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RESEARCH ARTICLE

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Constructing an intelligent agent-centric framework for supply chain traceability with blockchain integration

Abstract Blockchain technology (BCT) has significantly affected various core challenges in distributed systems, particularly traceability. Integrating BCT into supply chain management offers stakeholders enhanced security, traceability, and reliability. A comprehensive traceability system covering the complete process flow and product tracking is essential for meeting specific quality standards and making informed decisions during supply chain operations. An intelligent software-agent-oriented system with blockchain implementation could be a viable solution to address the need for operational traceability in a decentralized supply chain environment. This study presents a framework for supply chain traceability that includes comprehensive workflow tracking and control, considering both internal and external traceability perspectives. The effectiveness of the proposed framework has been evaluated in the context of a gasoline manufacturing and distribution supply chain. It demonstrates how the proposed framework helps to establish a resilient supply chain that ensures the accurate execution of activities throughout the entire supply chain lifecycle.

Keywords blockchain technology, multi-agent system, smart contract, supply chain management, traceability

1 Introduction

Supply chains (SCs) are crucial in facilitating the smooth movement of goods and services among different stakeholders. Supply chains require a robust system that enables active traceability and participant dependability to ensure operational efficiency and reliability. Traceability can be defined as the ability to access information related to the entire life cycle of a product through recorded identification (Olsen and Borit, 2013). It involves identifying, tracking, and monitoring the various components of a product, from raw materials to the finished goods. This concept allows for the monitoring of events within a system.

Blockchain technology (BCT) offers a solution to enhance traceability by granting authorized parties access to transaction data in the supply chain. Additionally, process traceability within a supply chain network (SCN) can be improved through process automation by integrating software agents.

This research aims to examine the intricacies of supply chain process execution and establish a comprehensive system context that ensures event traceability. This is crucial for understanding the operations of the supply chain at different points. Effective traceability involves monitoring the entire process flow to identify any nonconformities or defects that may occur during supply chain activities. An alert generation mechanism and emergency signaling system should be included to facilitate this.

A comprehensive traceability framework is proposed to simulate a manufacturing SC scenario within an agent-based execution environment. This framework addresses internal and external traceability concerns in supply chain management (SCM). Multi-agent systems (MAS) offer numerous advantages in enhancing traceability within SC systems. These advantages include their decentralized and autonomous nature, real-time monitoring capabilities, ability to exchange information, and adaptability for integrating intelligent decision-making procedures. Compared to traditional systems, the multi-agent approach provides a more adaptable and scalable solution for the complexities of modern SCs.

In the context of traceability within a blockchain-powered SC system, utilizing a MAS presents several noteworthy considerations when compared to alternative systems. First, MAS enables distributed intelligence,

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empowering individual agents with autonomous decision-making capabilities. This enhances traceability by allowing independent verification and recording of transactions on the blockchain. Secondly, MASs are inherently adaptable, responsive, and flexible, ensuring the traceability framework remains effective amidst evolving SC requirements. Collaborative information gathering among agents improves traceability by combining data from various sources, thereby enhancing the quality and reliability of information recorded on the blockchain. Furthermore, MASs exhibit resilience to node failures, preserving the integrity of the traceability architecture and ensuring uninterrupted monitoring functions. Dynamic task allocation optimizes traceability processes by assigning tasks based on agents' expertise and current SC demands. Additionally, MASs contribute to the decentralized consensus mechanism inherent in blockchain technology, bolstering the reliability and validity of the data recorded on the blockchain. Compared to alternative traceability systems, the MAS within the proposed framework offers advantages, including decentralized verification, real-time monitoring, cooperative information sharing, and adaptive decision-making.

In the context of MAS architecture, the term "intelligent" refers to the skills and capabilities of each software agent that enable decision-making, interaction with other agents, and adaptation to their environment. Autonomy allows agents to operate independently, making decisions without human intervention. Learning capabilities enable agents to improve performance by acquiring knowledge and experience. Adaptability allows agents to adjust their behavior based on changes in their environment or tasks. Communication abilities facilitate information exchange among agents, thereby enhancing collaboration.

Intelligent agents have problem-solving skills, enabling them to analyze complex situations and identify optimal solutions to achieve their objectives. Their behavior is goal-oriented, concentrating their actions on specific objectives. When making decisions, individuals assess different options and select actions that maximize the likelihood of achieving their goals. Additionally, intelligent agents exhibit flexibility and robustness, enabling them to handle unexpected situations and disruptions within a system. This multi-agent approach offers a more adaptable and scalable solution compared to traceability systems.

1.1 Motivation

In recent times, there has been a significant increase in research focusing on traceability within SCs. BCT has emerged as a trustworthy means of delivering effective traceability services within SC systems. However, existing literature fails to address the practical and technological intricacies crucial for implementing blockchain-driven solutions for SC traceability. This study aims to bridge this gap by comprehensively analyzing the systematic components of SCs that utilize BCT for traceability, particularly from a technological perspective. In pursuit of this, a holistic system framework has been developed, utilizing a software agent-oriented approach. This framework employs a MAS to oversee and diligently monitor blockchain-powered SC systems. The MAS ensures careful validation of the entire process flow across various stages, thereby enhancing the accuracy and reliability of the traceability process (Dasaklis et al., 2022).

1.2 Goal of the work

This research aims to address several important questions, including:

- Investigating the effectiveness of utilizing a MAS within a blockchain-powered SC to develop a comprehensive traceability framework capable of monitoring and validating the progression of processes across various stages.
- Exploring and evaluating different algorithmic or sequential problem-solving approaches to formulate robust traceability protocols tailored for SCs enhanced by BCT.
- Analyzing and assessing the impact of employing an intelligent software agent-oriented approach in establishing a reliable traceability system within SCs, focusing on ensuring stringent control over SC activities while upholding security, transparency, and performance standards.
- Developing and implementing strategies for rigorous testing and validation of diverse SC process scenarios to determine their compatibility with software agents, thus ensuring the reliability and effectiveness of the traceability framework in real-world applications.

2 Literature review

The existing literature in the related areas of research can be categorized into three main dimensions: (i) basic approaches focused on blockchain technology to address supply chain issues, (ii) solutions specifically designed to tackle traceability concerns in supply chains, and (iii) domain-specific aspects of supply chains that explore associated solution strategies. We identify the research gaps based on these criteria under the following subheadings.

2.1 Comprehensive supply chain facets

Marbouh et al. (2020) utilized a blockchain-powered framework to monitor critical information related to the COVID-19 pandemic, such as new cases, deaths, and recoveries. Their work demonstrates the effectiveness of this approach in ensuring data integrity, security, transparency, and traceability.

Sarfaraz et al. (2023) proposed a proof-of-authority (PoA) consensus mechanism to enhance information sharing and foster increased stakeholder trust when disseminating sensitive data. Their study focuses on mitigating issues related to the bullwhip effect, ultimately optimizing supply chain performance. By implementing a blockchain-based simulation model and the PoA consensus mechanism, they aim to improve supply chain efficiency and effectiveness.

Wang et al. (2022) presented a traceability system architecture designed for tracking food products across the supply chain through the integration of Radio Frequency Identification (RFID) technology and BCT. This architecture ensures decentralized data management with increased autonomy in data control. It also enhances traceability, transparency, and security within a food supply chain.

Zhang et al. (2020) have proposed an innovative blockchain-based system to ensure the traceability of concrete components. The system is based on a hybrid blockchain architecture consisting of three distinct smart contracts and an interactive source-tracing query method. This architecture ensures decentralization, transparency, and immutability, enhancing traceability.

In their research, Anupama Kumar and Anusha (2023) demonstrated the superiority of a cryptocurrency-focused supply chain network over a traditional supply chain network. Their work provides insights into the transformative role of blockchain technology within supply chain management.

2.2 Extensive supply chain traceability dimension

Cimino et al. (2011) proposed a novel framework for enhancing traceability within product supply chains by integrating automation, agent-based modeling, and a comprehensive traceability model aligned with the intricacies of business operations.

Chen et al. (2023) have developed a blueprint for an alcoholic beverage SCM using Hyperledger Fabric. Performance analysis of their blockchain-based system ensures that it is aligned with the demands of real-world supply chain operations and meets the necessary benchmarks.

Adamashvili et al. (2021) have utilized a simulation-based approach to develop a traceability system for wine SC that relies on BCT. A detailed analysis shows the potential impacts and advantages of integrating BCT in wine supply chains.

Hasan et al. (2020) have presented an innovative smart contract deployed on a blockchain platform, enabling seamless tracking and tracing of replacement parts within the supply chain. This contract facilitates a transparent and accountable flow of replacement parts from the manufacturer to suppliers and end users. An inventory system has been thoroughly designed by integrating BCT and an intelligent contract-based approach to enhance the accessibility, reliability, traceability, and security of a spare parts management system. This ensures an efficient and trustworthy ecosystem for all stakeholders.

Bocek et al. (2017) proposed a blockchain-based decentralized pharmaceutical supply chain management tracking system. Their work provides valuable insights into using blockchain to address issues in pharmaceutical supply chains.

2.3 Domain-specific supply chain traceability facets

Ravi et al. (2022) have utilized a Hyperledger Fabric-based framework to ensure data integrity, privacy, and security in a coffee supply chain. They have critically analyzed a traditional web-based infrastructure and highlighted the commercial advantages of an innovative blockchain-based system.

Cao et al. (2022) have proposed an intelligent blockchain-based trade network for a multi-tiered beef food SC. By implementing a multi-signature approach and proof of authority, they demonstrate the effective utilization of blockchain to achieve enhanced transparency and dependability in supply chain operations.

Cinque et al. (2020) have demonstrated a trustworthy management system for the Internet of Vehicles. This system implements effective authentication and authorization using blockchain nodes to establish trusted connections with the roadside components encountered by a vehicle during its journey.

Marchese and Tomarchio (2022) have proposed a BCT-based approach to enhancing quality, integrity, and traceability in agri-food SCs using Hyperledger Fabric. Their contribution to the advancement of supply chain systems in the agri-food industry shows the potential benefits of a blockchain-based approach. It provides a tangible prototype to demonstrate its feasibility and applicability.

Wang et al. (2021) have conducted a thorough examination of the impact of BCT on maritime logistics, with a specific focus on customs clearance efficiency and supply chain transparency in container cargo. Despite the potential increase in operational costs, the research proposes a spatial model to analyze inter-port competition, highlighting the value of blockchain technology in port logistics. Various utility-driven models have been utilized to investigate the relationship between net benefit and operational costs in determining the applicability of blockchain technology. The study addresses several challenges, including the high setup costs. It proposes a collaborative “BCT sharing + compensation” mechanism to achieve Pareto-optimality and resolve prisoners’ dilemmas in three lose-lose situations.

Liu et al. (2023) explored the use of BCT in maritime supply chains to address challenges in cross-border maritime supply chains. They proposed an integrated blockchain-based maritime SC model to facilitate effective operation management while ensuring decentralization, tamper-proof attributes, traceability, and intelligent operation execution. Table 1 provides a concise overview of the connections found in the existing literature and the identified research gaps. Additionally, potential solution approaches to address these gaps are outlined.

2.4 Research gaps

Drawing insights from the literature review, five research gaps have been identified, as detailed below.

