On providing a Blockchain-based reverse supply chain traceability of agrochemicals

Sobre o fornecimento de rastreabilidade da cadeia de suprimentos reversa de agroquímicos com base em Blockchain

Trazabilidad inversa de la cadena de suministro de productos agroquímicos basada en Blockchain

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ABSTRACT
Agrochemicals are often used to produce higher crop production rates; however, malicious misuse could cause environmental damage and health problems for both consumers and farmers. Furthermore, despite the increased control of agrochemicals through a regulated reverse supply chain, these products are also vulnerable to theft due to their high financial value. Today, no initiatives in the literature securely approach the problem of tracing agrochemicals along with the stakeholders, joining actions done by manufacturers, farmers, government, and return centers. This article presents the design, architecture, and prototype evaluation of a Blockchain based system for pervasive agrochemical traceability within reverse logistics chains (Agrochemicals Pervasive Traceability Model -

APTM), keeping up with agrochemicals along their route on the reverse logistic chain. APTM uses Blockchain technology to monitor eventual illegal activities, generating value for producers that operate strictly within the law. Our contributions are: (i) a gamification mechanism for producers that play the APTM rules; (ii) an architecture composed of modules, functionalities, interconnections, and rules to manage the agrochemical flow. APTM comprises five parts: authentication, route control, Blockchain recording, statistics, notification, and gamification. At the prototype level, our solution achieved a rate of 4,6 transactions per second and a monthly operating cost of approximately US$40.00. Experimental results obtained from prototype simulations demonstrated the system's ability to maintain 4.6 transactions per second (TPS), validate actor permissions, and manage data persistence across Blockchain, in addition to providing an online agrochemical data visualization along the reverse supply chain.

Keywords: Agrochemicals. Blockchain. Reverse Supply Chain. APTM.

RESUMO
Os agroquímicos são frequentemente usados para produzir maiores taxas de produção agrícola; no entanto, o uso indevido malicioso pode causar danos ambientais e problemas de saúde tanto para os consumidores quanto para os agricultores. Além disso, apesar do maior controle dos agroquímicos por meio de uma cadeia de suprimentos reversa regulamentada, esses produtos também são vulneráveis a roubos devido ao seu alto valor financeiro. Atualmente, nenhuma iniciativa na literatura aborda com segurança o problema do rastreamento de agroquímicos junto com as partes interessadas, unindo ações realizadas por fabricantes, agricultores, governo e centros de devolução. Este artigo apresenta o projeto, a arquitetura e a avaliação do protótipo de um sistema baseado em Blockchain para a rastreabilidade pervasiva de agroquímicos nas cadeias de logística reversa (Agrochemicals Pervasive Traceability Model - APTM), acompanhando os agroquímicos ao longo de sua rota na cadeia de logística reversa. O APTM utiliza a tecnologia Blockchain para monitorar eventuais atividades ilegais, gerando valor para os produtores que operam estritamente dentro da lei. Nossas contribuições são: (i) um mecanismo de gamificação para os produtores que jogam as regras do APTM; (ii) uma arquitetura composta de módulos, funcionalidades, interconexões e regras para gerenciar o fluxo de agroquímicos. O APTM compreende cinco partes: autenticação, controle de rota, registro de Blockchain, estatísticas, notificação e gamificação. No nível do protótipo, nossa solução atingiu uma taxa de 4,6 transações por segundo e um custo operacional mensal de aproximadamente US$ 40,00. Os resultados experimentais obtidos a partir de simulações de protótipos demonstraram a capacidade do sistema de manter 4,6 transações por segundo (TPS), validar permissões de atores e gerenciar a persistência de dados no Blockchain, além de fornecer uma visualização on-line de dados agroquímicos ao longo da cadeia de suprimentos reversa.

Palavras-chave: Agroquímicos. Blockchain. Cadeia de Suprimentos Reversa. APTM.

RESUMEN

Los productos agroquímicos se utilizan a menudo para obtener mayores índices de producción de los cultivos; sin embargo, su uso indebido malintencionado podría causar daños medioambientales y problemas de salud tanto a los consumidores como a los agricultores. Además, a pesar del mayor control de los productos agroquímicos mediante una cadena de suministro inversa regulada, estos productos también son vulnerables al robo debido a su alto valor financiero. En la actualidad, no existen iniciativas en la literatura que aborden de forma segura el problema del rastreo de agroquímicos junto con las partes interesadas, uniendo las acciones realizadas por fabricantes, agricultores, gobierno y centros de devolución. Este artículo presenta el diseño, la arquitectura y la evaluación del prototipo de un sistema basado en Blockchain para la trazabilidad omnipresente de productos agroquímicos dentro de las cadenas de logística inversa (Agrochemicals Pervasive Traceability Model - APTM), manteniendo el seguimiento de los productos agroquímicos a lo largo de su ruta en la cadena de logística inversa. APTM utiliza la tecnología Blockchain para monitorear eventuales actividades ilegales, generando valor para los productores que operan estrictamente dentro de la ley. Nuestras contribuciones son: (i) un mecanismo de gamificación para productores que juegan las reglas de APTM; (ii) una arquitectura compuesta por módulos, funcionalidades, interconexiones y reglas para gestionar el flujo de agroquímicos. APTM consta de cinco partes: autenticación, control de rutas, registro en Blockchain, estadísticas, notificación y gamificación. A nivel de prototipo, nuestra solución alcanzó una tasa de 4,6 transacciones por segundo y un coste operativo mensual de aproximadamente 40,00 dólares. Los resultados experimentales obtenidos a partir de las simulaciones del prototipo demostraron la capacidad del sistema para mantener 4,6 transacciones por segundo (TPS), validar los permisos de los actores y gestionar la persistencia de los datos a través de Blockchain, además de proporcionar una visualización de datos agroquímicos en línea a lo largo de la cadena de suministro inversa.

Palabras clave: Agroquímicos. Blockchain. Cadena de Suministro Inversa. APTM.

1 INTRODUCTION

As the population worldwide grows, feeding it properly is also a challenge. This fact pressures the current agricultural production system, especially in large monoculture areas, such as soybeans, corn, and cotton. In this way, agrochemicals are often not an option but an obligation to deliver higher production rates (Bystroff, 2021; Adam, 2021; Cilluffo and Ruiz, 2019; EPRS, 2021). In detail, agrochemicals have unique characteristics differentiating them from chemical products from other industries, such as high acquisition value, environmental toxicity, and the need to return empty packaging (FAO., 2016, 2015).

The agricultural production chain with agrochemicals and their logistics is extensive, with several players involving manufacturers, providers, farmers, and the government. Moreover, the movement of products should consider a reverse logistic chain (RLC), where agrochemicals must be returned to particular places that are in charge of eliminating them correctly (Marinagi *et al*., 2013). The 2022 report on sustainable supply chains points to digitalization as a global research opportunity (DIE, 2022). Moreover, the challenges that arose in 2020 due to the COVID-19 pandemic, which are still being experienced in 2023, bring about various difficulties in logistic chains and the requirements for agricultural products, thereby escalating the necessity for enhanced control and optimization (Raj *et al*., 2022).

Several factors can affect the RLC functioning (Pibul and Jawjit, 2021) (Huici *et al*., 2017): (i) improper application, unduly bypassing modules in the pipeline; (ii) theft of agrochemicals; (iii) lack of detailed and reliable monitoring; (iv) return of packaging. This way, we can summarize all four aspects of the lack of information about a product's characteristics, status, and location. By enabling this control, RLC stakeholders can improve confidence both in transactions and in eventual audits (van den Berg *et al*., 2020). The absence of formal and digital mechanisms indicates that we should rely on government regulation and the goodwill of the players to obtain a robust organization, which is sometimes mocked and generates an imprecise RLC snapshot (Pibul and Jawjit, 2021).

Farmers face several problems, from crop planning to product sales. In detail, some of the problems faced are pests (Grande and Rando, 2018), (Horikoshi *et al*., 2021), diseases (Murithi *et al*., 2015), improper use of raw material (Araujo and Oliveira, 2016), variation of prices of raw material (de Oliveira Neto, 2017; Bigaton *et al*., 2015), logistic problems (Maia *et al*., 2019) and storage. Furthermore, the theft of agrochemicals is widely cited by (Mattah *et al*., 2015). The need for digital systems to help monitor agrochemical products is addressed by (Valbuena *et al*., 2021). The authors indicate the need for an agrochemical monitoring system to reduce human and agrochemical risks.

When considering the agrochemical context, the literature today addresses various aspects. As a countermeasure to product piracy, sensors are designed to detect the use and volume of products (Blankenburg *et al*., 2015). In addition, there are different sources of problems: theft (Mattah *et al*., 2015); technological issues (Azoulay, 2019); security in agriculture (Gupta *et al*., 2020); aspects of the state's responsibility (Zikankuba *et al*., 2019). Reverse logistics ensures the return of the packaging to the origin (Hu *et al*., 2021), but greater integration of information between participants is necessary. Here, Blockchain can potentially be used in the traceability of transactions of various products, including empty packaging that should be forwarded for disposal, (Laouar *et al*., 2019).

