Blockchain-based Decision Support System for Water Management

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Abstract: With significant use in the last few years, Blockchain has become one of the most important technologies of the last decade. Due to its new paradigm and its decentralized approach, Blockchain has become a game changer in almost all business domains. Water resources management is one of the areas that were updated with these new concepts. The aim of this paper is to present a decision support system, developed on top of the Ethereum Blockchain infrastructure which would facilitate the supplier`s internal flows related to the water network incident management and validation. The proposed solution integrates the following technology stacks: Cyber-Physical Systems, Crowd-Sensing, and Serious Gaming. This solution was implemented so as to work autonomously for some specific flows and take decisions by itself based on some specifically defined criteria and also to provide suggestions to validators and speed up the validation flows based on data stored exclusively on Blockchain.

Keywords: Blockchain, Water Management Systems, Decision Support Systems, Internet of Things, Crowd-sensing Solutions.

1. Introduction

Water resource distribution and management are vital for the sustainability of water networks and food production. Therefore, in order to promote improvement and economic stability, it is imperative to investigate aspects of water security and availability that are intricately linked to water provisioning and the existence of these resources.

The evolution of technologies in the latest years and the emergence of new concepts and methodologies opened a new world for all domains, including the water distribution area. The complexity and importance of the problems related to water distribution require the integration of several systems based on various technologies. Blockchain, Serious Gaming, Crowdsensing applications, and Decision Support Systems in the context of Cyber-Physical Systems had raised awareness in a significant manner. Water is necessary and essential for sustaining life, economic development, and protecting the environment. According to United Nations (UN) estimates, by 2025, approximately 70% of the world's population will live in urban areas, and the current centralized water supply infrastructure will need major changes. However, by using emerging technologies such as Blockchain, the Internet of Things (IoT), and sensors, there is the possibility of more efficient water management. To provide a more comprehensive illustration of these emerging technologies, this section broadly describes the involvement and contribution brought by them within the water infrastructure.

Blockchain is a revolutionary and dynamic technology that can change the way centralized finance works (Dogo et al., 2019) and can support the growth of technological applications meant for developing the necessary infrastructure for smart facilities and Internet of Things (IoT)-based solutions that will promote and facilitate advanced management of water resources (Ferrag et al., 2018; Reyna et al., 2018).

Innovative applications based on Blockchain technology are currently being implemented for water treatment contracts, smart payments, sharing utility data and infrastructure information, water trading rights, and many other interesting applications (Global Water Intelligence, 2018). Furthermore, a smart contract is integrated into a Blockchain network, enabling the automated transfer of crypto currencies among various entities including consumers, smart water devices, and other relevant utilities when certain predefined conditions are met. The implementation of payment systems and smart contracts eradicates the inconsistencies and errors commonly associated with traditional methods for performance evaluation, and for maintaining and marketing water facilities. Embracing

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these intelligent approaches optimizes business transactions seamlessly, minimizes costs, and efficiently verifies/prevents fraudulent attempts.

Moreover, Blockchain technology can be leveraged for reporting, compliance, and audit review purposes. Distributed ledger systems within the water industry can be utilized to monitor compliance with government guidelines and regulatory authorities. Recording activities and their immutable characteristics on a Blockchain creates an auditable trail for auditors and enhances consistency. This transformation would significantly reduce the time and effort (thus, cost) that financial institutions expend on administrative details while simultaneously improving quality, accuracy, and trust.

In recent years, several proposals for Distributed Ledger Technology (DLT) solutions and decision-support tools have been introduced, aiming to assist professionals in effectively managing this complex decision-making process. The study of Ar et al. (2020) provides a noteworthy contribution to Blockchain applications in the water sector by addressing the crucial role of decision support systems (DSS) that bridge the gap between managerial and technical perspectives. It highlights the importance of monitoring, managing, and making optimal decisions to preserve water resources, tackle issues like water leaks, and control excessive water demand.

Sustainable water management in modern society involves significant challenges worldwide (Russo, Alfredo & Fisher, 2014).

Traditional water monitoring systems often rely on centralized data collection methods and specialized hardware, which can be costly and limited in its ability to capture relevant information about water-related issues from the consumer perspective (Adu-Manu et al., 2017).

In recent years, the emergence of new paradigms, such as crowdsensing and serious gaming, has offered alternative solutions to address these issues (Hangan et al., 2022).