- **Multi-tier traceability:** Despite the increasing adoption of traceability in direct supplier-customer interactions, comprehensive solutions for multi-tier traceability are lacking. This deficiency hinders the effective tracking of inputs and processes across different tiers, including suppliers, manufacturers, distributors, retailers, subcontractors, and collaborative partners. The research studies (Wang et al., 2022; Zhang et al., 2020; Cimino and Marcelloni, 2011; Chen et al., 2023; Adamashvili et al., 2021; Hasan et al., 2020; Liu et al., 2023; Swain and Patra, 2022a; Swain and Patra, 2024; Singh et al., 2023; Jabbar et al., 2021) addressed this gap and call for innovative solutions to advance the field of multi-tier supply chain traceability.
- **Dynamic real-time traceability:** Existing research often overlooks incorporating dynamic, real-time traceability systems, neglecting the need for promptly monitoring and adapting to disruptions, changes, and unforeseen occurrences in the supply chain. This aspect of agile response and management remains underexplored in the current literature. The research works (Wang et al., 2022; Zhang et al., 2020; Hasan et al., 2020; Cao et al., 2022; Wang et al., 2021; Liu et al., 2023; Swain and Patra, 2022a; Singh et al., 2023; Biswas et al., 2017; Basnayake and Rajapakse, 2019) focused on specific gaps in dynamic real-time traceability of supply chains, presenting opportunities for further investigation.
- **Integration of emerging technologies:** Recognizing the potential of emerging technologies such as blockchain, Internet of Things (IoTs), and artificial intelligence (AI) to enhance traceability, the current literature lacks comprehensive research on practical integration methodologies and the multifaceted implications of deploying these technologies in different supply chain contexts. The works (Wang et al., 2022; Zhang et al., 2020; Anupama et al., 2023; Cimino & Marcelloni, 2011; Chen et al., 2023; Adamashvili et al., 2021; Marchese and Tomarchio, 2022; Swain and Patra, 2022b; Singh et al., 2023; Nanda et al., 2023; Salah et al., 2019; Baralla et al., 2019; Swain and Patra, 2024; Tsang et al., 2019) highlighted the importance of incorporating emerging technologies to improve supply chain performance, particularly in terms of traceability accuracy and efficiency.
- **Human-centric factors in adoption:** There is a lack of understanding regarding the impact of human behavior and adoption dynamics when implementing traceability systems. Gaps exist in comprehending user preferences, training requirements, and the factors influencing the acceptance of traceability solutions among stakeholders. The research studies (Zhang et al., 2020; Hasan et al., 2020; Bocek et al., 2017; Kamath, 2018; Swain and Patra, 2023) emphasized the need for a human-centric approach to traceability systems in supply chains.
- **Data privacy and security:** There is a need for a more comprehensive exploration of the security and privacy concerns related to sharing sensitive traceability data among stakeholders. Existing research lacks a thorough examination of strategies to ensure data security and facilitate sharing. The studies (Marbouh et al., 2020; Sarfaraz et al., 2023; Wang et al., 2022; Anupama et al., 2023; Bocek et al., 2017; Cinque et al., 2020) discussed the requirement for a more secure traceability system that prioritizes data protection in supply chains.

Table 1 Summary of research reference solutions for targeting different issues in SC traceability

Sl. No	Identified research gaps (Connections)	Target solution approach	Related works
1	Multi-tier traceability	Holistic framework development:	Wang et al., 2022; Zhang et al., 2020; Cimino and Marcelloni, 2011; Chen et al., 2023; Adamashvili et al., 2021; Hasan et al., 2020; Liu et al., 2023; Swain and Patra, 2022a; Swain and Patra, 2024; Singh et al., 2023; Jabbar et al., 2021; Bandhu et al., 2023
2	Dynamic real-time traceability	Dynamic traceability protocols	Wang et al., 2022; Zhang et al., 2020; Hasan et al., 2020; Cao et al., 2022; Wang et al., 2021; Liu et al., 2023; Swain and Patra, 2022a; Singh et al., 2023; Biswas et al., 2017; Basnayake and Rajapakse, 2019
3	Integration of emerging technologies	Practical integration strategies	Wang et al., 2022; Zhang et al., 2020; Anupama et al., 2023; Cimino and Marcelloni, 2011; Chen et al., 2023; Adamashvili et al., 2021; Marchese and Tomarchio, 2022; Swain and Patra, 2022b; Singh et al., 2023; Nanda et al., 2023; Salah et al., 2019; Baralla et al., 2019; Swain and Patra, 2024; Tsang et al., 2019
4	Human-centric factors in adoption	User-centric design	Zhang et al., 2020; Hasan et al., 2020; Bocek et al., 2017; Kamath, 2018; Swain and Patra, 2023
5	Data privacy and security	Privacy-preserving techniques	Marbouh et al., 2020; Sarfaraz et al., 2023; Wang et al., 2022; Anupama et al., 2023; Bocek et al., 2017; Cinque et al., 2020; Bandhu et al., 2023

2.5 Approaches to addressing identified gaps (target solutions)

To address the existing voids in the research concerning SC traceability, the following approaches are contemplated:

- **Holistic framework development:** Researchers can develop comprehensive traceability frameworks that go beyond individual segments of the supply chain. These frameworks should include multi-tier traceability, providing a panoramic view of the entire supply chain from end to end.
- **Dynamic traceability protocols:** Creating traceability protocols that enable real-time data capture, sharing, and analysis offers a potential solution to address the lack of dynamic traceability. This approach would involve utilizing technologies such as blockchain and AI for continuous monitoring.
- **Practical integration strategies:** Researchers should formulate practical strategies to integrate emerging technologies like MAS and Blockchain effectively. Developing implementation plans and evaluating potential obstacles can provide valuable insights applicable to various supply chain scenarios.
- **User-centric design:** Researchers can implement a user-centered methodology to overcome hurdles in adoption. Conducting comprehensive studies to understand the motivations, concerns, and requirements of different stakeholders can guide the design of more user-oriented and accommodating traceability systems.
- **Privacy-preserving techniques:** Addressing concerns about data privacy and security can be achieved through research on privacy-preserving techniques, encryption methods, and data anonymization approaches that enable secure data sharing among supply chain partners.

Through these efforts, our research aims to make significant contributions to addressing the existing gaps in supply chain traceability. This endeavor enhances the scholarly field and promotes the practical implementation of robust traceability systems across various supply chain settings.

3 Methodology

3.1 Proposed framework

This research introduces a software agent-driven solution for end-to-end traceability of SC operations. Using a distributed architecture led by the primary agent (P-Agent), the framework employs a leading smart contract (PSC) to oversee supply chain processes. Assistant agents handle specific tasks such as supply and production. By combining a multi-agent approach with BCT, the framework ensures accurate tracking with minimal human intervention. The P-Agent supervises all phases of the supply chain, ensuring transparency and adherence to protocols. The objective is to establish a transparent, reliable, and traceable framework that governs supply chain operations and provides a comprehensive view of the traceability system through various agent roles, including S-Agent, M-Agent, D-Agent, and R-Agent for supply, manufacturing, distribution, and retail activities (Swain and Patra, 2022b).

3.2 Procedure for the framework’s deployment

Step-1: The first step in initiating a supply chain operation is to identify the roles of different agents. The P-Agent initiates the supply chain activity by calling the P_Op_Manage() method, as it manages and controls the entire supply chain. The PSC smart contract monitors the operations of the supply chain. The P-Agent tracks the functionality of the PSC. To trace specific states of the supply chain operation, a TrcTotalVal variable is initialized to 0, indicating the starting point of the operation. The P_Agent waits to start the raw material supply operation by providing the S-Agent with a random seed value until TrcTotalVal() = 0 and the operation status is “initiated.”

Step-2: The S-Agent initiates a supply operation by calling S_Op_Manage(). The S-Agent keeps track of the various states of the supply operation from creation to completion. After each operation, the P-Agent modifies the operational status to the specified state to enable further actions. If S_Op_Manage() fails during the supply operation, the S-Agent promptly informs the P-Agent about the problem. The SOMSC smart contract controls the supply operation of the supply chain.

The PAgtTraceability() pseudocode is utilized to assess the condition and progress of operations. To denote the successful completion of the raw material supply stage with an appropriate trace state name, the PAgtTracePosBitSet() pseudocode initializes the vector with a positive trace index at this point. Otherwise, the trace index value is set to −1, indicating an incomplete phase activity. The PAgtTraceThresholdCal() pseudocode is then employed to calculate the threshold value, subsequently used to initialize TrcTotalVal().

Step-3: Upon the conclusion of the raw material supply operation, the P-Agent executes the pseudocode M_Op_Manage() to commence the manufacturing process. The M-Agent retains control over the various manufacturing phases until their completion. Subsequently, the P-Agent updates the status to the “manufactured” state. The P-Agent receives notification of malfunctions during manufacturing via the M_Op_Manage() function. The MOPMSC smart contract governs the manufacturing process.

In this particular scenario, when the PAgtTraceability () is called, the traceability vector is populated with either +1 or −1, representing an efficient phase completion or an unfinished operation, respectively. The traceability threshold is then determined using the PAgtTraceThresholdCal() pseudocode.

Step-4: The D-Agent initiates the distribution process by employing the D_Op_Manage() pseudocode. The D-Agent regulates and monitors the distribution process, including inventory updates, from its inception until completion. The P-Agent updates the status to the "distributed" state. In the event of any divergence, the D_Op_Manage() pseudocode detects and alerts the higher-ranking agent. The distribution operation transactions are tracked and recorded using the SMSC.

After invoking the PAgtTraceability() function to assess the operation status, the traceability vector is set to either + 1 or −1, signifying the successful completion or failure of the current operational phase, respectively. The PAgtTraceThresholdCal() pseudocode is then called to complete the computation of the traceability threshold, which will be utilized in the subsequent steps.

Step-5: Following the P-Agent's thorough verification of the status and traceability threshold, the R_Op_Manage() pseudocode commences the retail operation. The R-Agent updates inventories while managing and monitoring the retail operations from start to finish. Upon completion, the P-Agent sets the phase status to "retailed." Any errors encountered during the retail operation are reported to the P-Agent through the R_Op_Manage() method, where they fail. The ROMSC smart contract is responsible for recording and tracking retail activity.

Following the updating procedure, the PAgtTraceability () pseudocode sets the traceability value to + 1 or −1. Finally, the PAgtTraceThresholdCal() pseudocode is called for the final computation.

Step-6: The P-Agent recognizes the completion of the retail activity and delivers the items to the customer. After completing the final traceability stage, the P-Agent signals the need to conclude the SC activity. A P-Agent alert is triggered to halt further activity when the traceindexbit is set to −1 during traceability rounds. The deployment of multiple blockchain-based smart contracts operates in parallel with multiple agents. A traceability process diagram for the entire traceability technique has been developed, as shown in Fig. 1.

3.3 Case study

3.3.1 Background: Gasoline Manufacturing and Distribution Supply Chain (GMDSC)

ABCFuelFirm, a renowned fuel cooperative in Odisha, India, prides itself on its well-established and widely recognized supply chain, which has been integral to its success. This cooperative maintains a robust and cohesive supply chain framework, which is crucial in coordinating the procurement, refining, and distribution of petroleum products across various sectors in Odisha. In this context, we present a comprehensive overview of ABCFuelFirm's gasoline manufacturing and distribution supply chain.

We provide a detailed outline of the entire GMDSC process, starting with Crude Oil Procurement, followed by Manufacturing operations, including Refining and Blending, then proceeding to Gasoline Distribution and Retailing, and concluding with the closure of GMDSC Operations at the customer end. Let's investigate the specific phases and their operational processes within the GMDSC.

- **Crude oil procurement:** This initial stage involves procuring crude oil, the raw material for the production of gasoline and other petroleum products. It includes sourcing and acquiring crude oil from various suppliers, considering cost, quality, and availability factors. Oil companies often have agreements with oil-producing countries or purchase crude oil from the open market.
- **Manufacturing operation as refining and blending:** During the refining and blending stage, crude oil manufacturing operations occur. The crude oil is transported to refineries where it undergoes complex refining processes to break it down into various fractions, including gasoline. These fractions are segregated based on their boiling points. Gasoline, a mixture of diverse hydrocarbons, is created by blending the different fractions obtained from refining. This blending process enables gasoline production with specific octane ratings and characteristics. Additionally, additives are incorporated to enhance performance and efficiency and to reduce emissions. Refining includes distillation, cracking, and reforming, which are crucial steps in breaking crude oil into distinct components. On the other hand, blending involves combining these refined components in precise ratios to achieve the desired gasoline properties, such as octane rating and volatility.
- **Gasoline distribution:** The distribution of gasoline is a pivotal stage, which includes fuel transportation from the refinery to terminals, distribution centers, and storage facilities, facilitating retail sales. Various modes of transportation, including pipelines and tanker trucks, are employed to ensure the efficient delivery of fuel to multiple locations.
- **Gasoline retailing:** Consumers can purchase gasoline at retail locations, predominantly gas stations. Establishing and managing these gas stations that cater to customers' fuel requirements is integral to gasoline retailing. Responsibilities include overseeing fuel inventories, pricing, and delivering exceptional customer service.
- **GMDSC operation closure at customer end:** The final phase of the GMDSC involves the interaction between the supply chain and the end customer. This includes the customer's gas purchase, vehicle fueling, and the completion of the GMDSC cycle. Furthermore, this stage involves managing financial transactions, implementing loyalty programs, and ensuring a positive client experience.