Blockchain is a chain of blocks, where each node has blocks of data, a timestamp, and a code hash that refers to the previous node, enforcing the chain of data immutably (Sultan *et al*., 2018). The Blockchain technology was initially designed to support cryptocurrencies (Maesa and Mori, 2020). However, it can be used today for other purposes, including supply chain tracking, crypto assets, and contracts between people who do not know each other. The authors (Gozali *et al*., 2024) indicate pesticide supply chain requires the use of Blockchain technology and Blockchain technology can be used to support data-related risk mitigation" in this supply chain. In addition, the application of Blockchain in the traceability of agricultural products is guaranteed by the use of Blockchain (Lv *et al*., 2023a).

This study was motivated by the increased demand for traceability of high value products in the agricultural supply chain, discussing gaps in monitoring and related technologies. Although previous studies cite isolated works (such as IoT, digital certification and even Blockchain application), there is a lack of a modular architecture model for Blockchain and designed for the reverse chain of agrochemicals. We present the operational flow, engagement for participants via gamification, focusing on responsibility and enabling the return of used packaging.

In this context, this article introduces a model named APTM (pervasive traceability of agrochemicals) to improve the traceability of agrochemical products in RLC. APTM provides an architecture and rules for players' collaboration, recording activities in Blockchain when moving the products along the logistic chain. Moreover, APTM can generate alerts by monitoring transactions. Our contributions are twofold: (i) a Blockchain-based architecture for agrochemical monitoring, detailing the players' roles, messages, modules, and technological issues; (ii) a gamification strategy to improve the position of those farmers who adopt the architecture. The proposal has substantial social and environmental contributions because it allows the control of the movement of inputs, the engagement of participants, and the registration of transactions in a scoring system, improving the competitiveness of its members.

The article's organization is as follows: Section 2 presents the related work and details the area's opportunities. Section 3 presents the agrochemical traceability model. Section 4 elucidates aspects of measuring and evaluating the model and details about the prototype developed. Section 5 shows the results, highlighting achievements and limitations. Finally, Section 6 points out the article's main conclusions, reanalyzing contributions, limitations, and future work.

2 RELATED WORK

This section presents some initiatives within the scope of the present work, including the following keywords: Blockchain, traceability, and agrochemicals. Due to counterfeiting and product diversion, traceability can be essential in developing countries, especially Africa.

The United States Government Accountancy Office conducted a study on Blockchain technology in areas that are not for cryptocurrency purposes, such as supply chain, voting systems, asset registration, and registration of government operations, among others. (GAO, 2022) indicated broad applicability but kept the recommendations for action as the need for public policies and standards for such interoperability, as well as suggesting that public managers act with the participation of regulations only. (van den Berg *et al*., 2020) recommended improvements in legislation and the use of integrated pest control in agrochemicals. They see the opportunity to develop modular and integral models for other solutions.

Onwona Kwakye *et al*. (2019) present the law on pesticides in Ghana. In this country, the government maintains a pesticide sales register. They also present the steps for the registration of pesticides and address the issue of product labels. Li and Huang (2018) address the governance of reverse logistics for pesticides, citing four factors that influence reverse logistics: economics, legal, corporate responsibility, and environmental protection. Regarding recycling points, it barely mentions legislation; this is the step that this author calls the recovery link, indicating that farmers should return the purchased waste. Mengistie *et al*. (2017) deals with the possibility of private certification of the governance of environmental problems and pesticide use along the chain, carried out in Ethiopia, and concludes that certification alone does not solve all problems. Bush (2022) indicates the need for government entities (in particular the legislature) to take sides in regulating Blockchain technology and its applications.

Jiang and Raeder (2022) modeled an architecture and business processes to support a Blockchain to obtain an easy-to-understand vision for the business area about the advantages of Blockchain adoption; indicate improvements in the prioritization of strategic decisions; using the Archimate tool during modeling. **?** present a benefit analysis of Blockchain adoption. Gerakoudi-Ventouri (2022) indicate a need for more research on how Blockchain can affect decision-making in a supply chain. In da Silva and dos Santos (2022), by applying questionnaires to professionals in the logistics sector, the authors tried to measure the level of knowledge about Blockchain and the adoption of this technology in logistics companies. Brookbanks and Parry (2022) examined the impact of Blockchain on the degree of trust between buyersupplier (in the wine supply chain), the implementation of Blockchain introduced the possibility of shared data, reduced data duplication and visibility of the entire process. Zhao *et al*. (2020), by citing that Blockchain technology is underrated in certification programs, have proposed a Blockchain to support the certification of energy users.

Blockchain has grown in several areas in the pharmaceutical industry, including counterfeiting prevention, counterfeit traceability, prescription monitoring, drug distribution, traceability, and security. Zakari *et al*. (2022) presents a study identifying enablers for adopting Blockchain technology in logistics chains. They indicate the main technological advantages and external pressure, in addition to the impacts of casual technology adoption on cost reduction and interest in customer traceability, (Maher A.N. and Ashish Kumar, 2022). Lenge *et al*. (2022) proposed architecture of Blockchain and RFID via a conceptual approach, which supplies a Blockchain with data originating from IoT devices and sends it directly to a Hyperledger implementation.

Huici *et al*. (2017) carried out a survey between 2014 and 2016 on the collection of empty packaging. They identified a series of situations, such as disposal in inappropriate places, lack of knowledge of the cleaning procedure, and residue in packaging. This indicates the need for more knowledge and clear procedures during the disposal and operationalization of this step, highlighting a deficiency in the absence of a clear procedure overseen by a consortium where participants are required to engage at every phase and the deficiency that gamification involvement can address. Gerakoudi-Ventouri (2022) indicate a path in logistics chain management projects that can view the entire product life cycle. van Putten *et al*. (2020) indicate that adopting the model via a consortium can reduce the process's implementation, use, and evaluation costs.

Silva *et al*. (2020) points to the possibility of expanding the adoption of Blockchain technology for the traceability of products. Brookbanks and Parry (2022) cite the introduction of Blockchain in the form of a consortium and the participation of government entities are points that can be explored by this proposal, as the authors comment on the lack of reliability between the participants and the system. Smiderle *et al*. (2020) mention how an opportunity in the adoption of gamification in the logistics chain is to treat players not as natural persons, as many studies on engagement with gamification have observed; in this way, personality traits and various aspects of the logistics chain that can be automated and handled via software are eliminated.

Many challenges in adopting Blockchain in supply chains are presented by Bosona and Gebresenbet (2023) in a literature review, such as legal and technological frameworks, investment costs, and standardizations, among others, in addition to indicating that Blockchain traceability systems are used with products such as vegetables, meat, and milk; are also tracked by stakeholders with centralized database systems. Literature review studies prepared by Yogarajan *et al*. (2023) address a thematic spectrum indicating the importance of policies for Blockchain adoption, factors, challenges, and their impacts (social, economic, political, technological, and environmental).

Lv *et al*. (2023b) indicate that deeper studies on the practical adoption of traceability using Blockchain are necessary with the possibility of future application of qualitative and quantitative methods. Kalimuthu and PrabuPelavendran (2024) address the possibility of using Blockchain integrated with IoT by sharing data, suggest the study with machine learning algorithms, cite network capillarity or connectivity in rural areas as difficulties, point out the need for development of algorithms and technologies for the agricultural sector. Ordoñez *et al*. (2024) address how Blockchain technology can be used in sustainable agriculture, carrying out a literature review concluding that Blockchain can facilitate traceability and trust in the sustainable sector, indicate as future work that smart contracts and non-fungible tokens can represent digital assets, indicate difficulties for large-scale implementation in addition to more specific research in the sector.

Despite the growing interest in blockchain applications for supply chains, our review did not identify any models that specifically address the reverse logistics of agrochemicals in a comprehensive and integrated manner. As such, direct comparative analyses with existing approaches are not feasible. This reinforces the novelty of APTM and its unique focus on regulatory compliance, traceability, and gamification within the agrochemical sector.

