the data comes to fore for both technology implementation in SC. Here, Blockchain again reduces risks of data tampering and fraud with its decentralized nature, and provides enhanced data security. AI on the other hand, can monitor equipment performance and predict failures before they occur. Automated inspection processes powered by AI can help identify defects in products early in the production cycle. These will help on the coordination and collaboration among various stakeholders in SC.

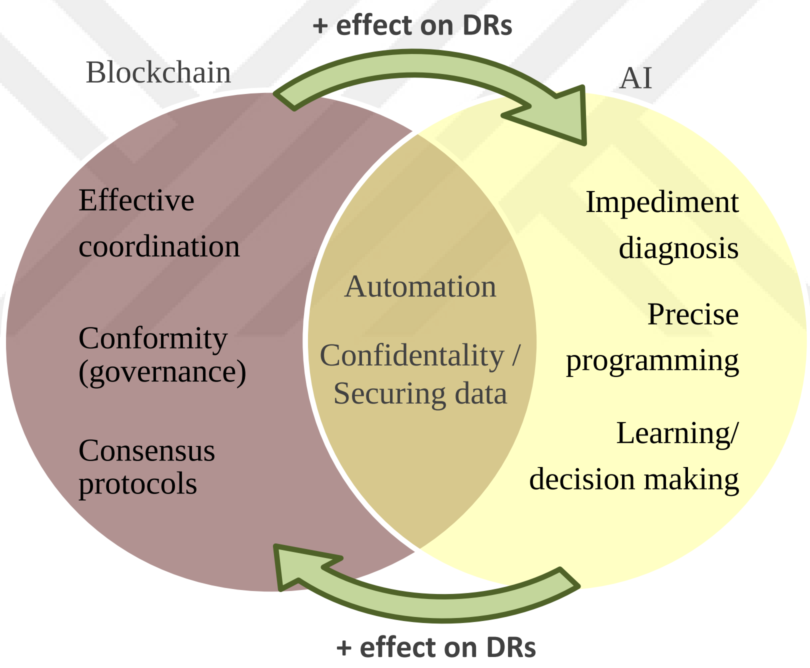


Figure 6.5: Top DRs for Blockchain and AI

To support top these five Blockchain DRs, different features of Blockchain can be considered. Blockchains can be categorized as public, private, or consortium (Rivera et al., 2024). The main distinctions among public and private Blockchains are the consensus protocol and the authorizations necessary to access the network. Public Blockchains allow processes to be visible to all participants and allow open participation in the process. Private Blockchains are Blockchains that allow sharing among companies and limit access to the network. Consortium Blockchains can be defined as partly specific and permitted Blockchains. When applied in businesses, private Blockchains are preferred (Erol et al., 2021). So, this disseertation also focuses on private Blockchain structure. Given these characteristics from the literature, Table 6.2 shows which top DRs of Blockchain supports what and how in a SC.

Table 6.2: DR consideration for Blockchain Implementation in SC

Which DR	***Supports what SC topic***	***Supports how***	***Which Blockchain***
Automation	Procurement Fulfillment /Payments Inventory management Logistics/Transportation	Smart Contracts Cryptocurrency	All types
Effective coordination	Real time feedback loop Trust enhancement SC synchronization	Transparent bookkeeping Peer-to-peer network	All types
Conformity	Complience Regulatory Reporting Accountability	Transaction tracking and historical data Smart contracts	All types
Data and transaction confidentiality	Risk Management Security Resilience	Immutable distributed ledger Cryptography	All types
Consensus protocols	Collaboration Service enhancement	Agreement mechanisms (e.g. Proof of stake (PoS), PoA, Multi-signiture, PBFT)	All types

By enabling transparency, reducing administrative overhead, and improving security, Blockchain can revolutionize nearly every aspect of the SC. It enhances efficiency, reduces fraud, increases trust among stakeholders, and enables real-time decision-making across procurement, production, transportation, and customer-facing operations. Blockchain’s decentralized, immutable ledger helps create a more seamless and trustworthy SC ecosystem.

To support the top five AI DRs, different features of AI can be considered. Explainable AI is a critical one in regulated industries and scenarios where trust and understanding of AI decisions are paramount (Wagar, 2024). It focuses on ensuring the decision making processes of AI systems are understandable and transparent for humans. The goal is to provide insights into how and why a model made a particular decision or prediction, thereby increasing trust and facilitating easier debugging and improvement of AI systems. It ensures these advancements remain accessible, understandable, and trustworthy for humans (Goścień, 2025). Given these characteristics from the literature, Table 6.3 shows which top DRs of AI supports what and how in a SC.