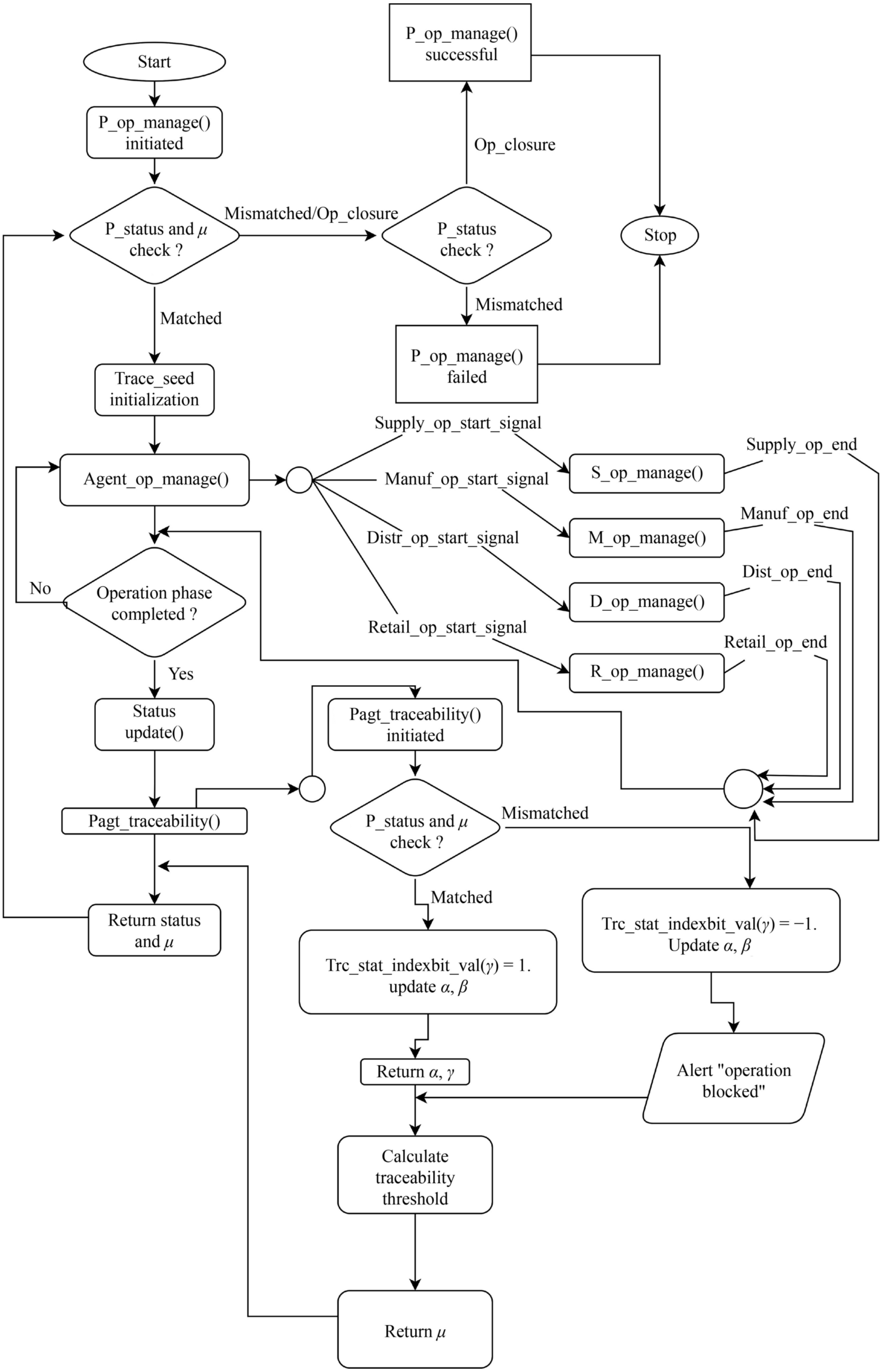

Fig. 1 An agent-oriented distributed traceability system framework workflow diagram.

These stages outline the key processes in gasoline manufacturing, distribution, and the GMDSC. Each stage plays a critical role in maintaining a consistent and efficient flow of gasoline from the initial crude oil procurement stage to the end customer's consumption.

3.3.2 Traceability details of GMDSC

Traceability is a crucial aspect of the gasoline SC as it tracks the product from its origin to the final customer. The major components of traceability are as follows:

- **Raw material tracking:** Traceability begins with identifying the source of the crude oil used to manufacture gasoline. The oil's origin, movement, and management are documented.
- **Refining process:** Every stage of the refinement process, including mixing various fractions and adding additives, is documented. This ensures that the final product meets the desired specifications.
- **Identification of the batch or lot:** Gasoline is frequently produced in batches or lots. Each batch is given a particular identifier that may be used to follow it as it moves through the SC.
- **Storage and transportation:** Data are kept on the storage tanks, pipelines, ships, and trucks used to move gasoline. This includes information about the places, the times, and the numbers.
- **Distribution points:** Gas stations and distribution centers both maintain traceability. Gasoline is tracked as it moves from terminals to specific stations, ensuring precise inventory management.
- **Retail transactions:** Gas station transactions, including sales, amounts sold, and prices, are recorded for further traceability.
- **Documentation and records:** Extensive records, including digital documents, analog records, and electronic systems, are kept at every stage.

3.3.3 Issues in traceability of GMDSC

- **Complex supply chain:** Maintaining comprehensive traceability is difficult because of the gasoline SC's size, complexity, and wide range of stakeholders.
- **Data accuracy:** Incorrect records and hampered traceability might result from human errors in data entry.
- **Integration challenges:** Integrating traceability solutions across several companies, systems, and platforms can be challenging.
- **Infrastructure and technology:** Not all stakeholders possess the technological aptitude to establish and maintain traceability systems.
- **Data security and privacy** issues are raised by disclosing specific SC information.
- **Regulatory variations:** Traceability standards may vary throughout regions, making it more challenging to maintain compliance.
- **Cost:** Implementing traceability solutions can be expensive for smaller businesses.

The featured case study reveals the complex nature of the fuel manufacturing and distribution SC. This multifaceted process includes various stages, from raw material extraction to end-user engagements. Notably, the case study highlights the importance of operational efficiency, safety, and environmental stewardship in managing the SC dynamics of a critical resource like gasoline. The proposed framework is applied as a solution scenario within the gasoline SC context to address these complex challenges and implement a viable solution. The primary objective is to improve traceability, ensure product quality and safety enhancements, and build customer trust.

3.4 Framework implementation on GMDSC: An illustrative scenario

This paper presents an innovative agent-based traceability framework for optimizing the gasoline manufacturing and distribution SC. The study begins by identifying the roles played by various agents, marking the start of SC operations. The GMDP-Agent takes a proactive stance by invoking the GMDSC_Op_Manage() method, thereby acquiring control over the entire SC's operations. The GMD_SC smart contract facilitates operational oversight, vigilantly monitoring the functionalities of GMD_SC through the GMDP-Agent's oversight. Beginning with a TrcTotalVal variable at zero, this study observes the GMDP_Agent awaiting the start of raw material supply operations until TrcTotalVal() reaches zero, concurrently marking the operation status as "initiated." Subsequently, raw material supply begins as the GMDP_Agent transmits a random seed value to the GMDS-Agent.

The GMDS-Agent's engagement follows as it invokes GMDS_Op_Manage() to start the supply operation. Throughout the operation, the GMDS-Agent maintains vigilance over different supply operation states. The SC's inception was marked by procuring raw materials, mainly crude oil, and transporting them to refineries. The GMDS-Agent actively monitors this transfer task. Upon operation completion, the GMDP-Agent modifies the operational status to the designated state as "Crude_Oil_Procurement." Any disruption prompts the GMDS-Agent to notify the GMDP-Agent swiftly. The GMDSOM_SC smart contract exercises control over the supply operation within the SC.

The GMDPAgtTraceability() pseudocode confirms operational states and conditions, determining successful completion or incomplete phase activity. This phase's successful culmination is denoted by initializing the trace-index vector with a positive value, whereas insufficient activity is represented by a trace-index value of −1. The GMDPAgtTraceThresholdCal() pseudocode computes the threshold value, establishing TrcTotalVal().

The GMDP-Agent executes the GMDM_Op_Manage() pseudocode, initiating the manufacturing process. The GMDM-Agent oversees the various manufacturing phases until their fulfillment. The complex refining of crude oil into different fractions, including gasoline, involves careful separation based on boiling points. Gasoline is then synthesized by blending these fractions and incorporating additives for enhanced performance, efficiency, and emissions reduction. The refined gasoline is stored before being transported to distribution terminals. The GMDM-Agent actively monitors the entire process. Following phase completion, the GMDP-Agent designates the phase status manufactured as “Refined_and_Blended.” Anomalies during the manufacturing process prompt alerts from the GMDM-Agent to the GMDP-Agent. The GMDMOPM_SC smart contract oversees manufacturing processes.

Distribution operations are initiated by the GMDD-Agent using GMDD_Op_Manage() in step four. The refined gasoline is stored and then transported to distribution terminals, later loaded onto tanker trucks for delivery to gas stations. The GMDD-Agent comprehensively oversees the distribution process, including inventory updates, from initiation to conclusion. Post-completion, the GMDP-Agent updates the status to “Gasoline_Distributed.” Deviations in the GMDD_Op_Manage() invoke alerts to the superior agent. GMDSM_SC facilitates the recording and tracking of distribution operations.

Following these steps, GMDPAgtTraceability() determines the operational phase’s effectiveness or failure, initializing the traceability vector accordingly. GMDPAgtTraceThresholdCal() completes the computation of the traceability threshold.

The next step involves initiating retail operations through the GMDR_Op_Manage() method. Gasoline is loaded onto tanker trucks and transported to gas stations. Underground storage tanks at gas stations hold the gasoline until it’s pumped into customers' vehicles. The GMDR-Agent oversees retail operations from initiation to conclusion, managing inventories and monitoring the process. Post-operation, the GMDP-Agent updates the phase status to “Gasoline_Retailed.” Anomalies are communicated to the GMDP-Agent through the failure of the GMDR_Op_Manage() method. The GMDROM_SC smart contract governs retail activities.

Following updates, GMDPAgtTraceability() configures the traceability value, reflecting the successful completion or failure of the phase. GMDPAgtTraceThresholdCal() finalizes the traceability threshold calculation.

As retail activity concludes, the GMDP-Agent finalizes item delivery to customers in the last step with status specification as the “GMDSC_Operation_Closure.” With the ultimate traceability stage achieved, the GMDP-Agent signals the conclusion of SC activity. An alert halts further activity if the traceindexbit is set to −1 in any traceability round. Figure 2 illustrates a comprehensive operational flowchart for GMDSC.

An experimental configuration using the AgentPy simulation platform, which uses Python to create the agents and the goal-oriented functions that go along with them, has been developed and tested. The open-source Remix Solidity IDE and the decentralized Ethereum platform are the most suitable for blockchain implementation. The Web3.py module could integrate the Ethereum blockchain with the Python-oriented AgentPy environment.

4 Findings and analysis of framework

Any SC may utilize our platform to increase traceability. As MAS automate it using blockchain technology, this architecture enhances security, traceability, resilience, and effectiveness. The fundamental innovation lies in combining MAS principles for SC operations with BCT-based smart contracts to create a dual-level traceability system that tracks both the product and the process used to obtain it.

Technically, an exemplary process traceability approach improves operational effectiveness and delivers respectable SCM. The suggested model applies to all events spanning the lifespan of a traceable item (product) within the SC and is designed for end-to-end SCs. MAS deployment offers a standard system that tracks individual processes and product transit from supplier to customer. This work provides an overview of SC processes while demonstrating the entire concept of internal traceability. Maintaining traceable data items and transaction records is the primary aim of the created architecture.

4.1 Result analysis of the basic framework

This research paper presents a comprehensive framework to enhance SC traceability. The framework employs a two-level security approach to address traceability concerns from both external-level and internal-level perspectives. The first level includes external-level operations across the entire SC, while the second level focuses on internal-level operations within each step of the SC cycle. The paper highlights the challenges associated with traceability issues and emphasizes the need for effective mitigation strategies to prevent disruptions in SC flow. The technical foundation of the framework emphasizes resilience, contributing to improved SCM and operational efficiency.