3 THE APTM MODEL

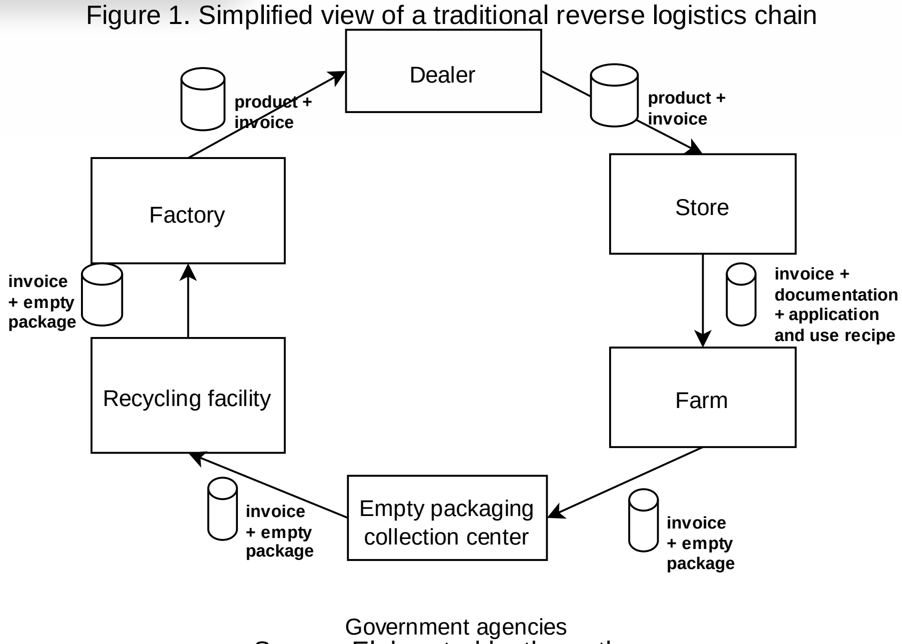
This section presents the computational architecture and core mechanisms of the Agrochemical Pervasive Traceability Model (APTM), describing its modular components, data flows, and the underlying logic that supports Blockchain-based traceability in reverse logistics scenarios (previously presented in (Monteiro *et al*., 2021)). This model aims to maintain information on agrochemical transit within an RLC, providing modules for flow control, data inference, push notification, gamification, and DLT transaction recording. This model can meet several opportunities listed in the previous section to monitor the transit of agrochemicals in the RLC.

The problem statement can be summarized as the lack of ability of all members of the reverse chain of agrochemicals to track an empty package and locate a package at a certain point in the chain at any time. The model allows individual traceability of elements (full or empty packs) and provides an overall view of the status of the reverse chain.

3.1 OVERVIEW OF THE CURRENT MANAGEMENT OF AGROCHEMICALS SUPPLY CHAIN

APTM is based on the RLC depicted in Figure 1. In this figure, the arrows represent the flow of products and empty packages with their respective documentation. The transit of this type of product must have sales documentation and an invoice. For example, Figure 1 illustrates the logistics chain and the data presented on each hop, detailing when we have a complete package and an empty one. The leading players in an RLC are Factory, Dealer (or a regional distributor), Store, Farm, Disposal center (or Recycling Facilities), and Government agencies.

Figure 1. Simplified view of a traditional reverse logistics chain



Source: Elaborated by the author.

Considering the scenario depicted in Figure 1, we perceived that the transit of materials is not constant. In detail, it is sometimes random or seasonal. Despite factories having production schedules, farmers buy products according to harvest planning. Once the products are sent and go around the players, each player has a storage time, particular use, and sending to the next player according to its reality. Government agencies participate in parts of the flow according to their administrative sphere. In APTM, government agencies can participate in the model as a whole.

Regarding data transit, one of the most significant difficulties is the sharing of information between public institutions (Yang and Maxwell, 2011), (Twizeyimana and Andersson, 2019), (Kim and Kreps, 2020), (Drake *et al*., 2004). This situation makes product monitoring impractical. As for data transit, this proposal aims to unify the players interface by providing a framework to manage transactions, facilitating the chain's complete visibility from beginning to end.

APTM allows for resilience regarding expansion in the number of players, routes, and products that transit through the RLC. The model uses emerging technologies like Blockchain and IPFS to document transactions and support multiple operations. Transactions product movement data to be stored on the

Blockchain (the data sent are, for example, origin, destination, product, timestamp). IPFS was chosen due to its ability to offer data redundancy and efficient performance in storing files of different sizes.

Transactions are considered operations for sending product movement data to be stored on the Blockchain (the data sent are, for example, origin, destination, product, and timestamp). According to Rodrigues *et al*. (2021), the exchange of information between two parties connected to the Blockchain network is called a transaction, which in turn is recorded in a data set.

Moreover, APTM allows the management of the participation of known players in the process via authentication, integrating private and public players or associations. By maintaining source, destination, date, time, and agrochemical data, APTM provides a data history on which various analyses can be established later. Blockchain technology allows us to keep data immutable and visible to associated players. Finally, APTM presents an opportunity for players' participation in the correct management of agrochemicals, where gamification policies can take place to act on subsidizing government actions such as tax incentives for the producers.

In the context of gamification (In gamification, the actor involved when completing a task within a level receives a reward in the form of points or a badge (for example, a medal) as a form of incentive), the APTM proposal is appealing, as the current legal requirement to report the movement of empty packaging does not prevent the use of banned products; accumulating points through gamification incentivizes farmers to engage and claim tax incentives. Gamification was carried out with a simple counting method: each package is equivalent to one point and by the sum of points.

APTM assumes that there are at least two players representing government agencies. Moving products typically involves collecting taxes charged by a public agent, and environmental protection and inspection involve another public agent (Kulin and Sevä, 2019). In this way, the model requires at least two players to perform certain operations, such as creating players and authorizing them to start operations, in addition to being able to see the RLC data. Each player will be able to remain with agrochemical products indefinitely. The model will use DLT technologies: Blockchain and IPFS. Only the summary of transactions is recorded on the Blockchain. In the IPFS, we have the storage of other data of greater size, such as accessory documents of a transaction (files in PDF format, for example). When it comes to monitoring an RLC, we focus on obtaining a comprehensive understanding of the movement of goods. The main goal is to simplify and identify products, where product identification can also be made by reading bar codes, QR codes, or RFID.

Product data can be imported by reading XML files of invoices generated by the factory. This version of the model does not document the movements of agrochemicals within farms. Also, APTM does not consider geographic distances between players or when a product (or empty package) is parked with a given player. Thus, we address only the RLC pathway cycle. Finally, players such as government (or government agencies) and factories preexist in the model.

APTM presupposes the use of a permissioned Blockchain in the form of a private consortium. The model is not tied to any specific Blockchain, having been designed to give freedom of choice of technological implementation; that is, the model is agnostic about the choice of physical implementation. Blockchain technology was chosen to allow the immutable recording of product movements in records distributed among participants in the agrochemical reverse chain.

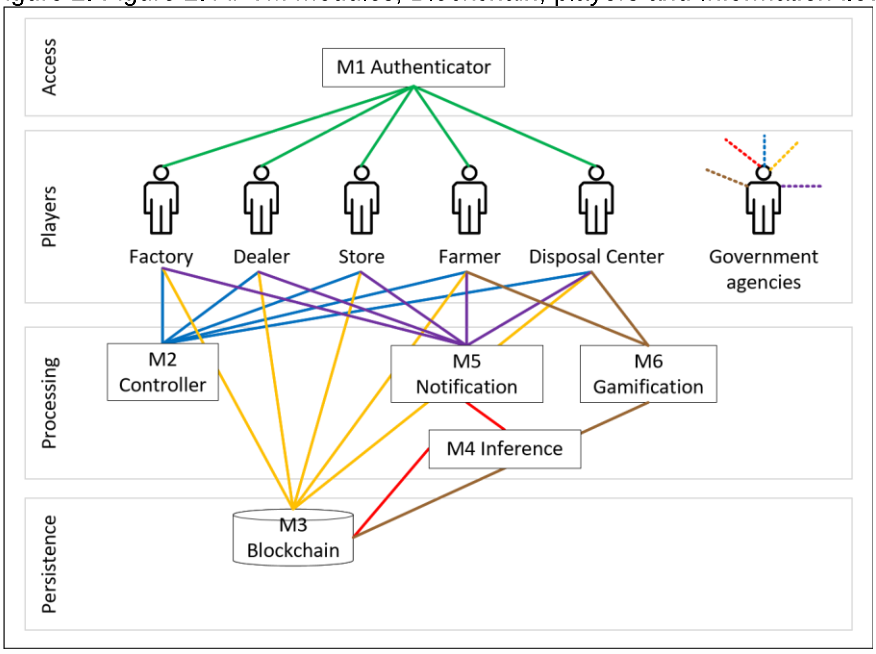
3.2 ARCHITECTURE

The six modules of APTM are: (M1) Authenticator, (M2) Controller, (M3) Ledger, (M4) Inference, (M5) Notifier, and (M6) Gamification. Each module plays a specific role in the secure and traceable operation of agrochemical reverse logistics. The subsections below describe each module in detail, including internal submodules and their operational flow. The APTM system architecture consists of six interdependent modules, each encapsulating a distinct set of services (e.g., identity management, rule enforcement, transaction logging). These modules communicate via service interfaces and collectively implement a distributed application logic atop permissioned Blockchain infrastructure.