Table 6.3: DR consideration for AI Implementation in SC

Which DR	***Supports what SC topic***	***Supports how***	***Which AI***
Intelligent process automation	Inventory management Demand forecasting Order Process/Procurement Logistics/Transportation	Collecting data Analyzing patterns Real time information processing	Discriminative Generative
Impediment diagnosis	Cost reduction Service enhancement	Analyzing patterns Predicting potential failures Generating reports	Discriminative Explainable
Precise programming	Infrastructure Cost reduction Service enhancement	Advanced analytics ML	Discriminative Generative Explainable
Securing data	Risk Management Security Resilience	Generating new (synthetic) data	Generative Responsible
Learning & decision making	Actionable & customized insights Estimation	Classification Object recognition Analyzing patterns & customer behaviors	Discriminative Generative Explainable

Generative, discriminative, responsible, and explainable AI employ contrasting methods to address different challenges. While generative models explore the fundamental structure of data, learning its patterns and connections, discriminative models focus directly on optimizing the decision boundary for maximum classification accuracy, and explainable models focuses on techniques and models that can deliver insights for the decision making process of AI systems, making the AI system operations understandable and transparent. Recognizing these distinct strengths is essential when selecting the appropriate tool for a specific task. By harnessing the capabilities of all different models, more precise and adaptable ML solutions can be created, ultimately influencing the way SCs interact with AI technology.

6.5. Implications on Sensitivity and Comparisons of IIFP based GDM

With the conclusion of Section 4 and 5, several points can be discussed and conclusions can be drawn as the answer of RQ6.5. For the aggregation of the expert preferences, the parameter δ is used for controlling the weight of both confidence and consistency degrees of individual assessments. The sensitivity analyzes show that the changes in this parameter can have effect the weights of factors and change the priority and ranking. This effect is clear especially when the decision makers have diverse opinions (evaluation matrices are distinctly different) and they have various diverse consistency and confidence degrees (which would result on different decision maker priorities). A good example to see this change is the sensitivity analysis results of Section 5.7.2. When δ is taken as 0.9 in evaluation of CN31-CN1 and the whole decision making process is solved for the AI HoQ model, its effect in the DRs is seen in Table 6.4.

On the other hand, sensitivity analysis in Section 4.4.4 shows that when CC and CF values of the experts are similar to each other, then the weights of experts for decision making are stable even if the δ value changes. The sensitivity analysis in Section 5.5.3 shows that when consistency and confidence values of the experts are diverse, the weights of experts are then changing based on the best consistency and confidence values, which might effect the CN and DR weights. However, even the expert weights are changing, if their evaluations (comparison matrices) are similar to each other, then this is also not making a significant change in the CN and DR weights.

Table 6.4: AI DR score results based on sensitivity analysis

δ = 0.3	*DR-1*	*DR-2*	*DR-3*	*DR-4*	*DR-5*	*DR-6*	*DR-7*	*DR-8*
	-0.706	-0.663	-0.378	-0.816	-0.337	-0.752	-0.725	-0.770
	7	5	2	14	1	**10**	**8**	**11**
	DR-9	*DR-10*	*DR-11*	*DR-12*	*DR-13*	*DR-14*	*DR-15*	*DR-16*
	-0.670	-0.654	-0.931	-0.504	-0.780	-0.743	-0.795	-0.863
	6	**4**	16	3	12	9	13	15
δ = 0.9	*DR-1*	*DR-2*	*DR-3*	*DR-4*	*DR-5*	*DR-6*	*DR-7*	*DR-8*
	-0.706	-0.663	-0.370	-0.816	-0.338	-0.752	-0.699	-0.752
	8	5	2	14	1	**11**	**7**	**10**
	DR-9	*DR-10*	*DR-11*	*DR-12*	*DR-13*	*DR-14*	*DR-15*	*DR-16*
	-0.660	-0.671	-0.941	-0.503	-0.780	-0.743	-0.795	-0.853
	4	**6**	16	3	12	9	13	15

When the effect of different operator is checked, the performed comparison analyzes show that usage of different operator in decision making can affect the factor, criteria, or CN (so the DR) weights. It was observed that when expert weights in CC-IOWA are found in accordance with IFWA (same ranking – similar weights), the criteria weights are not affected as in Section 5.7.3. However, when expert weight differ (due to IFWA calculation as it does not use consistency and confidence degrees) it has effect on the final criteria weights which can be seen in Sections 4.4.5 and 5.5.4.