The framework’s efficacy is demonstrated through practical implementation using Python and the AgentPy package. A simulated test run successfully verifies traceability operation in the SC. The results of this framework analysis are systematically presented in Table 2 (Part-A and Part-B) and Figs. 3 to 7. This table provides an overview of successful traceability operations and instances of process disruption at various SC stages, shedding light on potential concerns. Trc_Index_Bit_val = 1 (TR-True Traceability) indicates successful process

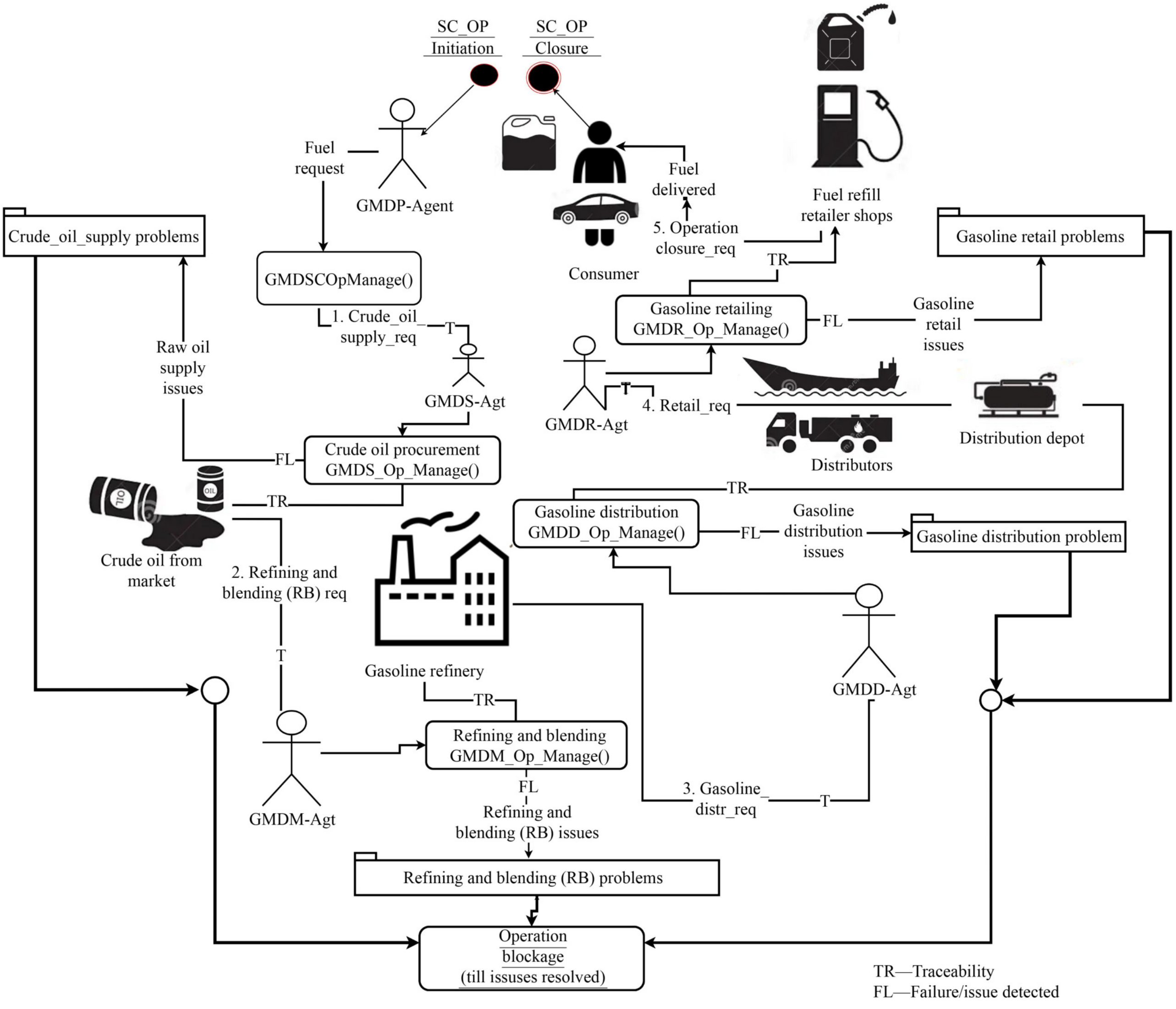

Fig. 2 GMDSC traceability system framework's OP_Flow diagram.

completion with correct traceability, while −1 (FL-Traceability Failure) signifies operation obstruction with immediate distortion reporting. Trc_Index_Bit_val = 0 denotes operations that have not yet commenced (NA). The placeholders "{{ }}" and "{}" convey ExternalTraceIndexBit and InternalTraceIndexBit values, respectively.

4.1.1 Output scenario of the proposed framework

Our technique uses operational agents within the SC framework to evaluate traceability activities. P-Agent and phase-specific agents (S-Agent, M-Agent, D-Agent, and R-Agent) comprise the two main functional agent classes. Phase-specific agents focus on certain SC phases, while P-Agents concentrate on the entire SC as external traceability factors, as depicted in Fig. 3. Pie charts show the percentage of each agent's efforts during each process stage. Figures 4–7 present a thorough internal traceability perspective, delivering insights into the traceability activities within each SC phase. The focus is on the supply, manufacture, distribution, and retail stages of S-Agent, M-Agent, D-Agent, and R-Agent. These agents ensure accurate data and product tracking within their respective phases and contribute to internal traceability. In the plot section, the designated numerical values represent the extent of effort an agent exerts for the corresponding stage within a specific phase of the SC operation.

From the external traceability perspective, Fig. 8 provides an overview of the traceability efforts during all SC phases. P-Agents are crucial since they supervise the entire SC and ensure that external traceability criteria are followed. The pie chart in Fig. 8 illustrates a comprehensive external traceability scenario and demonstrates how P-Agents cooperate in upholding traceability throughout the entire SC. The efforts made by Agents at various points in the operation are visually represented in this picture.

Table 2 Result demonstration of traceability framework (Part-A)

Sl. No.	Supply chain stage	Software agent details	External traceability status	Internal traceability status	Successful traceability (Positive outcome {TR})	Unsuccessful traceability result with Op_Blockage (Negative outcome {FL})
1	**SC Initiation**	**P-Agent**	Initiated	–	**{{NA}}**	**{{NA}}**
					{NA}	**{NA}**
2	**Supply**	**P-Agent** **S-Agent**	Initiated	Created	**{{NA}}**	**{{NA}}**
					{NA}	**{NA}**
			Initiated	Requested	**{{NA}}**	**{{FL}}**
					{TR}	**{FL}**
			Initiated	Received	**{{NA}}**	**{{FL}}**
					{TR,TR}	**{TR,FL}**
			Initiated	Responded	**{{NA}}**	**{{FL}}**
					{TR,TR,TR}	**{TR,TR,FL}**
			Initiated	Produced	**{{NA}}**	**{{FL}}**
					{TR,TR,TR,TR}	**{TR,TR,TR,FL}**
			Initiated	Item available	**{{NA}}**	**{{FL}}**
					{TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,FL}**
			Initiated	Shipped	**{{NA}}**	**{{FL}}**
					{TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,FL}**
			Initiated	Completed	**{{NA}}**	**{{FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,FL}**
			Supplied	Finished	**{{TR}}**	**{{FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,TR}**
3	**Manufacture**	**P-Agent** **M-Agent**	Supplied	Created	**{{TR}}**	**{{TR}}**
					{NA}	**{0}**
			Supplied	Requested	**{{TR}}**	**{{TR,FL}}**
					{TR}	**{FL}**
			Supplied	Received	**{{TR}}**	**{{TR,FL}}**
					{TR,TR}	**{TR,FL}**
			Supplied	Responded	**{{TR}}**	**{{TR,FL}}**
					{TR, TR, TR}	**{TR,TR,FL}**
			Supplied	Produced	**{{TR}}**	**{{TR,FL}}**
					{TR, TR, TR, TR}	**{TR,TR,TR,FL}**
			Supplied	Shipped	**{{TR}}**	**{{TR,FL}}**
					{TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,FL}**
			Supplied	Completed	**{{TR}}**	**{{TR,FL}}**
					{TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,FL}**
			Supplied	MInventory Updated	**{{TR}}**	**{{TR,FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,FL}**
			Manufactured	Finished	**{{TR, TR}}**	**{{TR,FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,TR}**

4.2 Analysis of the impact of BCT and MAS-oriented framework on GMDSC

The suggested framework is implemented in the context of the GMDSC, and the resulting scenario is presented in this section based on the result analysis of the framework. A comprehensive internal traceability perspective is provided in Figs. 9–12, which offer insights into the internal traceability activities within each phase of the GMDSC. Figure 13 provides a comprehensive overview

Table 2 Result demonstration of traceability framework (Part-B)

Sl. No.	Supply chain stage	Software agent details	External traceability status	Internal traceability status	Successful traceability (Positive outcome {TR})	Unsuccessful traceability result with Op_Blockage (Negative outcome {FL})
4	**Distribution**	**P-Agent** **D-Agent**	Manufactured	Created	**{{TR,TR}}**	**{{TR,TR}}**
					{NA}	**{NA}**
			Manufactured	Triggered	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR}	**{FL}}**
			Manufactured	Received	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR}	**{TR, FL}**
			Manufactured	Distr inventory checked	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR,TR}	**{TR,TR,FL}**
			Manufactured	Order fulfilled	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR,TR,TR}	**{TR,TR,TR,FL}**
			Manufactured	Order confirmed	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,FL}**
			Manufactured	Order shipped	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,FL}**
			Manufactured	Completed	**{{TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,FL}**
			Distributed	Finished	**{{TR,TR,TR}}**	**{{TR,TR,FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,TR}**
5	**Retail**	**P-Agent** **R-Agent**	Distributed	Created	**{{TR,TR,TR}}**	**{{TR,TR,TR}**
					{NA}	**{NA}**
			Distributed	Requested	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR}	**{FL}**
			Distributed	Registered	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR}	**{TR,FL}**
			Distributed	Retail inventory checked	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR,TR}	**{TR,TR,FL}**
			Distributed	Item available	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR,TR,TR}	**{TR,TR,TR,FL}**
			Distributed	Order confirmed	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,FL}**
			Distributed	Order shipped	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,FL}**
			Distributed	Completed	**{{TR,TR,TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,FL}**
			Retailed	Finished	**{{TR,TR,TR.TR}}**	**{{TR,TR,TR,FL}}**
					{TR,TR,TR,TR,TR,TR,TR}	**{TR,TR,TR,TR,TR,TR,TR}**
6	**Operation closure**	**P-Agent**	Completed	Finished	**{{TR,TR,TR,TR,TR}}**	**{{TR,TR,TR,TR,FL}}**
					{-}	{-}
			Sc_Op Closure	Finished (true)	**{{TR,TR,TR,TR,TR,TR}**	**{{TR,TR,TR,TR,TR,FL}**
					{-}	{-}

of the traceability efforts across the phases of the GMDSC from an external traceability perspective. The accompanying pie charts depict the traceability scenarios, illustrating how the GMDP-Agent collaborates with other agents to maintain traceability within the supply chain.