The modules and their descriptions are: (M1) Authenticator, which is responsible for identifying the player when entering the system; (M2) Controller determines which players can communicate, so defining rules and actions; (M3) Ledger, which performs the persistence operations of previously authorized transactions on the Ledger; (M4) Inference, where some more specific features such as averages, groupings, and sums can be implemented (other recognition patterns may require more elaborate algorithms); (M5) Notifier performs a series of alert shots for the players when the Inference module triggers certain notifications; (M6) Gamification, which performs the quantification of actions performed by a player and maintains a score, allowing its award. Figure 2 illustrates the APTM modules.

While Figure 2 presents a general overview of the APTM modules and their association with actors, the detailed flow of information and internal interactions is explained in the following paragraphs. Specifically, the direction of data exchange, transaction triggering, and message propagation are outlined in the descriptions of submodules (M1.1–M6.2) and Figure 3.

Figure 2. Figure 2. APTM modules, Blockchain, players and Information flow



Source: Elaborated by the author.

The model was designed to identify the transit of agrochemicals within an RLC. The model securely stores information about transactions with each action of one of the RLC players. Upon receiving a product, the player performs local processing with the information that is of interest to it and subsequently sends it to the next player, generating output information. In a traditional model, players also interact with government entities. In Figure 2, in a general view, we can observe the various interrelationships between players and modules that follow a processing flow from left to right. Each player uses an application to interact with the model's modules. Modules are services made available to player applications.

Upon entry, players must go through an authentication process performed by the authenticator module. After successful authentication, players can start interacting by triggering the modules: entry (M1), controller (M2), Blockchain ledger and IPFS (M3), and inference (M4). The outputs are messages sent to the notifier module (M5) and the processing of the gamification module (M6). In APTM, it is essential to emphasize that the recording speed is not critical since the coherence is in carrying out the data transit within the model, persisting properly in the Blockchain. Figure 3 presents a more detailed view of the model. In this figure, each module has sub-modules to stratify the functionalities.

This figure illustrates the hierarchical organization of components. Functional blocks (e.g., routing, inference, scoring), with operations such as accreditation (M1.1), product routing (M2.1 – 2.3), transaction persistence (M3.1), and gamification logic (M6.1 – M6.2) implemented through software functions in the prototype. Although Figure 3 focuses on the structural decomposition of modules, the functional roles of each submodule (e.g., M2.3 for product transfer, M5.1 for notification triggers) are implemented as service-oriented routines within the prototype and described in the following paragraphs.

The information transmitted and stored on the Blockchain is related to the movement of agrochemicals. In M1.1, we have the accreditation process that inserts new instances of players as participants in the model, Figure 4 (This simplified diagram illustrates the decision points and flow of actions within the accreditation process. It is intended for conceptual understanding rather than formal UML modeling.). At a minimum, the government player conducts accreditation of other players. In addition, M1.2 performs the authentication process of the players when they start operations in the model. The authentication must make the player's identity and permissions available to all other modules.

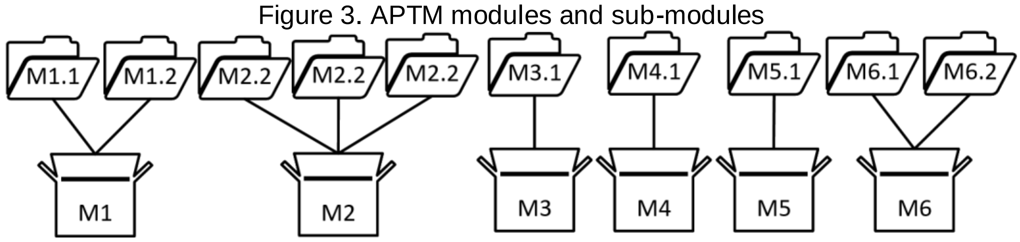
In a permissioned blockchain setting, data access is restricted to authenticated participants who are approved through the accreditation process (M1.1) and verified via authentication (M1.2). Sensitive information such as product details or player identity is visible only to parties with appropriate permissions, reducing the exposure risks commonly associated with public blockchain networks. M2.1 inserts routes in the "from-to" format, allowing routing table maintenance, Figure **??**. This diagram depicts the logical sequence of actions involved in managing active product routes between players. It is not a UML artifact, but rather a conceptual representation of routing operations.

The routing table can have criteria such as routing priority or temporary cancellation of routes. This process is consulted prior to any product movement operation. M2.2 queries the routing table, while M2.3 transfers agrochemicals, moving them between players according to the routing table. M3.1 automatically records transactions on a Blockchain every time the product is moved. M4.1 assembles the dataset to perform statistics operations, while M5.1 triggers messages to certain players. In M6.1, the farm player delivers the empty packages to the disposal center, Figure **??** (This visual describes the conditional logic for handling discrepancies and issuing score points. Its intent is to illustrate system behavior in an accessible format.).

The disposal center inspects and verifies the respective documentation. If there is any discrepancy, the farm presents a justification through supplementary documentation issued by another responsible body. A government agency conducts a final compliance check, and points are recorded. M6.2 is a module that retains additional documentation files in a Blockchain and IPFS.

By joining the semantics of all modules, we have the life-cycle transit of agrochemicals. We selected the six essential processes that comprise the input, processing, and output steps. In these stages, the first is the accreditation of the player to move products. The second is related to the control of product routes, and the last implements gamification in the delivery of products. The execution of each

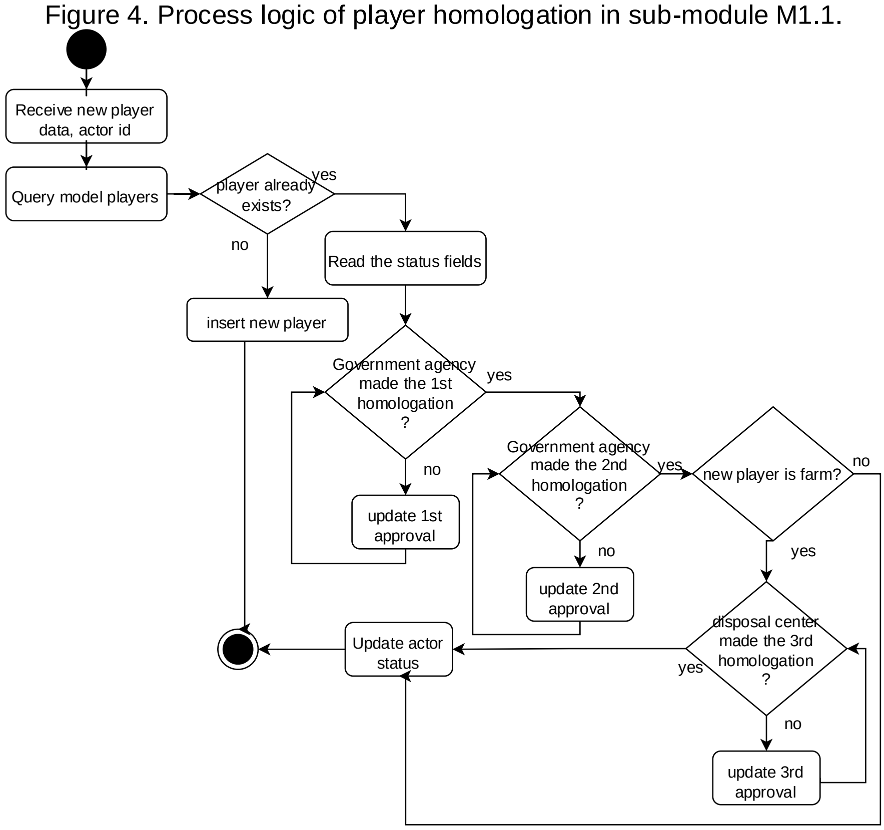
Figure 3. APTM modules and sub-modules



Source: Elaborated by the author.

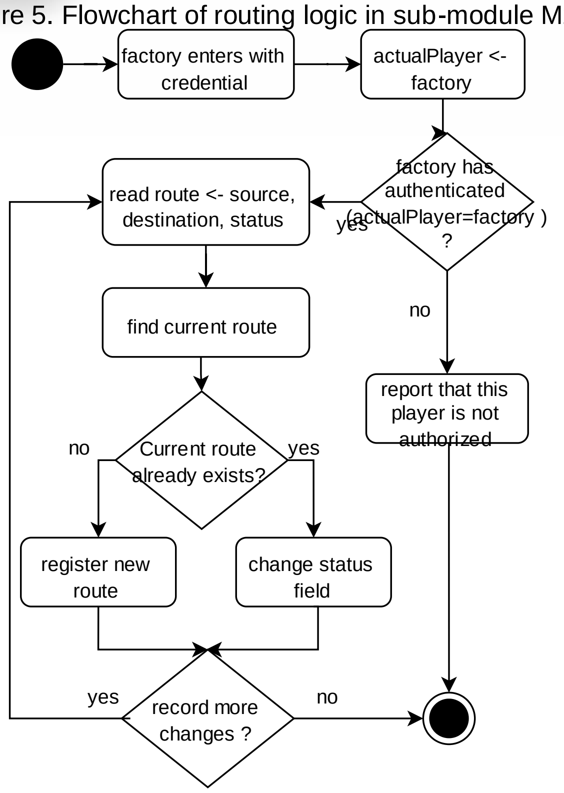
Flowchart occurs when the player needs to move products.