When the whole decision making process is solved by IFWA operator for the Blockchain HoQ model, its effect in the DRs is seen in Table 6.4. The overall results showed that in all three evaluations in Chapters 4 and 5, sensitivity and comparison of the results is dependent on the used aggregator operator and constant parameters involved in the computation. The main reason for this result is due to CC-IOWA operator considering the consistency and confidence degrees while aggregating the expert evaluations. This property gives the method its power. Therefore, this thesis recommends the CC-IOWA operator.

Table 6.5: Blockchain DR score results based on comparison analysis

CC-IOWA	*DR-1*	*DR-2*	*DR-3*	*DR-4*	*DR-5*	*DR-6*	*DR-7*	*DR-8*
	-0.500	-0.707	-0.444	-0.496	-0.475	-0.341	-0.318	-0.118
	12	**15**	**8**	**11**	10	6	5	4
	DR-9	*DR-10*	*DR-11*	*DR-12*	*DR-13*	*DR-14*	*DR-15*	*DR-16*
	-0.592	-0.721	-0.465	-0.595	0.663	-0.389	0.441	0.088
	13	16	**9**	14	1	7	2	3
IFWA	*DR-1*	*DR-2*	*DR-3*	*DR-4*	*DR-5*	*DR-6*	*DR-7*	*DR-8*
	-0.484	-0.689	-0.474	-0.502	-0.476	-0.341	-0.318	-0.155
	11	**15**	**9**	**12**	10	6	5	4
	DR-9	*DR-10*	*DR-11*	*DR-12*	*DR-13*	*DR-14*	*DR-15*	*DR-16*
	-0.619	-0.757	-0.455	-0.647	0.663	-0.364	0.448	0.088
	13	16	**8**	14	1	7	2	3

6.6. Concluding Remarks on Implications

The integration of Blockchain and AI in SC offers numerous benefits. This dissertation strongly advises the integration of these two technologies in SC to achieve more resilient and gigitalized SC structure. Below points summarizes the enhancements from the usage of these technologies.

Blockchain integration:

- Transparency: Blockchain technology provides an immutable and secure ledger for all transactions in the SC, enhancing visibility and traceability of goods, all transactions, and interactions from origin to end consumer.

- Traceability: In sectors like food and pharmaceuticals, Blockchain allows for tracking the entire lifecycle of a product, which is vital for recalls and regulatory compliance. It enables real-time tracking of goods, inventory, and shipments.
- Security: The decentralized nature of blockchain reduces risks of data tampering and fraud, ensuring that all participants in the SC can trust the information. It ensures the integrity of data and prevents data breaches, cyber attacks, and other forms of tampering.
- Immutability: Once data is recorded on the Blockchain, it cannot be altered or deleted.
- Decentralized: Blockchain operates on a decentralized network, reducing reliance on a single central authority.
- Smart Contracts: Automated contracts that execute when predetermined conditions are met can streamline processes like order fulfillment and payments, improving efficiency and reducing delays.
- Collaboration: By providing a single source of truth, Blockchain supports collaboration among various stakeholders in the SC, aligning objectives and reducing conflicts.

AI integration:

- SC Optimization: AI algorithms can analyze data from various sources to optimize SC routes for delivery, reducing transportation costs and improving delivery times.
- Automated Decision Making: AI can automate routine tasks, such as data entry, reporting, and invoicing, freeing up resources for more strategic activities.
- Demand Forecasting: AI with ML algorithm can analyze historical data and market trends to accurately predict demand, enabling more effective inventory management and reducing excess stock or shortages.
- Risk Management: AI-powered systems can identify potential risks and anomalies in the SC, allowing for proactive mitigation strategies.
- Decision-Making: AI can analyze large amounts of data to identify patterns and trends, helping stakeholders make informed decisions quickly.

- Predictive Maintenance: AI-powered predictive maintenance can detect potential equipment failures, reducing downtime and increasing overall efficiency.
- Quality Control: Automated inspection processes powered by AI can help identify defects in products early in the production cycle.

Joint (Blockchain and AI) integration:

- Enhanced Decision Making: By combining Blockchain's transparent and tamper-proof data with AI's predictive capabilities, organizations can make more informed decisions.
- Increased Efficiency: Automation of tasks and improved SC optimization can lead to significant cost savings and increased productivity.
- Improved Customer Experience: Real-time tracking and accurate demand forecasting enable faster delivery times, reduced lead times, and improved customer satisfaction.
- Increased Trust: The transparent nature of blockchain can increase trust among stakeholders, including suppliers, customers, and partners.

By leveraging the strengths of both Blockchain and AI, organizations can create a more efficient, transparent, and secure SC that drives business growth and customer satisfaction.