We specifically explore BCT and MAS's transformative

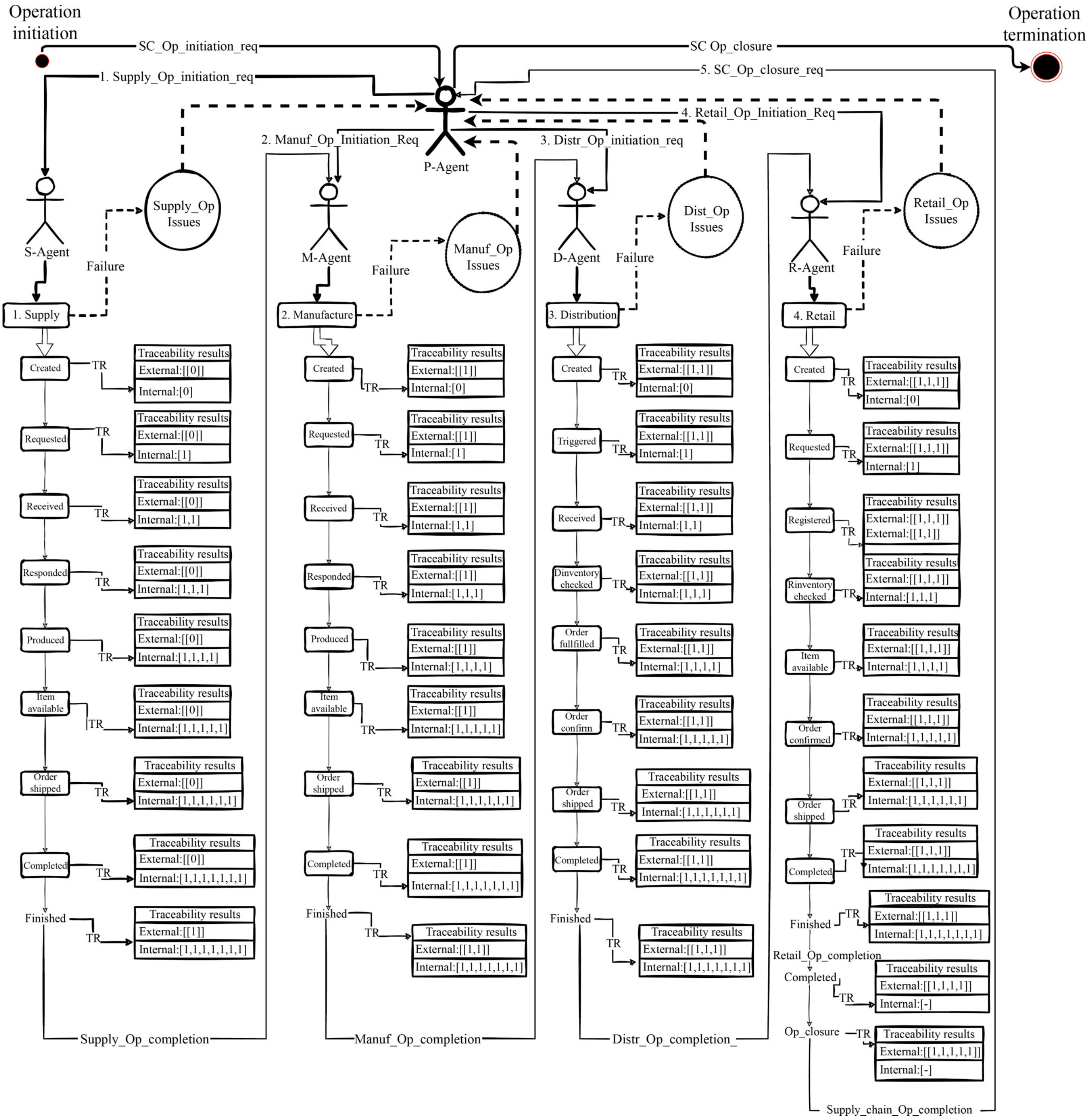

Fig. 3 An agent-oriented SC traceability system framework design and analysis.

influence on GMDSC traceability and examine how these technologies can synergistically enhance traceability throughout the GMDSC.

1) BCT in GMDSC traceability: BCT offers an immutable and decentralized ledger that securely records transactions and data across the GMDSC. The transparency and security provided by BCT significantly enhance traceability efforts. Blockchain enables:

a. **Provenance tracking:** Each step in the GMDSC can be recorded on the blockchain, allowing stakeholders to trace the origin of products.

b. **Immutable records:** Data integrity is ensured by the fact that once data has been put into the blockchain, data cannot be changed or removed.

c. **Smart contracts:** Self-executing smart contracts can automate and enforce agreements, streamlining GMDSC processes.

2) MAS in GMDSC traceability: MAS employs intelligent agents that can autonomously interact and make decisions within a complex environment. In GMDSC traceability, MAS offers:

a. **Agent coordination:** Agents can collaborate to collect and share traceability data, ensuring real-time visibility in GMDSC.

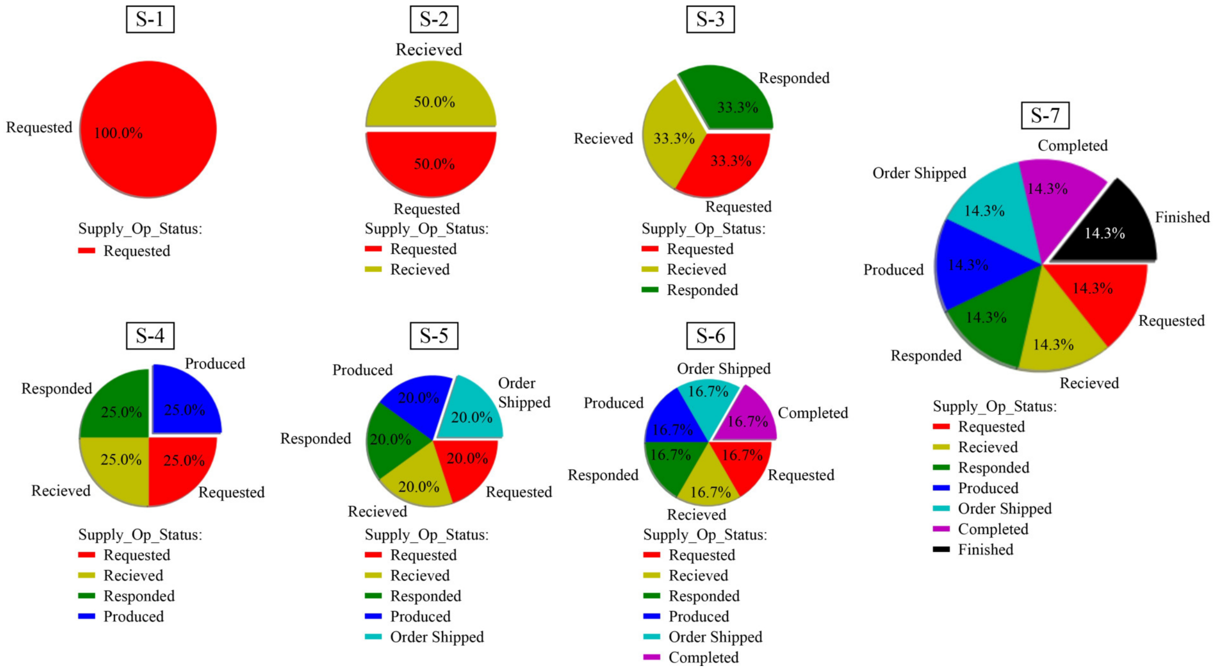

Fig. 4 Details of supply operation traceability plots from internal traceability view point (S-Agent's prospective).

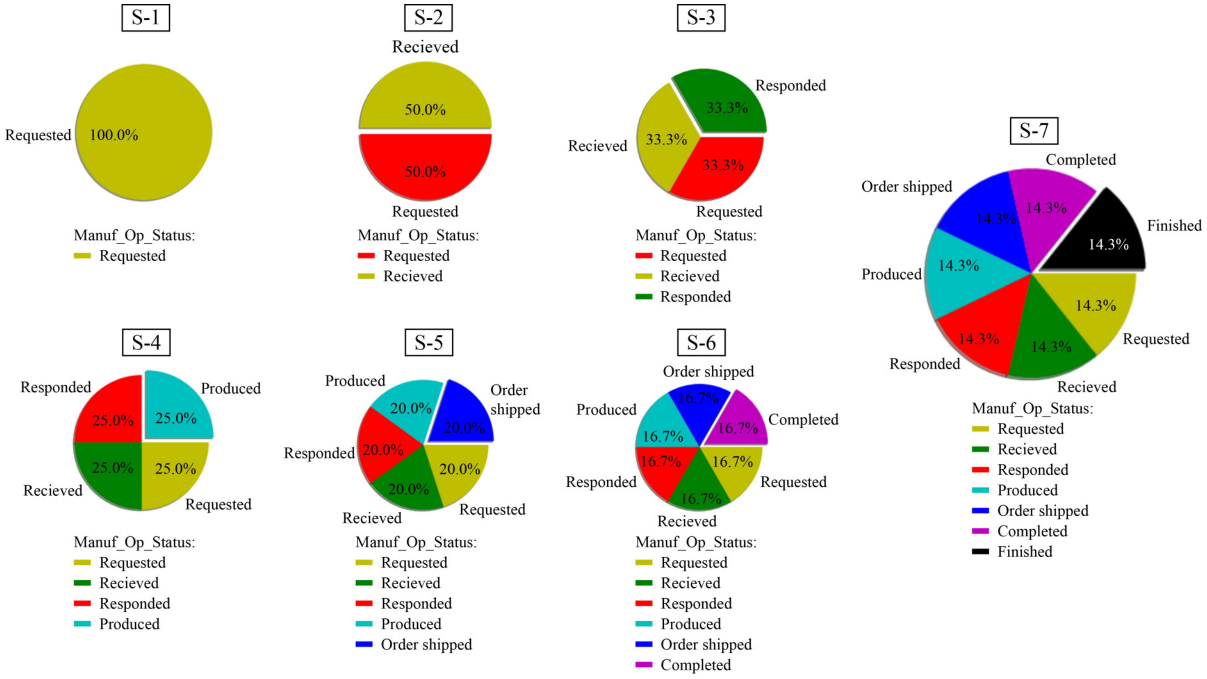

Fig. 5 Details of manufacturing operation traceability plots from internal traceability view point (M-Agent's prospective).

b. **Decision support:** MAS can support decision-making by analyzing data, predicting GMDSC disruptions, and recommending actions.

c. **Adaptability:** Agents can adapt to changing conditions and optimize GMDSC processes for improved traceability.

3) Synergy between blockchain and MAS in GMDSC traceability: The integration of BCT and MAS can significantly enhance both benefits. BCT provides an immutable ledger for data recording, while MAS facilitates intelligent decision-making and agent coordination. This synergy leads to the following advantages:

a. **Real-time traceability:** Agents can update the blockchain with real-time data, providing stakeholders

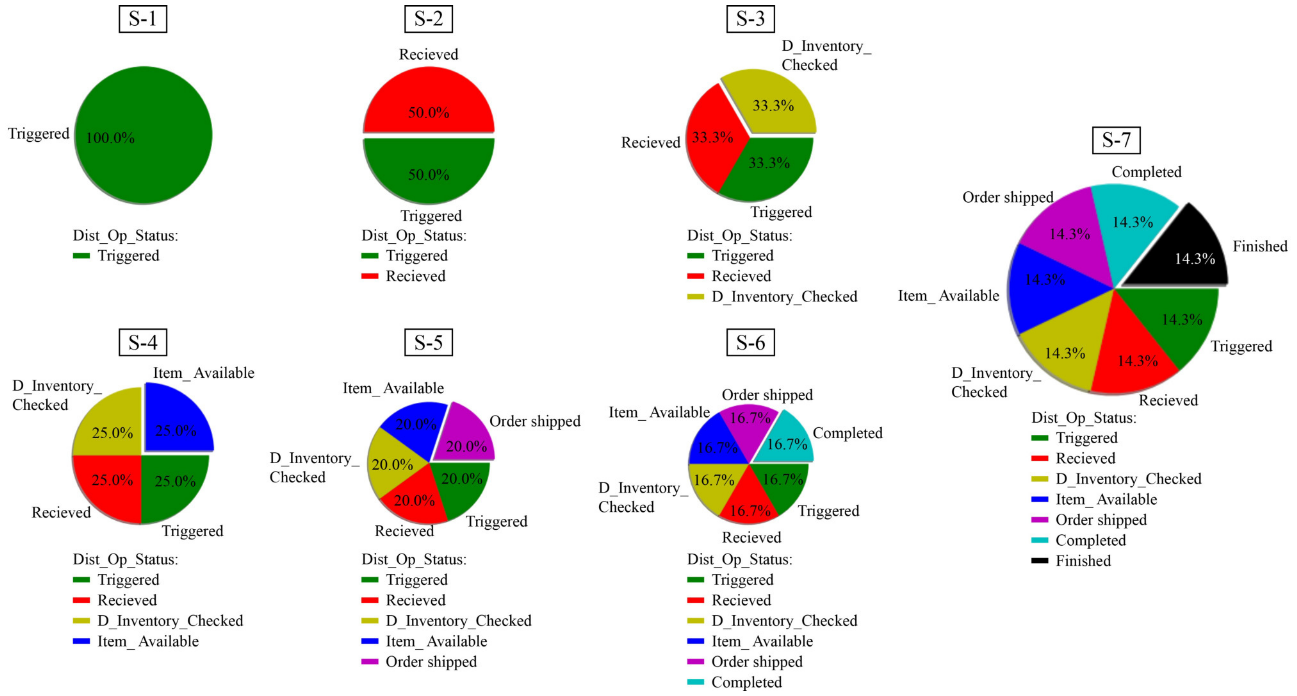

Fig. 6 Details of distribution operation traceability plots from internal traceability view point (D-Agent's prospective).