Figure 4. Process logic of player homologation in sub-module M1.1.



Source: Elaborated by the author.

Figure 5. Flowchart of routing logic in sub-module M2.1.



Source: Elaborated by the author.

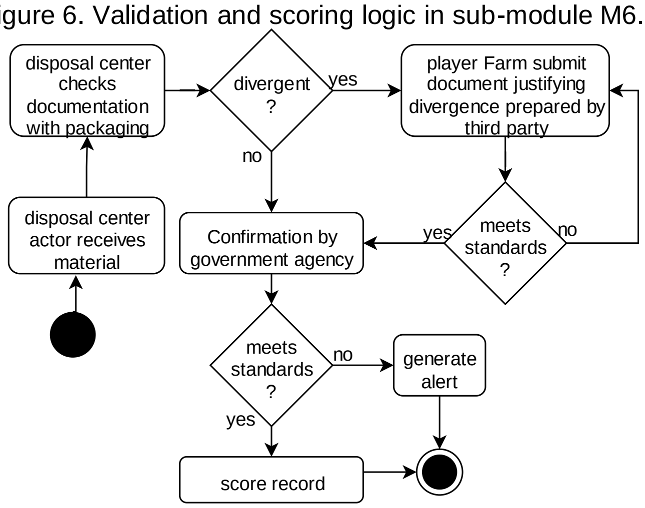
In Table 1, we have a schematization of the permission system. The permissions column summarizes the actions that players are allowed to carry out. Permissions are shown by plus and minus signs. The number of players can be increased according to demand, allowing for greater scalability. The model is not limited to the number of players, such as factories, distribution centers, stores, and farms.

3.3 OPERATIONAL SCENARIOS

This section presents example scenarios that illustrate how the APTM model operates in practice. Each scenario is divided into three stages: input, processing, and output. We simulate the product lifecycle from manufacturing to disposal, including route registration, authentication, and gamification-based scoring.

Each product has a unique identification number. The factory sends products to its distribution centers. Each distribution channel has its representative stores operating in a particular commercial territory that serves some farms within this territory. Each farm purchases the products it is interested in and in quantity according to its harvest planning. The products are taken to the farm for storage and will be applied according to the individual and farm planning schedule. Subsequently, the empty packages are stored and undergo a drilling and washing process. Once this cleaning process is completed, the packages are sent with their purchase documentation (invoice) to the distribution center that serves the region where the farm is located. The Disposal Center checks the material and sends it for further processing (recycling, incineration, disposal, or other), as the case may be. We will detail the three steps below:

Figure 6. Validation and scoring logic in sub-module M6.1.



Source: Elaborated by the author.

In the model Entry phase, the events described below occur: Accreditation is done by sub-module M1.1. The player, a government agency, registers and approves all instances of players in the model. Two instances of government players are required to ratify a valid accreditation. For example, the player instance "government1" creates and pre-approves the registration. Later, the player instance "government2" finalizes the accreditation. At this stage, the M1.2 participant authentication functionality is also present. Authentication is only performed once. At least two government agencies have properly accredited the player.

The model runs when transferring products (or empty packages) to each other, and the M2 controller module must first be consulted. The controller module has "from-to" rules that indicate who can communicate with whom. This module performs the traffic routing function within the model. The M2.1 sub-module allows the registration of routes in the routing table. The Factory player constructs the routes. The M2.1 module can, as the factory deems necessary, turn off a route (based on its business needs). After that, a transfer via that path will no longer be possible. Sub-module M2.2 is responsible for consulting routes to serve other parts of the system or other players. When players want to initiate a product transfer, they must first refer to the controller module and then proceed. The M2.3 sub-module performs product movements. Every operation performed on the model is recorded on a Blockchain. Each transfer operation (or transaction) generates a record that is passed to the M3 module.

The main outputs of the model are notifications and gamification (at each product delivery, points are added to the delivery person). The notification submodule M6.1 registers the receipt of the material, checking the empty packages and their documentation. In cases of divergence, the farm presents additional documentation prepared by a third party (another competent body that handles the type of occurrence and issues a report justifying the divergence of the material presented). This information is later added to the delivery process. These files that complement this movement of agrochemicals go to the IPFS. A government agency conducts a

Table 1. Description of the authentication roles and their actions for each player

Players	**Roles**	**Functionalities**	**Permissions**
Factory	Make the product available for movement	Create the asset within the model	+ and - asset
	Move product to next RLC player	Start shipping in the supply chain	+ include movement
	Receive packaging for recycling, or other destination	Receive the empty package	+ include empty packaging
	Manage distribution routes	Edit the communication routes table	+ and - route
Dealer	Receive the products	Store the product temporarily	+ include movement

	Move product to next RLC player	move the product	+ include movement
Store	Receive the products	Store the product temporarily	+ include movement
	Move product to next RLC player	Move the product	+ include movement
	Receive the order from the farmer	Store the document	+ include movement
Farmer	Receive the products	Store the product temporarily	+ include movement
	Use the products	Operations within the farm are not recorded	+ include movement
	Move product to next RLC player	Moving the empty package	+ include movement
	Make the empty package available for handling	Create the asset (empty package)	+ e - asset
Government	Monitor movement	View the transactions of other players	Query dataset.
agencies	Authorize the entry of	Manage and create the players in	
	players in the	the model	+ include players
	circuit, issue the green	Consult the score and generate the	
	certificate	delivery certificate	+ include certificate.
Disposal	Receive empty packages and their	Update farm score	+ include documents
center	documents		
	Move empty package to next		+ include
	RLC player	Moving the empty package	movement
	Participate in the homologation of farm-type players	Manage players	+ include players

Source: Elaborated by the author.

final document check of the model. Subsequently, the points are recorded on the farm score. Sub-module M6.2 writes data to Blockchain and IPFS. Finally, Module M1 and its sub-modules are prerequisites for players to participate in the functioning of the APTM. Modules M2, M3, M4, M5 and M6 are needed to analyze hypothesis H1. Modules M3, M4, and M6 are needed to analyze hypothesis H2.

3.4 DATA VALIDATION AND CONFIRMATION

Data is inserted into the model through validation and confirmation steps. When players are created in the input phase, two public bodies validate the players, and finally, the disposal center confirms the entry into the farm-type player’s circuit. The disposal center is an integral part of the RLC entry process, as it is responsible for "closing" the cycle. In modeling, the Factory player is tasked with documenting and managing the routes through which products move, as well as adding the shipping routes to its business partners. In this way, the Factory player is the authority on the information that the Controller module uses. There is no movement on previously unregistered routes. In the final step, the disposal center receives, checks with documentation, and validates empty packages; if there is a discrepancy, the Farm player presents additional documentation (issued by the responsible government agency). This extra documentation is saved on IPFS. Moreover, finally, a government agency finalizes the inspection of what was informed, confirming the delivery, the farm points are registered, and a delivery receipt is issued. The last stage verifies the data to ensure the accuracy of the delivery. This phase also involves incorporating gamification by tracking points for each task completed (from packaging to the corresponding documentation provided).

3.5 MODEL ENTITIES

The entity-relationship model is a graphical representation of entities and their interrelationships that describe things of interest in the domain of a knowledge area. It is used for conceptual modeling of a database (Badia, 2004) and system analysis (Song and Froehlich, 1995).

The diagram presented in Figure 7 serves as a high-level conceptual map of the entities in the APTM ecosystem. It is designed to illustrate only the main entities, without focusing on the relationships between them. Rather than depicting implementation-level details, it provides an overview of the components relevant to system logic and module interactions.