The use of crowdsensing, which leverages the collective power of individual smartphones and IoT (Internet of Things) devices, has been applied in various domains (Ganti, Ye & Lei, 2011). In water management, crowdsensing enables the collection of data from diverse sources, including citizens, sensors, and other connected devices (Predescu et al., 2021b; Ma, Zhao & Yuan, 2014). By engaging the public as active participants in data collection, crowdsensing empowers individuals to contribute to environmental monitoring efforts, leading to a more comprehensive understanding of water resources.

Serious gaming, on the other hand, harnesses the engaging and immersive nature of video games to simulate and solve complex problems (Bellotti, Berta & De Gloria, 2010). Serious games are used for training specialized personnel of various domains (Gheorghita & Anghel 2016) by simulating different scenarios from various domains that otherwise would have been very costly to reproduce (air emergencies, space engineering tasks, complex industrial systems, etc.) By integrating serious gaming into decision support systems, this gamified approach fosters collaboration and participation and enhances interactions between stakeholders in water distribution systems (Predescu & Mocanu, 2019).

To combine these concepts and technologies, this research article focuses on a Blockchain-based decision support system for water monitoring that leverages the power of crowdsensing and serious gaming. The integration of Blockchain technology into a crowdsensing platform for decision support ensures data integrity, security, and transparency, enabling the creation of a decentralized and tamper-proof environment for water management, with improved incentives for participants (Wei, Wu, & Long, 2020). By using crowd-sensed data for the decision-making process and serious gaming for stakeholder involvement, a cyber-physical system aims to extend water management scenarios and enhance the sustainability of water resources.

This paper is structured as follows. In Section 2, a comprehensive review of related literature is conducted, wherein the effects of Cyber-Physical Systems, Blockchain, Decision Support Systems, Serious Gaming, and Crowdsensing solutions on water resource management are examined. Section 3 presents the proposed methodologies for the proposed blockchain-based decision support solution. In Section 4, the actual implementation of this system is explained, showing the challenges encountered and their corresponding solutions. Lastly, Section 5 provides an overview of the conclusions derived from this work, along with the prospective future steps to be undertaken for practical implementation.

2. Related Work

During the last years, a lot of new concepts have emerged and considerable technological advancements have taken place, e.g. Blockchain, IoT (Internet of Things), Crowdsensing, and AI (Artificial Intelligence). Together with more established concepts and technologies (e.g. Decision Support Systems or Cyber-Physical systems), solution architects started to design more and more complex systems with an increasing impact on human lives.

This section will present a dive into these concepts and how they can be combined in order to obtain a strong, solid, and durable application for water infrastructure management.

2.1 Water Management

In the context of increasing demands for water supply in large metropolitan areas, the need for a centralized and coordinated water supply system arises which necessitates more sustainable and efficient solutions for infrastructure management.

For example, the article of Dogo et al. (2019) explores the impact of Blockchain and IoT on water management and examines storm water management, water quality monitoring, and direct-to-consumer reporting as well as payment and smart contracts to sustainably address the challenges of the global water crisis induced by climate change and rapid population growth.

Another approach by (Pincheira et al., 2021) explores how the energy-efficient integration of IoT-based sensors and Blockchain can be used to drive certain behaviors in agricultural practices. The novelty of the study lies in the use of a system architecture comprising an IoT device to measure water consumption and a smart contract public Blockchain infrastructure that is of interest for the various stakeholders in water management and regulates the distribution of incentives among farmers.

The authors Xia, Chen & Song (2022) propose a system to improve the traditional way of storing water data. This system will cover the entire “supply-use-consumption-discharge” process. In this regard, the monitoring data is encrypted and transmitted using a peer-to-peer network, being more secure and reliable, and the risk of its manipulation or loss is avoided. This innovative model brings multiple benefits, such as reducing costs, increasing data security, and improving the use and protection of water resources.

In conclusion, given the urbanization trends and the needs related to population growth, it is crucial to develop and implement innovative and sustainable solutions to ensure access to clean water and meet future demands in an environmentally responsible manner.

2.2 Blockchain and Cyber-Physical Systems

In recent years, Blockchain has become an indispensable technology in robust systems. Through consensus algorithms, secure protocols, and distributed data storage, solutions become safer and more reliable.

An important number of studies have highlighted solutions from various fields where Blockchain plays a key role in CPS applications.

Such an example of a Blockchain-enabled CPS is described in (Rathore, Mohamed & Guizani, 2020) and consists in a notary system that uses Blockchain to avoid different types of scams. The solution is based on the creation of unique certificates, to easily check the integrity of the data. Similarly, Blockchain was successfully integrated into education, the solution being described in the paper of Fernández-Caramés & Fraga-Lamas (2019).