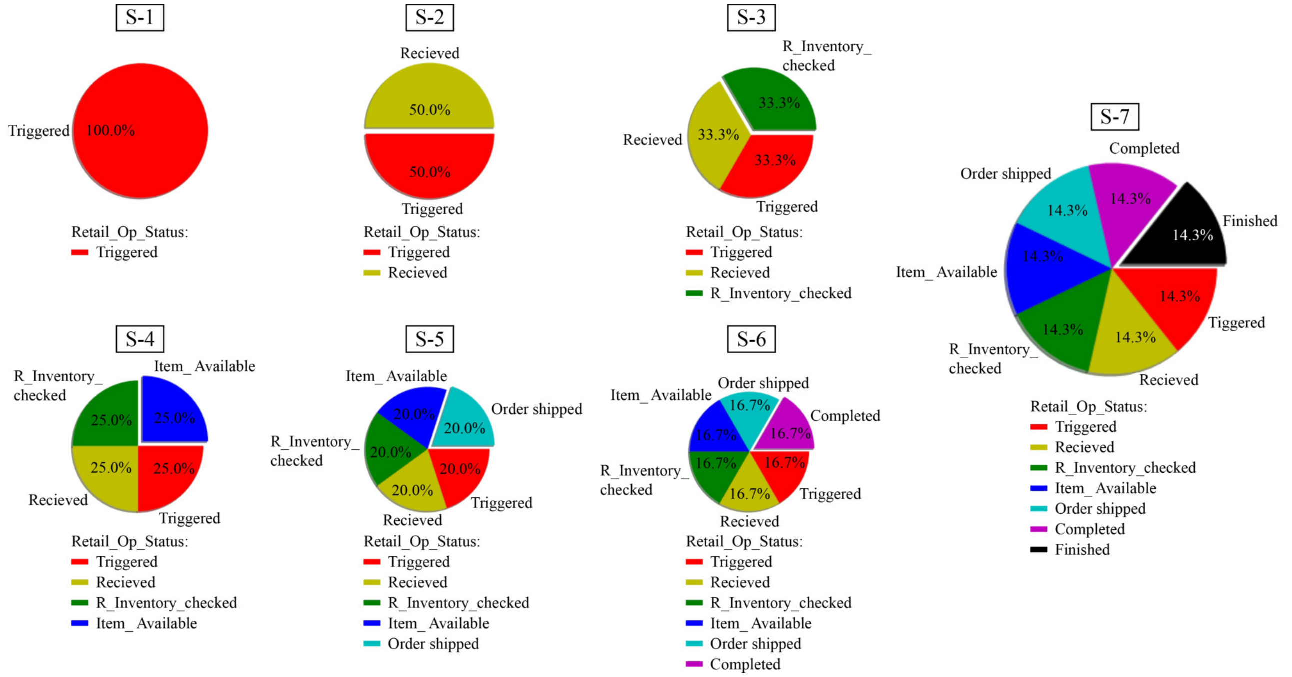

Fig. 7 Detail settings of retail operation traceability plots from internal traceability view point (R-Agent's prospective).

with up-to-the-minute information on product status.

b. **Efficient compliance:** Smart contracts can automate compliance checks and trigger alerts for non-compliance, reducing manual oversight.

c. **Improved fraud detection:** Blockchain's transparency and MAS's data analysis capabilities enhance fraud detection by identifying irregularities in the SC.

4.3 Efficacy of the proposed framework

The effectiveness of the framework can be assessed based on rationality, sustainability, and robustness. In the following section, we will evaluate the efficacy of the research traceability framework from these perspectives in our research paper.

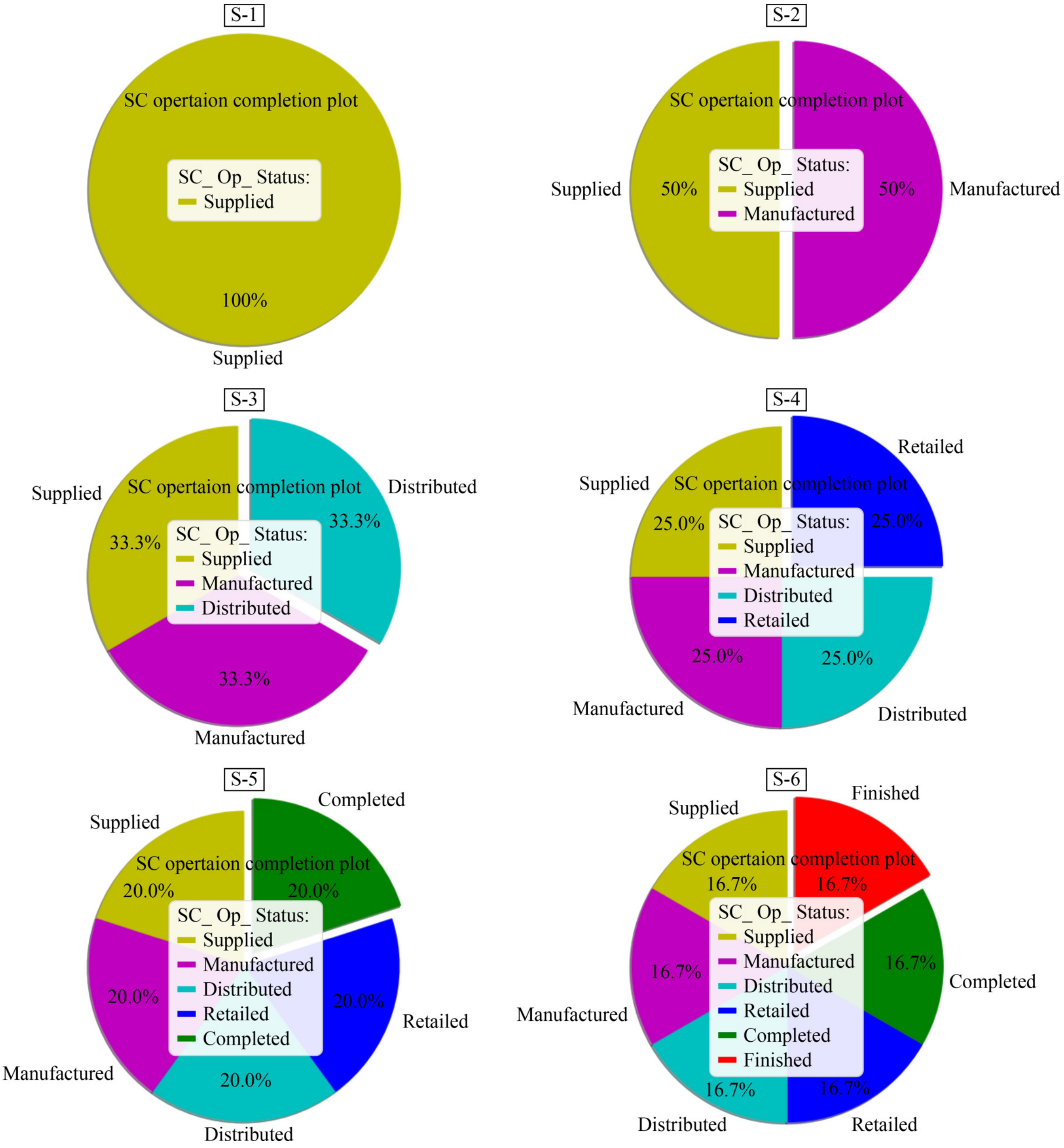

Fig. 8 Details of complete SC operations traceability plots from external traceability view point (P-Agent's prospective).

4.3.1 Rationality, sustainability, and robustness of the framework

1) Rationality

- **Agent roles and responsibilities:** The allocation of distinct roles to different agents, such as P-Agent, S-Agent, M-Agent, and R-Agent, demonstrates a rational approach to efficient supply chain management. Each agent's responsibilities align with their expertise, enhancing decision-making and overall process coordination.
- **Sequential operational flow:** The step-wise process, from raw material supply to retail and customer delivery, mirrors real-world supply chain operations, showcasing rationality. This logical progression ensures a coherent and controlled execution of activities.
- **Smart contract integration:** The incorporation of smart contracts in the operational phase framework rationalizes execution by automating actions and enforcing predefined rules. This promotes transparency, reduces the risk of errors, and ensures consistent processes.

2) Sustainability

- **Traceability enhancement:** The framework's focus on traceability and status monitoring contributes to sustainability by promoting accountability and transparency throughout the supply chain. This aligns with sustainable practices that emphasize responsible sourcing and ethical operations.
- **Error detection and mitigation:** The integration of

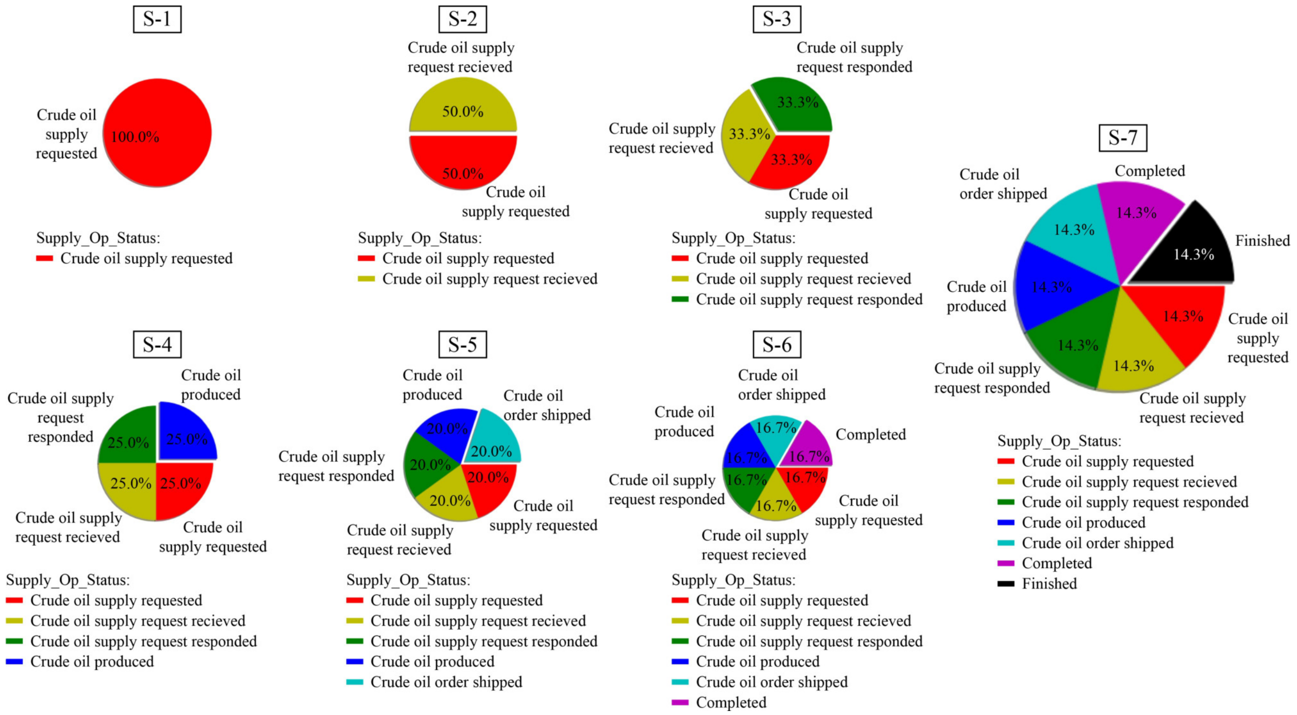

Fig. 9 Details of GMDSC supply operation traceability plots from internal traceability view point (GMDS-Agent’s prospective).