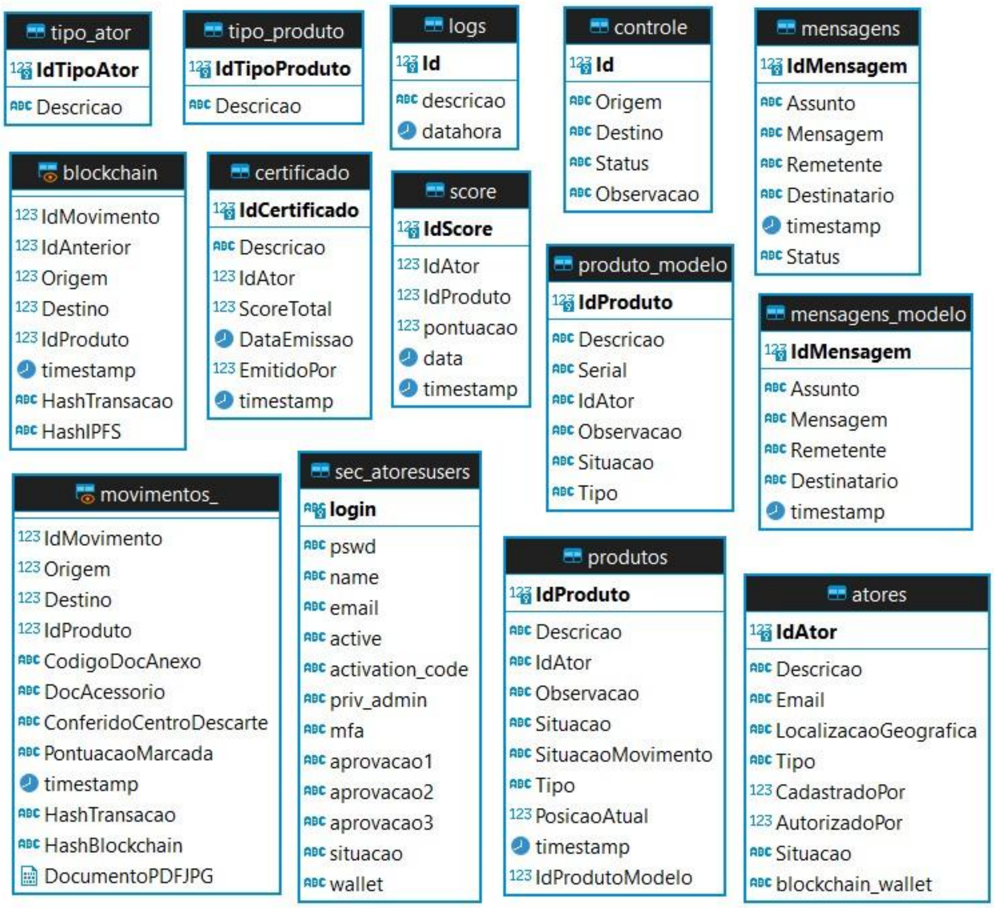
The entities and their functionalities are as follows: 1) Table: type_actor, presents fields to be used as a categorization of players. 2) Table: type_product, presents fields that are used in the simulator as a way of categorization of products by groups. 3) Table: logs, presents simulator operation logs. 4) Table: control, table used by the control system or movement flow routing within the system, it is the table used to determine which routes are active and can be used. 5) Table: messages, table used by the notification system as a message pool or output box for notifications generated within the simulator. 6) Table: messages_model contains predefined messages or warnings that can be reused by the notification sub-module. 7) Table: Blockchain implements the model Blockchain. 8) Table: certificate used to generate a proof of delivery by the disposal center to the farm informing the total points. 9) Table: score used to total farm points. 10) Table: product_model, used as a template to generate products by the factory player. 11) Table: products, contains the description of the product and its handling identifier. 12) Table: sec_atoresusers, used by the authentication sub-module. 13) Table: movements, records the movement of products between players. 14) Table: players, contains the model's characters.

4 EVALUATION METHODOLOGY

The literature consulted did not present a standard for comparing and testing systems supported by Blockchain operating with the supply chain. Some authors compare transactions per second (Keresztes *et al*., 2022; Guerpinar *et al*., 2021); others use criteria such as customer satisfaction (Karl *et al*., 2018; Ahmed, 2021). In addition, some authors evaluate prototyping (Lopez *et al*., 2022) and using prototyping with dashboard (Nelson *et al*., 2016) to visualize results. They also compare and evaluate cost, (di Angelo and di Stefano, 2010; Ruhago *et al*., 2022). Other authors make comparisons with standards regarding their software compliance, (Castellanos Ardila *et al*., 2022; Carturan *et al*., 2022).

The number of transactions per second was also confirmed by monitoring the RLC through the dashboard, expenses, and ensuring compliance with regulations to prove this work hypothesis. More precisely, this section presents the evaluation methodology. Here, we will discuss the development of the evaluation criteria. This chapter is divided into implementation aspects, data load, evaluation parameters, evaluation scenarios, and implemented prototype.

Figure 7. Conceptual entity model used in APTM



Source: Elaborated by the author.

4.1 IMPLEMENTATION ASPECTS

To validate the model’s functionality, a software prototype (Sylim *et al.*, 2018) was implemented, simulating real-world scenarios of product movement using a web based interface connected to a MySQL backed Blockchain-like ledger. This implementation allowed empirical measurement of transaction throughput and verification processes across all players in the RLC.

The model can be seen in 3 stages: input, processing, and output. The input is responsible for the authentication process of the players and their proper accreditation to operate the other functionalities of the model. Once players have undergone authentication, they can start operations according to their profiles. The factory player can create products and manage product movement routes. The government player is responsible for creating instances of players (or accounts in the prototype). Factory, Distribution Center, Store, and Farm players move agrochemical products. The disposal center player receives empty packaging and registers a score on the Farm player score. The government agency participant participates in the initial and final stages and can have access to movement data.

The prototype uses a database with which the players can store and process data as transactions are carried out with the products; the database simulates the (Xu *et al*., 2019) Blockchain. A MySQL database was used, as well as other approaches that used the Blockchain database (Koussema and Haga, 2020; Cai *et al*., 2022; Singh *et al*., 2022; Perez and Domingo-Palaoag, 2021; Yue *et al*., 2019; Sa *et al*., 2022) and MySQL Blockchain projects such as Megadex, TencentDB, ChainifyDB, Signum Blockchain, and FalconDB, (Peng *et al*., 2020). All data related to movement are fed into a movement table. Each movement requires prior consultation with the control module to use active (or authorized) routes. These routes are given in a table. Each product has a representation via a unique identifier so that its movement can be monitored (Hasan *et al*., 2019). Movement data is recorded internally in the model; only a transaction extracted via a hash is directed to the IPFS. The IPFS is occasionally used to store more information related to unique particularities of a movement (for example, a divergence of products caused by an event external to the model, theft or theft, etc.). Agrochemical products are represented in the model as assets and are the target of monitoring.

The Farm player, at the end of the transit of an agrochemical in the final player (Disposal Center), receives one point for each package delivered. The model (on the Blockchain) also records and accounts for this score. With the recording of each movement, the government agency or other partner of interest can access the situational reality of the RLC via a monitoring panel (dashboard). A prototype (Khan *et al*., 2022; Elverum *et al*., 2016) used a scenario evaluation approach. This evaluation was performed on a minimal prototype with small features that could represent the small-scale operation of the model as a whole.

Due to displacement costs, the geographic dimension that the model could serve, the number of real players, the need for displacement, and the COVID-19 pandemic, we chose to carry out laboratory tests in the design, prototyping, and evaluation phase. The evaluation aimed to simulate the model, seeking to preserve the conditions of use of the various players. Each test was carried out via a web application, representing the operation by an "employee" or "operator" of the players. These "users" were simulated using the prototype in browsers. The prototype's interface was configured to allow each user, representing a player, to use only the functionalities assigned to him. In this way, one can perceive the prototype's behavior individually from each player's perspective. Subsequently, a general assessment was conducted by observing the data generated by the agrochemical product movement table transactions. The individual evaluation of the functionalities of each player was carried out using the prototype modules separately, comparing each operation with the movement of products. A web browser was configured to work anonymously without cache generation during the individual evaluation of each player's functionalities.

The evaluations generated by the interaction with the Blockchain document the model during the persistence of the record of transactions involving the movement of the product. The differences between Blockchain operations were measured. Each operation submitted to the Blockchain (transaction extract) is collected and stored as proof that the transaction took place. We did not identify a specific metric for the counting of packages in the literature review carried out in Sections 2 and 3, nor a previous publication on the subject (Monteiro *et al*., 2021). Therefore, the simple sum of units was used to score the final phase that involved gamification. The model is agnostic regarding the recommendation of proprietary technologies due to the cost of adoption and maintenance. The current version of the model comprises software with low licensing costs, which may allow for better adoption. The main economic barrier to adherence to the model could be acquiring connectivity in rural areas for the Farm player.

The implementation adopted a blockchain simulation using a MySQL database with hash generation to validate the system's logic and performance without tying the model to a specific blockchain framework. This choice reflects APTM's blockchain-agnostic architecture, which is compatible with enterprise blockchain solutions such as Oracle Blockchain Tables and Microsoft SQL Server Ledger. The model is technologically agnostic regarding blockchain platforms, offering implementation flexibility based on system requirements and available infrastructure. The focus was on verifying core functionalities such as transaction immutability, actor validation, and traceability rather than binding to a specific platform.