7. CONCLUSION AND PERSPECTIVES

This dissertation proposes a comprehensive analysis for implementing Blockchain and AI in SCs by investigating success and risk factors for these technologies as well as the CNs and DRs for system implementation. It is suggesting two ANP and HoQ evaluation frameworks combined with IIFPs. Despite the multiple benefits of the Blockchain and AI technologies, there is a clear gap in the literature regarding the assessment of success and risk factors for both technologies and the absence of roadmaps for practitioners on CNs and DRs to implement a successful SC structure based on these technologies.

Most of the studies in the literature solely deal with one type of factors (risk or success, customer or system needs), and mostly focus on one specific point or area in their evaluations. Some of these also fail to consider the uncertainties and deficiencies in the evaluations of experts. In order for these technologies to provide the expected benefits, both critical success and risk factors should be carefully examined, both CNs and critical DRs that answers these CNs must be ensured in SC integration.

To fill these gaps, this dissertation presents four assessment models with ANP and HoQ tools. The incorporation of IIFPs enhances the efficacy of the proposed methodology for practical applications. Given that Blockchain is a nascent technology, understanding of its implications remains limited. Furthermore, while AI is a more established field, its applications in SC are still evolving. Consequently, experts may provide incomplete information regarding these technologies. The proposed assessment models help overcome the lack of decision maker experience or knowledge during evaluations. To test the feasibility of the recommended models, applications were implemented with assistance from domain experts.

Additionally, sensitivity and comparative analyses were performed to verify the validity of the frameworks. As a result, this study contributes to the literature by developing an integrated approach to calculate the different opinions of experts in the evaluation of factors, and by proposing new assessment frameworks, each of which includes different clusters (criteria) and factors (sub-criteria).

The unique *theoretical contributions* of this dissertation can be summarized as following:

- Section 2 reflects how academia perceive the Blockchain, AI, and Blockchain-AI in SC, and gives directions on the gaps in the literature.
- Section 3 reflects how to evaluate the proposed GDM frameworks to handle uncertainty and incompleteness arising from experts' linguistic evaluations, and contributes to the literature by the integration of IIFPs into the ANP and HoQ for the first time.
- Section 4 reflects the prominent success and risk factors for Blockchain and AI in SC for the first time, defines their priorities with an implementation, and demonstrates the results.
- Section 5 reflects the customer requirements and design specifications for both Blockchain and AI in SC with two design models, defines their priorities with an implementation, and demonstrates the results.
- Section 6 reflects the managerial implications and discussions based on the results of previous chapters and applications.

This study also offers *practical contributions*. It can prepare SC practitioners for the implementation of this technology as following:

- Understanding and having a view of success and risk factors for Blockchain and AI in SCs can help organizations improve their digitization strategy.
- The outputs of the study can serve senior executives to proactively manage the technology adoption and implementation decision or the current transformation processes.
- The case applications can help to manage the information and expert views arising from the emergence of this type of digitization in SCs.

Limitations of this study can be summarized as following:

- The choice of success and risk factors for Chapter 4 and the choice of CNs and DRs for Chapter 5 can be changed. The selection and assessment of these factors is subjective, resource-intensive and may be limited by the availability of information. A different evaluation of the model can also lead to different findings. Therefore, the application is not expected to reflect the entirety of the topics related to success and risk factors or CNs and DRs for Blockchain and AI in SCs.
- Section 5 considers that system DRs for both Blockchain and AI are independent and does not correlate among themselves in HoQ. However, key practices may interact with each other in some cases. Such relationships can be also investigated in future work.
- The decision maker groups for evaluations involve five experts who are highly experienced in related areas. However, this number can be increased.

Future research directions can be summarized as following:

- To extend the proposed frameworks in Chapter 4 and 5, and develop new evaluation factors.
- To extend the proposed frameworks in different sectors. The Blockchain and AI based models of the study are applied in SC area and the case study in Chaper 5 is applied in a logistics company. However, sectoral differences are also effective on the construction and application of these models (e.g. as Blockchain needs consensus and approval processes, less crowded SC networks can work more effectively, but more crowded SC networks might have some delays and effects). Therefore, future work can take such effects and sectoral differences into account in the models.
- The application of different MCDM approaches to the same decision making problem. Although the difference and advantage of the decision making model is provided through difference GDM operators in Chaters 4 and 5, the difference in the MCDM applications can also be evaluated and results can be analyzed.

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BIOGRAPHICAL SKETCH

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PUBLICATIONS

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- Büyüközkan G., Tüfekçi, G., Uztürk, D. (2021). Evaluating Blockchain requirements for effective digital supply chain management. *International Journal of Production Economics*, 242, 108309.

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