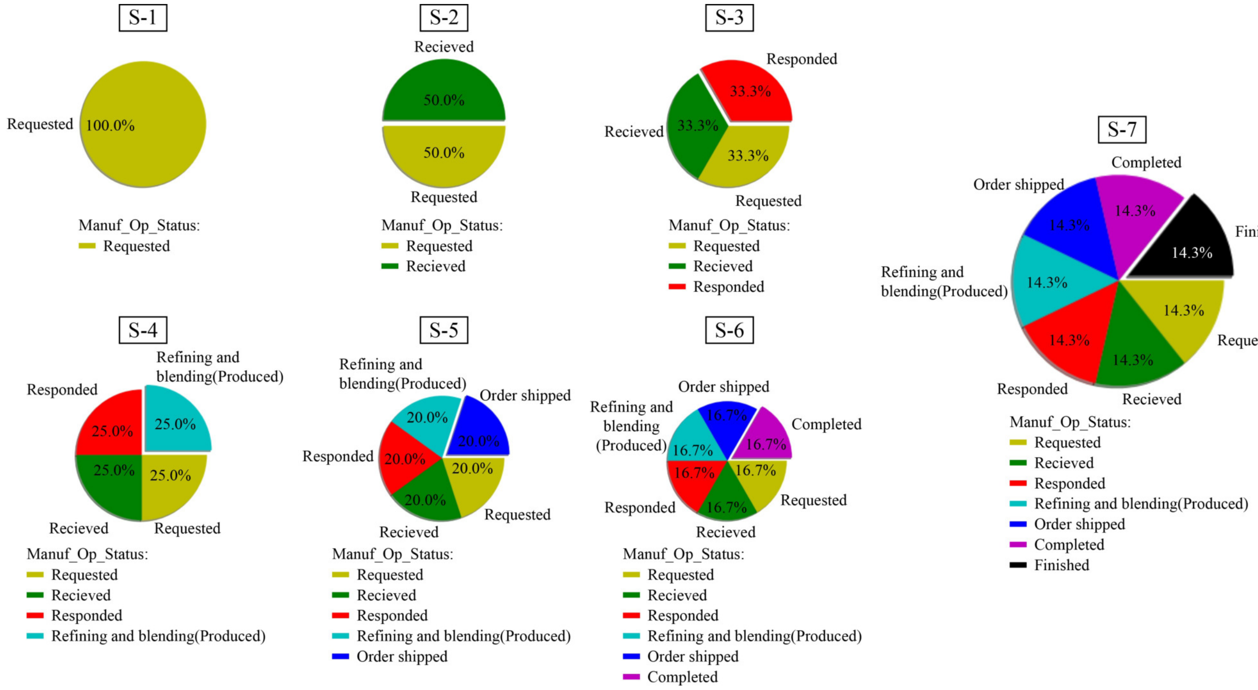

Fig. 10 Details of GMDSC manufacturing operation traceability plots from interna traceability view point (GMDM-Agent’s prospective).

alert mechanisms, such as S/M/D/R_Op_Manage(), which alerts the P-Agent about supply/Manufacture/Distribution/Retail issues, promotes sustainability by facilitating prompt error detection and resolution. This minimizes disruptions and resource wastage.

- **Real-time monitoring:** The use of smart contracts and agent interactions for real-time operations monitoring fosters sustainability by enabling immediate response to anomalies, reducing the potential for resource losses and operational inefficiencies.

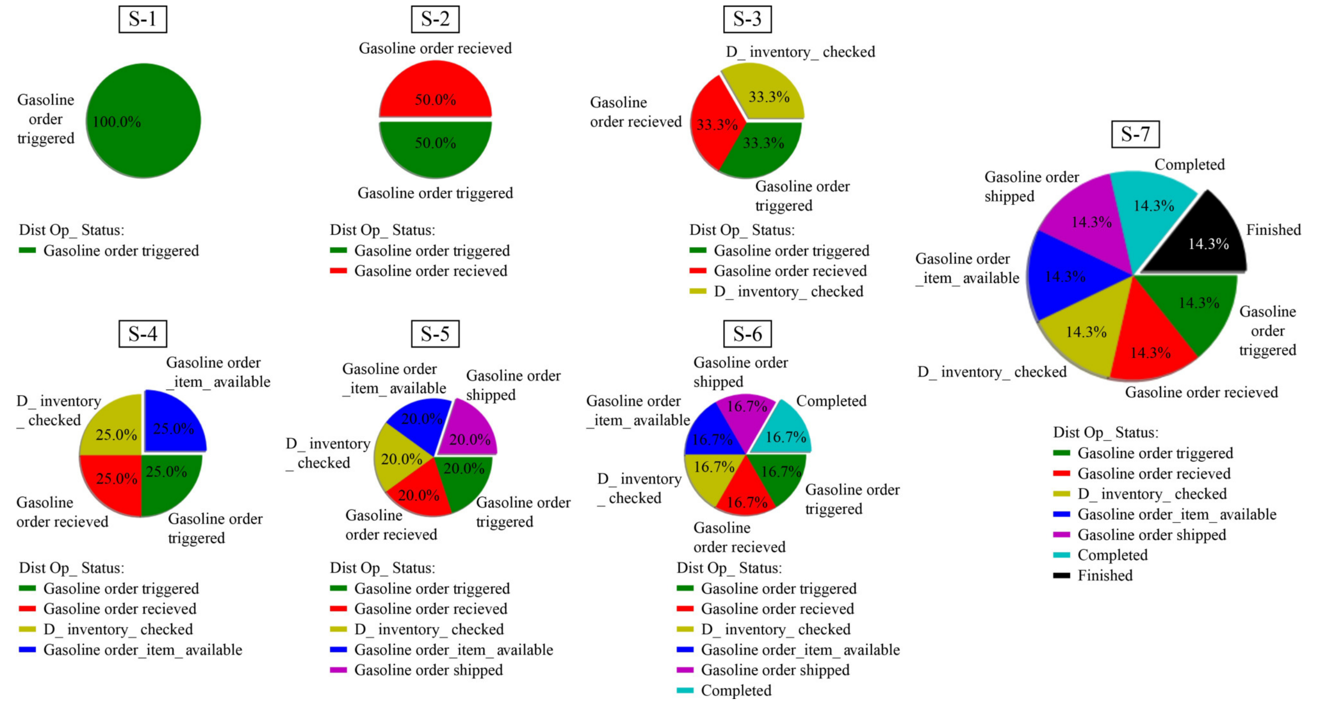

Fig. 11 Details of GMDSC distribution operation traceability plots from internal traceability view point (GMDD-Agent's prospective).

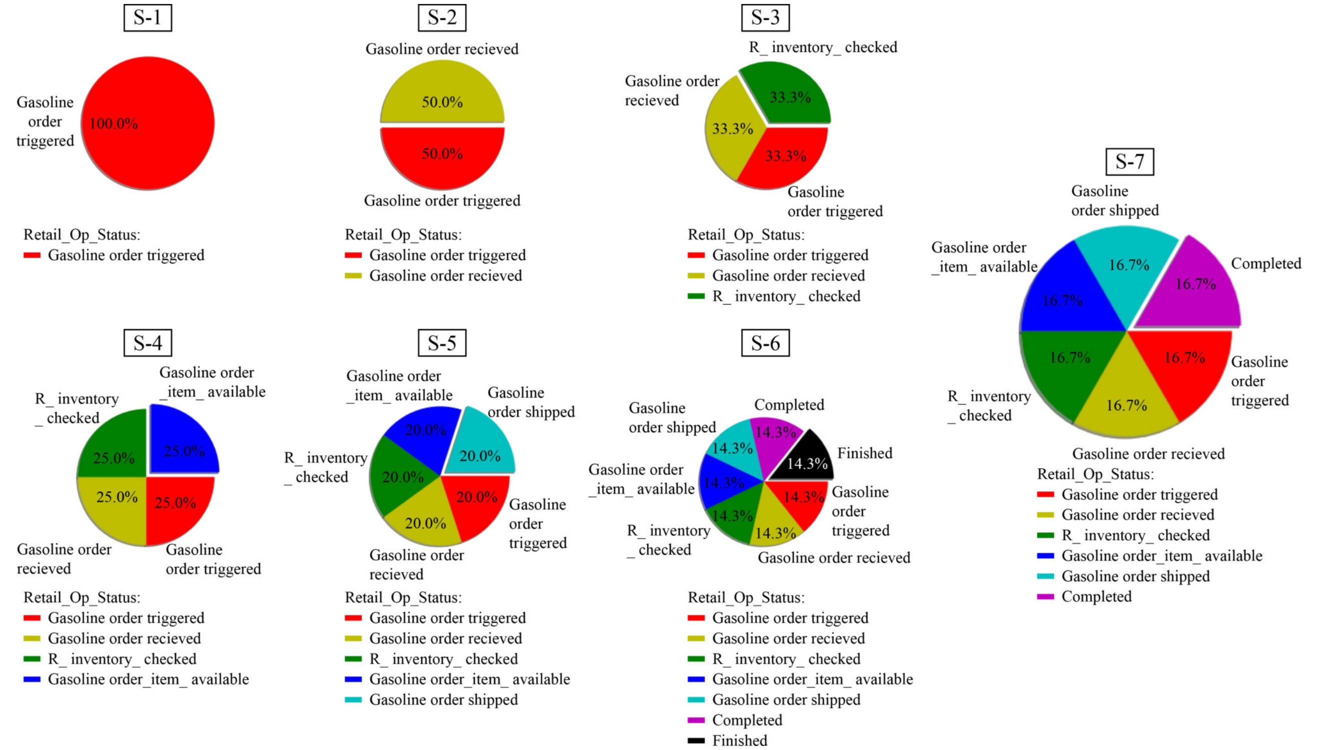

Fig. 12 Details of GMDSC retail operation traceability plots from internal traceability view point (GMDR-Agent's prospective).

3) Robustness

- **Resilience:** The involvement of multiple agents and smart contracts enhances robustness by introducing resilience. If one agent or contract encounters issues, others can continue functioning, ensuring the SC remains operational and minimizing disruptions.
- **Error handling and reporting:** The framework's focus on error reporting mechanisms, such as S/M/D/R_Op_Manage(), alerting P-Agent about Supply/Manufacture/Distribution/Retail errors, contributes to robustness

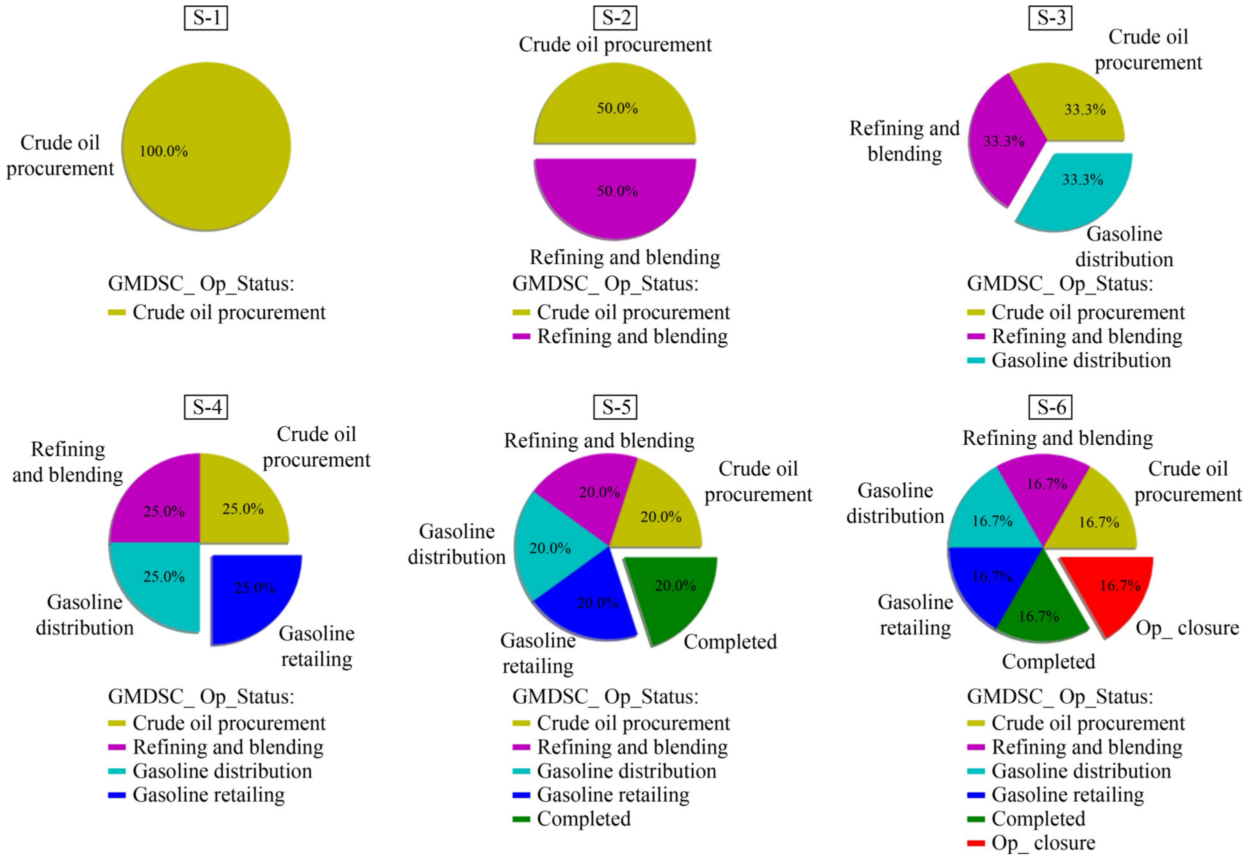

Fig. 13 Details of complete GMDSC operations traceability plots from external traceability view point (GMDP-Agent’s prospective).

by enabling swift identification and communication of problems for corrective action.