4.2 TECHNOLOGIES AND INFRASTRUCTURE DESCRIPTION

The following technologies were employed to develop a simulator: A) in the hardware layer or physical devices: 2 vCPU, 30 GB SSD, 4 GB RAM, 128 GB vRAM, network interface. B) operating system and network protocol: Linux Ubuntu and TCPIP protocol. C) MySQL database (according to the technical specification of ITU-T DLT D3.1, which includes relational databases such as MySQL (ITU-T, 2019) as a storage method) and Microsoft SQL Server. D) Web application developed with HTML, CSS, Javascript, and PHP also requires web server and browsers.

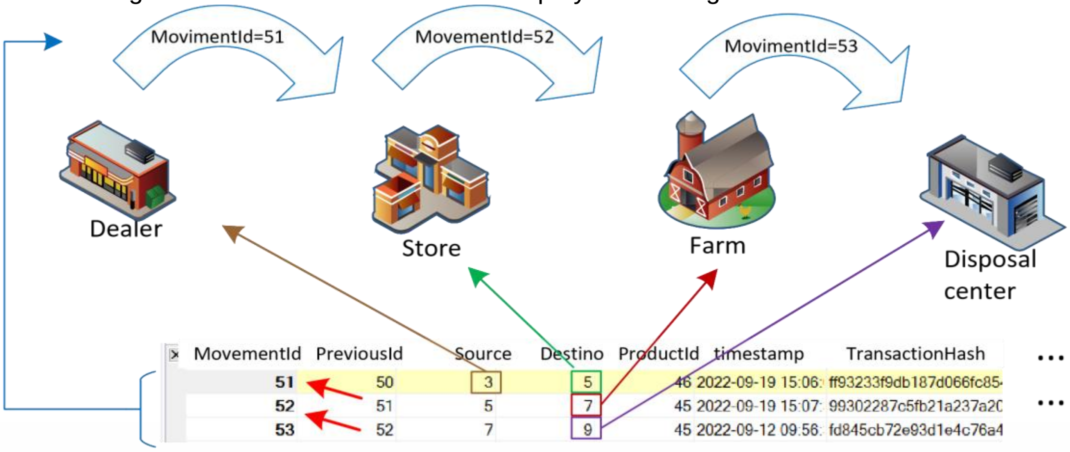
The selected hardware represents a minimum configuration for running Linux with a graphical interface (KDE or Gnome) and supporting a database service. The operating system was selected in such a way as to allow the prototype to run directly on it or via a virtual machine, in addition to having no cost as proprietary software. Other software was selected to reduce the cost of the prototype.

4.3 PRODUCT MOVEMENT OVERVIEW

The prototype operation involves the movement of products. This movement is registered on the Blockchain. Each movement is a jump, where the player receives the material, retains it until the time of utilization, and then forwards it to the next player in the RLC, performing a "jump" or movement of the product. The movement set is recorded and can be seen in Figure 8. In this figure, we have the players, three movements (or product jumps between players), and three records showing details, such as origin, destination, previous record, transaction hash, etc. A more extensive set of fields and other movements allow you to follow various aspects of the RLC. You can observe the state of the RLC as a whole.

The state of the RLC or its current context can be seen through a dashboard or control panel that allows visibility of (Sithole *et al*., 2016; Lubis *et al*., 2020) operations. The state of a logistics chain is related to the visibility of its operation and the ability of a company to track a product from its manufacture to the consumption stage (Ahmed *et al*., 2021). The dashboard is a view composed of several visual controls (widgets), such as charts, tables, and counters. Each visual control is programmed to perform an auto update (or refresh) every 3 seconds, keeping the dashboard updated. Underneath each visual control (or widget) are the business rules that communicate with the persistence layer and perform queries, bringing the data shown on the dashboard. Figure 9 presents the dashboard and visual controls that the prototype users perceive; shows the backstage of each widget with its internal function.

Figure 8. Product transfers between players and registration on the Blockchain



Source: Elaborated by the author.

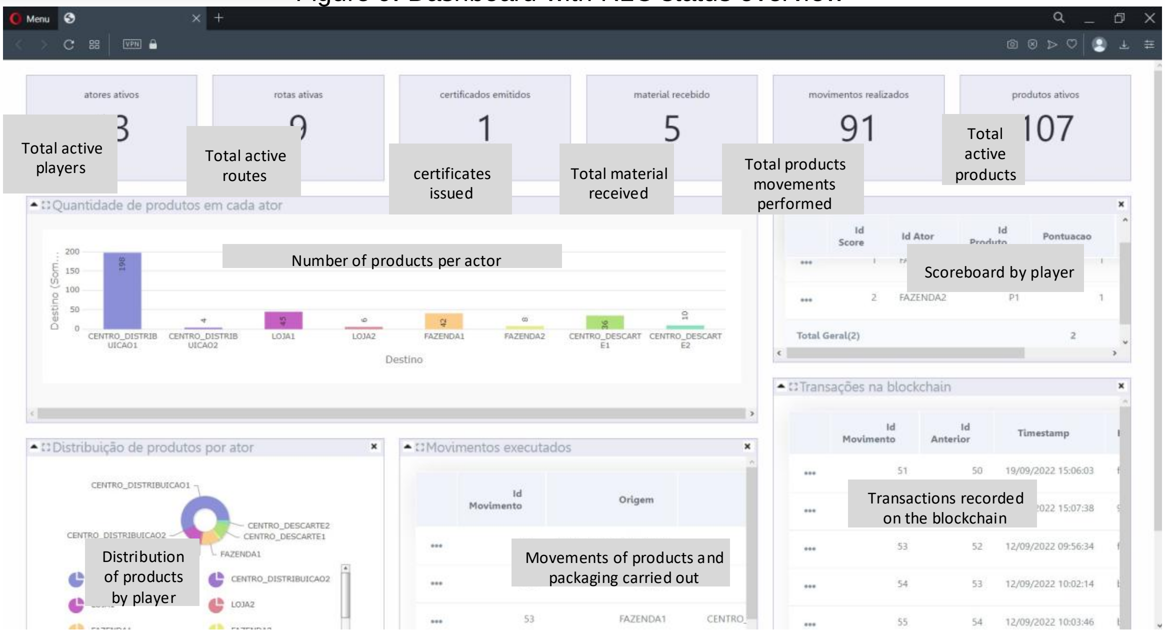
4.4 DATASET DESCRIPTION AND DATA LOAD

The prototype can provide views for consultation. In this way, the prototype works as a data-producing process. The software also creates a communication channel or data tunnel with external applications. This communication channel allows readonly access (via an account with a password) to previously assembled views. An external application authenticates and connects to views as a data-consuming process. This external application can, after the connection, perform data analysis as it deems necessary.

Transactions submitted and executed on the Blockchain (Prashar *et al*., 2020; Wang *et al*., 2020) were measured to evaluate the transaction record of product movements. This section defines artificially generated data for the evaluation loads in the prototype (James *et al*., 2021). Artificially generated data represent what could be acceptable synthetic data in a simulation (Chan *et al*., 2022; Virgilio, 2011; Smith *et al*., 2018). The simulation suggests that it is feasible to achieve outcomes within the existing dimension of an RLC. The simulation-based performance evaluation is indicated by several authors, such as (Zhao, 2017), (Parker, 2022) and (Kaizer *et al*., 2015). The literature review did not detect a proposal similar to this specific case, so loads of data were defined to evaluate the prototype.

The generation of synthetic data used random data generation mechanisms. These data have nothing to do with real players, locations, or products. They are essentially synthetic yet realistic enough to evaluate our application. These generators are freely available on the Internet to create data sets aimed at software testing (as an example, we cite: Generate data and online data generator or Mockaroo). Artificial data generators were employed for scenarios involving data such as players and products. For each transaction table, a data type is selected (integer, date, or character, according to the availability of field types in Mockaroo, for example).

Figure 9. Dashboard with RLC status overview



Source: Elaborated by the author.

The structure and semantics of the synthetic data follow the conceptual model described in the previous sections, including tables and fields. Transactions were populated using random data generation mechanisms (e.g., Mockaroo), configured to reflect realistic logistics scenarios. Although the data are synthetic, they emulate the expected behavior and format of transactions in the APTM ecosystem, enabling valid performance and consistency testing.

Then, the generated quantities are grouped into tables of 500, 1000, 2000, 4000, and 8000 records. Data relating to the movement were generated via a script that performs the following operations: it generates random data for the fields necessary for the movement (product, origin, and destination), adds a timestamp and hash, and sends it to the Blockchain for performance evaluation.

The MySQL used in the Blockchain simulation also performs a hash calculation function for each transaction received related to the movement of products. The MySQL database was chosen because it complies with the ITU-T DLT D3.1 technical specification on distributed ledger technologies (ITU-T, 2019), in addition to market movements for the adoption of Blockchains within database servers by Oracle (Hall, 2021; Rakhmilevich, 2020) and Microsoft (Anderson, 2021; Microsoft, 2024), and other projects like OpenChain (Openchain, 2015) FISCO BCOS (BCOS, 2019) that also use database as a storage layer. This function receives transaction identifier, source, destination, and timestamp data and processes the hash, recording the result in the transaction Hash field.

4.5 NOTIFICATIONS

The prototype notification system was designed to send messages as specific actions occur. It is a message broker concept. In the prototype for testing purposes, a simulation was created involving a "from-to" message from one player to another informing the movement of a product. This message can be configured so that for each action generated by M2 and M3, the recipient player receives a message in the format: {ORIGIN} sent the product {PRODUCT} to {DESTINATION} in {DateTime}, for example: *LOJA2 sent product P2 to FAZENDA1 on 21/11/2022 16:19*. Messages must occur automatically without user intervention. These messages can be configured according to the consortium management policy.

5 RESULTS

The authors Lambert and Pohlen (2001) present several metrics such as the number of orders, the cost of sale, and the cost of manufacture, among others; Karl *et al*. (2018) cites customer satisfaction, on-time delivery, etc; criteria that are not used in APTM. As well as Prashar *et al*. (2020); Wang *et al*. (2020), model performance evaluations were performed in the Blockchain transaction log. Lukinskiy *et al*. (2014)'s approach evaluated a supply chain with 20 transactions that monitored the movement of products. This approach is focused on the business area (high level) and less on the operational level (low level). However, Blockchain reviews focus on transactions per second. In this way, a random value was adopted, five hundred (500) transactions, from then on, double one thousand (1,000), two thousand (2,000), four thousand (4,000), and eight thousand (8,000). A data load was performed for each grouping. A script submitted the data to the Blockchain.

The evaluation was executed using a controlled hardware environment (2 vCPU, 3GB RAM), and performance metrics such as transactions per second (TPS) and system latency were recorded. The model sustained an average throughput of 4.6 TPS, and page load latency remained within 1.7 seconds under simulated usage conditions, confirming its feasibility for small-scale deployments.

One computer developed the application, and the other the Blockchain, separated via the Internet. The execution of a script with synthetic data is performed in a loop until the selected number of records is reached. The script works as follows: it initializes variables similar to the fields of the movement table, generates integer values, and sends them to the Blockchain inside a loop represented by the desired number of executions. At each execution, the timestamp field is filled in, and the number of executions performed per second can be evaluated. The number of completed transactions was grouped based on their transaction timestamp, with the Unix epoch time serving as the identification for each transaction group. Subsequently, a count of transactions per unit of time was performed, resulting in a table with two columns (unit of time (t1, t2, and t3, for example) x number of transactions at that time). A timetable (t1, t2, and tn, for example) was annotated by the number of transactions at that time. For example, the table shows T1 = 2 transactions and T2 = 5 transactions... Tn = n transactions within a universe of x executions. Subsequently, a count of transactions per unit of time was performed, resulting in a table with two columns (unit of time (t1, t2, t3) x number of transactions at that time). A timetable (t1, t2, tn) was annotated by the number of transactions. For example, the table shows T1 = 2 transactions and T2 = 5 transactions... Tn = n transactions within a universe of x executions. The average number of transactions per time unit was 4.65.

By late November 2022, Bitcoin had an average confirmation time of 565.82 minutes or 9.4 hours[1], and transaction ranges can take anywhere from 10 minutes to an hour, (Klemens, 2021). Coinlist waits for 30 confirmations to consider an ETH transaction completed, which can take 5 minutes up to 4 hours[2]. The cryptocurrency press has been reporting on ever faster Blockchains

[1] YCharts https://ycharts.com/indicators/bitcoin_average_confirmation_time
[2] CoinList https://coinlist.co/help/how-long-do-ether-transactions-take

(Komolafe, 2022), (Ogundare, 2022). If the most considerable interval of the submitted transactions was adopted and a calculation was performed using the transaction timestamp, these were carried out in approximately four and a half seconds (4.6) in the TPS. If the model is compared with other Blockchains, the speeds differ on hundreds or thousands of times greater scales.

The evaluation of data inserted into the model can also be visually accompanied by the dashboard mentioned in previous sections about the RLC. This dashboard presents several views of the data in the RLC. Another aspect related to performance is the memory footprint of the prototype. The page load time was approximately 1.71 seconds (with an empty cache). Memory consumption was around 15 MB after page load. They are measured in Firefox version 107 64bit. These numbers were shown to be adequate for running the previously presented prototype, especially compared to the values proposed by (Zhou *et al*., 2013) of 8 seconds. Heitzman (2020) cites 3 seconds in 2020, and Smith *et al*. (2019) cite tolerance between 4 and 11 seconds. When the prototype received data, it was possible to visualize the scoreboard with the points in Figure 9. Counting points may occur more slowly than the transit of products between players. For example, a farmer may have to store empty packages indefinitely until he has gathered enough quantity to justify going to the disposal center. The score is assessed by visualizing it in the point widget within the dashboard. Each package received is assigned a point, which enables the display of points on the panel.

The gamification process is simulated through point accumulation each time a player successfully delivers empty packages to certified disposal centers (M6.1). Although no real-world validation of behavioral effects was performed, the model illustrates how compliance can be incentivized using a scoring mechanism under blockchain-based validation.

A cost survey was conducted to run a node on a computer as a virtual private server (VPS) installed in a company that provides hosting services. The standard machine configuration used for comparison purposes was 2 vCPU, 3GB RAM, and 50GB disk. Despite the available configurations in the hosting calculators, similar configurations were selected. Thus, the average monthly cost per VPS is approximately US$39.8 per machine. For the implementation of the APTM, considering this previous average cost with seven players, the annual value could be approximately US$ 280.00.

6 CONCLUSION

This article presented APTM, a computational model to monitor the reverse logistics chain of agrochemicals. Using a modular structure, APTM allows reverse traceability of agrochemical products, making it possible to follow them from the factory to the delivery of the packaging at the disposal centers. Unlike related work, we have modeled a Blockchain solution to accomplish this, detailing what should be stored in-chain and off-chain. APTM allows the recording of scores for activities carried out at the end of the life cycle of the reverse logistics chain (RLC), generating points for the participating players as an incentive mechanism. Thus, the scoring system generates value for the farm, allowing for on-demand claims, such as tax incentives with government agencies.

We have addressed both static and dynamic aspects in the combination of agrochemicals and RLC. We have players, routes, and the scoring methodology for the first set. For the second set, we have our own movement of product solution. As social contributions, we are helping to improve health and environmental conditions. As numerical results, the APTM prototype has 4.6 TPS, 1.7 seconds of application load, and an approximate monthly cost of US$40.00 per player. We analyzed these achievements as encouraging, highlighting the solution's viability. The model can also be adapted to handle other sensitive and expensive products, such as fertilizers, without further modifications, proving its adaptability and flexibility.

It is important to note that the reported 4.6 TPS is based on a simulated prototype environment and was not designed for real-time processing at this stage. The model assumes a permissioned blockchain setting, where transaction throughput can be adapted to the volume and governance structure of the participants. Future implementations on more scalable blockchain platforms may achieve significantly higher performance.

The advantage of adoption is the possibility that all participants in the Blockchain can register their data and prove that the production chain is traceable. For farmers, it is a path to farm certification and the first step towards certification. The government's advantage is that it can monitor the production chain and implement a future credit market with tax reductions for participating farmers. The model paves the way for adopting a green economy through blockchain technology.

As this study focused on the architectural design and simulation of the APTM model, real-world deployment and field validation were not within the project's scope due to time and budget constraints. Future work includes collaboration with industry stakeholders to conduct pilot testing and assess the model's robustness in real operational environments.

As a future work, we indicate the development of modules for integration with pest control and ERP systems. Moreover, we envisage integrating with decentralized autonomous organization (DAO) type systems, allowing the Treasury player to exchange points for other products or receive tax benefits. Finally, the inclusion of mobile computing with 5G technology and the evaluation of energy consumption metrics are aspects that could be addressed in the continuation of this work.

DECLARATIONS

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COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

GENERATIVE AI IN SCIENTIFIC WRITING

The authors declare that generative AI tools were employed exclusively to enhance the clarity and grammatical accuracy of the text. The manuscript is original and stems from unpublished scientific research. The conceptual development, as well as the detailed design and description of the proposed model, were entirely conceived and authored by the researchers without the use of AI.

CONTRIBUTIONS

E.S.M conceived of the idea presented and wrote the initial manuscript. E.S.M. designed the APTM project. R.R.R encouraged E.S.M. to investigate. R.R.R and A.M.A. verified the article. All authors discussed the results and contributed to the final manuscript.

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