- **Decentralized control:** The distribution of control among different agents, coupled with the automation of smart contracts, enhances robustness by reducing the likelihood of single points of failure and enabling agile responses to changing circumstances.

In summary, the outlined framework demonstrates rationality through well-defined agent roles and sequential processes, sustainability through traceability enhancement and error detection, and robustness through resiliency, real-time monitoring, and decentralized control. By addressing these aspects, the framework aims to enhance SC efficiency, transparency, and resilience in line with rational, sustainable, and robust practices.

4.4 Examining the system framework across temporal phases

Indeed, let’s structure the advantages of employing an Intelligent Agent-Centric Framework compared to the absence of the framework in a chronological timeline to reveal the benefits over time:

1) Initiation phase (Time T0):

- **Without framework:**

▪ Lack of autonomous decision-making: The system operates reactively and cannot make independent decisions.

▪ Limited adaptability: The system struggles to adapt to environmental changes or unforeseen disruptions.

- **With intelligent agent-centric framework:**

▪ Autonomous decision-making: Agents can make intelligent decisions based on predefined rules, goals, and learning mechanisms.

▪ Enhanced adaptability: Agents dynamically adjust to changes, fostering a more responsive and flexible system.

2) Early implementation (Time T1):

- **Without framework:**

▪ Limited collaboration: The system may struggle to communicate and collaborate effectively, leading to suboptimal coordination.

▪ Fixed strategies: The system operates with static methods, lacking the ability to learn from experiences or adjust its approaches.

- **With intelligent agent-centric framework:**

▪ Improved collaboration: Agents engage in effective communication and collaboration, leading to better coordination and information sharing.

▪ Dynamic strategies: Agents can adapt their approach based on learning from interactions, resulting in more efficient and effective decision-making.

3) Mid-implementation (Time T2):

- **Without framework:**
  - ▪ Increased complexity: As the system grows, managing interactions becomes more complex and challenging.
  - ▪ Limited scalability: The absence of an intelligent framework may hinder scalability as the system expands.
- **With intelligent agent-centric framework:**
  - ▪ Managed complexity: The framework provides mechanisms to manage and organize complex agent interactions.
  - ▪ Scalability: The intelligent framework supports scalability, allowing the system to handle many agents and tasks.

4) Maturity phase (Time T3):

- **Without framework:**
  - ▪ Cumbersome maintenance: Maintaining and updating the system becomes labor-intensive without intelligent automation.
  - ▪ Suboptimal performance: The lack of continuous learning may lead to stagnation in performance.
- **With intelligent agent-centric framework:**
  - ▪ Automated maintenance: The framework may incorporate self-healing mechanisms, reducing the manual effort required for system maintenance.
  - ▪ Continuous improvement: Agents continuously learn and adapt, leading to ongoing improvements in system performance.

5) Long-term impact (Time T4 and beyond):

- **Without framework:**
  - ▪ Resistance to change: The system may resist adaptation to new technologies or evolving requirements.
  - ▪ Limited future-proofing: The absence of an intelligent framework may result in a system that struggles to meet emerging challenges.
- **With intelligent agent-centric framework:**
  - ▪ Future-proofing: The framework is designed to accommodate changes, ensuring the system remains relevant and effective in the face of evolving technologies and requirements.
  - ▪ Easier integration: The intelligent framework facilitates the integration of new technologies and methodologies, enhancing the system's long-term viability.

This timeline thoroughly explains how the Intelligent Agent-Centric Framework advances the system's sustainability, efficiency, and evolution over time by highlighting its benefits.

5 Conclusions and discussion

In conclusion, the SC landscape has experienced a transformative shift, with modern innovative SCM systems replacing traditional ones, driven by recent advancements in the industry. Integrating a comprehensive traceability system wields significant influence over product development and the seamless execution of SC processes in innovative SC-driven sectors. This empowerment facilitates early defect identification and rectification within SCs, enhancing the system's overall resilience.

The fusion of BCT and MAS offers a promising approach to ensuring activity traceability across expansive applications. The proposed architecture shows its ability to transparently and consistently oversee SC operations, improving operational efficiency. This study has resulted in the development of a decentralized agent-oriented tracing system, harnessing BCT to expedite SC activities reliably and transparently. This advancement highlights the evolution toward more robust and efficient SCM in the contemporary business landscape.

5.1 Proposed traceability schema limitations

- **Dependence on P_Agent:** The success of the traceability architecture heavily relies on the performance of the P_Agent, which becomes a single point of failure. Any potential failure in P_Agent could significantly impact the overall effectiveness of the SC traceability process.
- **Validation and verification challenges:** Ensuring the validation and verification of blockchain nodes and transactions within the SC context poses a formidable challenge. The complexity of these processes may impede the seamless execution of the proposed traceability framework.
- **Limited security focus:** The research does not explicitly address security-related concerns in the proposed traceability framework. This limitation leaves a critical aspect unexplored, highlighting the need for future studies to explore the security implications associated with the implementation.
- **Scalability and efficiency validation:** Evaluating a system's scalability and efficiency in various live operational environments is crucial to ensuring its viability and effectiveness on a larger scale.
- **Integration with legacy systems:** Integrating the proposed traceability architecture with legacy supply chain systems presents a significant hurdle. This challenge requires careful consideration and strategic planning to overcome potential conflicts and ensure a smooth coexistence between the new framework and established systems.
- **Complexity of implementation:** The research recognizes the multifaceted dimensions of implementing traceability architecture within supply chain operations. The complexity of these dimensions adds a layer of difficulty, emphasizing the need for a comprehensive understanding and strategic approach during implementation.

5.2 Research contributions

The presented study makes dual contributions to SCM in theoretical and practical dimensions by effectively addressing the inherent obstacles in managing traceability within SC operations. The following sections outline the theoretical and empirical advancements introduced by our research:

5.2.1 Theoretical contribution

The outlined SC operation process introduces a structured framework for enhancing traceability through agent-based interactions. Each step in the process, facilitated by distinct agents and smart contracts, contributes to a comprehensive theoretical understanding.

1) Multi-tier traceability:

- *Acknowledged gap*: Lack of all-including solutions for multi-tier traceability.
- *Theoretical contribution*: The theoretical framework introduces various agents (P-Agent, S-Agent, M-Agent, R-Agent) that collectively oversee the entire SC process, potentially bridging the multi-tier traceability gap by engaging different entities across the SC. The theoretical contribution lies in specifying the distinct roles of diverse agents, such as P-Agent, S-Agent, M-Agent, and R-Agent, and elucidating their interactions. This conceptual framework establishes the groundwork for a multi-tier system that collaboratively oversees the entire SC process.

2) Dynamic real-time traceability:

- *Acknowledged gap*: Insufficient incorporation of dynamic, real-time traceability systems.
- *Theoretical contribution*: The proposed framework includes operational states and intelligent contracts, enhancing real-time traceability by enabling swift transitions between states in response to dynamic changes in the SC. Describing distinct functional states (e.g., initiated, supplied, manufactured, distributed, retailed) and their transitions enriches the theoretical perspective. This approach outlines the SC lifecycle and its real-time traceability viewpoints.

3) Integration of emerging technologies:

- *Acknowledged gap*: Limited research on practical integration methodologies of emerging technologies (blockchain, agent technology, AI) for traceability.
- *Theoretical contribution*: Smart contracts, particularly those related to BCT, are integrated into each operational phase, providing a theoretical foundation for integrating blockchain in SC traceability. However, the extent of coverage for other emerging technologies like agent technology and AI needs clarification. Integrating smart contracts (PSC, SOMSC, MOPMSC, SMSC, ROMSC) into each operational phase contributes to solidifying the theoretical framework. Combining these contracts demonstrates how BCT can enhance traceability and automate the monitoring and control of various SC operations.

4) Human-centric factors in adoption:

- *Acknowledged gap*: Inadequate understanding of the impact of human behavior and adoption dynamics in traceability systems.
- *Theoretical contribution*: The outlined framework focuses more on agent roles and interactions, operational states, and smart contract integration rather than explicitly addressing human-centric factors in adoption. This represents a potential gap in the theoretical contributions.

5) Data Privacy and Security:

- *Acknowledged gap*: Limited exploration of security and privacy concerns in disseminating traceability data.
- *Theoretical contribution*: While the integration of BCT is mentioned, specific details regarding strategies for ensuring data security and facilitating efficient data sharing are not explicitly outlined. This suggests a potential gap in addressing the identified concern. The theoretical introduction of traceability threshold calculation (PAgt-TraceThresholdCal()) signifies a novel concept ensuring traceability accuracy. This calculation influences the traceability value, allowing for the differentiation between successful and unsuccessful phases.

5.2.2 Practical contribution

The outlined framework's practical contribution lies in its potential implementation in real-world SC applications, promoting operational efficiency and transparency.

- **Agent-Driven SC control:** The framework offers a practical approach to decentralized SC control by introducing distinct agent roles responsible for managing each SC phase. This approach can enhance decision-making, responsiveness, and accountability in SC operations.
- **Smart contract implementation:** Integrating smart contracts to manage different SC phases aligns with the practical trend of adopting BCT for improved traceability. This can result in more secure, transparent, and auditable SC operations.
- **Traceability enhancement:** The practical implementation of traceability thresholds, calculated through the PAgtTraceThresholdCal process, can enhance traceability accuracy and reliability. This implementation aligns with the industry's pursuit of real-time and accurate tracking of goods and processes.
- **Process visualization:** The outlined process steps provide a practical guide to visualizing and executing SC operations. This can **assist** SC managers and practitioners structure their processes and understand the roles of different agents and contracts.
- **Agent communication:** The framework emphasizes agent-to-agent communication for error reporting (e.g., S/M/D/R_Op_Manage() alerting P-Agent). This aligns with practical scenarios where rapid communication is crucial for resolving operational issues and minimizing disruptions.

6 Future scopes

This research article outlines future endeavors in traceability enhancement. The focus is on developing a system capable of determining the traceability threshold using hashing techniques, including a diverse array of hash function implementations. Our research trajectory aims to thoroughly investigate the impact of distinct hashing algorithms on SC traceability. The objective is to discover the optimal approach that provides a well-defined blueprint for BCT-driven SC operations. As part of our forward-looking approach, the impending implementation of the proposed framework requires integrating physical IoT devices for traceability realization.

Blockchain and MAS offer considerable advantages, but some challenges need to be addressed, namely scalability, integration, and adoption. Future research should prioritize the development of standardized protocols and frameworks for seamlessly integrating these technologies into SCs. Furthermore, there is potential to explore the application of artificial intelligence and machine learning in conjunction with Blockchain and MAS to enhance traceability and decision-making. Through these focused efforts, this research article aims to provide valuable insights into the advancements and innovations that drive the enhancement of traceability threshold determination and assessment, offering a comprehensive perspective on improving SC operations. Although we recognize the significance of studying traceability in various industries, the article's length constraints do not allow for an exhaustive examination of multiple case studies. Nevertheless, it is important to mention that the Agent-Oriented Distributed Traceability System Framework has been successfully implemented and tested in the blood distribution SC within the healthcare industry. Although the GMDSC is the primary case study, the framework's adaptability and effectiveness can be extended to diverse industries with unique SC characteristics. Future research efforts may focus on exploring additional cases to validate the framework's feasibility across different industrial contexts.

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