At the same time, Cyber-Physical Systems (CPS) are in continuous development, being up to date with next-generation computing, physical, and network operations. The paper by Hölbl et al. (2018) proposes the implementation of a CPS Smart Building (CPS-SB) network that consists of a private Ethereum blockchain system and is based on smart contracts. Such CPS-SB systems have evolved rapidly, being created in several parts of the world. The Edge Building in Amsterdam, the Leadenhall Building in London, the Capital Tower in Singapore, the Siemens HQ in Masdar City, and the Al Bahr Towers in Abu Dhabi are just some of the existing examples.

The integration of Blockchain technology in a CPS-SB leads to a safe system, ensuring increased security. If traditionally, the development of an application that allows a protocol for communication between devices or data monitoring for the purpose of making decisions represented a consistent basis, nowadays these aspects are necessary but not sufficient. Without a secure and transparent system, most applications are not sustainable.

On the other hand, there are many opportunities for creating new architectures thanks to the Ethereum 2.0-specific tokens ERC-20 and ERC-1155/ERC-721.

The transition from the proof-of-work (PoW) consensus mechanism to the proof-of-stake (PoS) model in Ethereum 2.0 has addressed key scalability and energy consumption concerns (Saad et al., 2021).

This upgrade has paved the way for the development of more efficient and sustainable decentralized applications (dApps) built on the Ethereum platform.

The major characteristics of Ethereum ERC-20 include a fixed supply (which makes the token deflationary and stable), the ability to instantly transfer and query account balances, and readily trackable events, all within a decentralized framework. Additionally, ERC-1155 (multi-token contract) offers the ability to manage numerous token types within a single contract, handling both fungible and non-fungible assets, transferring these assets in batches, as well as managing information or URIs for the held tokens.

Researchers have explored various aspects of this evolution, including the enhanced transaction throughput and reduced fees, the introduction of shard chains to support parallel processing, and the potential for increased privacy through mechanisms like zero-knowledge proofs (ZKPs) (Wang & Li, 2021). These advancements have fostered a fertile ground for innovation, stimulating the creation of new types of Blockchain applications and redefining the possibilities of decentralized systems in a post-Ethereum 2.0 era (Arslanian, 2022).

2.3 Decision Support System

Constant monitoring of water consumption is an important step in water conservation and decision-making to maintain a sustainable water supply system.

Drăgulinescu et al. (2021) propose the SWAM project (Smart Water Management System for better environmental sustainability) with a focus on data security. Moreover, the solution integrates Blockchain technology to prevent threats that may appear in water quality monitoring, used in agriculture.

Another approach involving decision support systems is described in (Munir, Bajwa & Cheema, 2019) and is based on fuzzy logic to develop a smart watering system (SWS). Furthermore, an Android mobile application is implemented through which the fuzzy logic module sends decisions regarding the watering needs of a plant. The system collects data in real time from sensors installed in gardens and small fields in order to decide on the program for watering the plants. Moreover, Blockchain technology has been used to ensure the necessary security in the IoT system and Fuzzy Logic to provide intelligent decisions on watering requirements.

In the same way, the system described in (Zeng et al., 2023) combines the Internet of Things (IoT) with Blockchain technology to effectively monitor agricultural fields. The Blockchain network ensures data security and increases trust among community members. Moreover, the prototype manages the water resources across the communities and maintains a good quality of the seeds.

Blockchain technology, combined with decision support systems, holds great potential for water management. By integrating these two technologies, it can enhance the efficiency, transparency, and accuracy of decision-making processes related to water resources. Blockchain technology can provide a secure and immutable platform for storing, sharing, and verifying water-related data. It enables decentralized and transparent record-keeping, ensuring that information is tamper-proof and can be accessed by relevant stakeholders in real time. This decentralized nature of Blockchain ensures that decision support systems can rely on accurate and trustworthy data when analysing and recommending actions in water management.

While the integration of Blockchain and decision support systems in water management is a relatively new and evolving field, there are several examples and research initiatives showcasing their potential. WaterChain (Tracxn Technologies Ltd., 2023) is a Blockchain-based platform that aims to improve water management and conservation. It utilizes Blockchain technology to provide a transparent and immutable ledger for recording water usage, transactions, and quality data.

Furthermore, Water Ledger is another project, led by the University of Melbourne that explores the use of Blockchain technology for managing water entitlements in Australia (Dogo et al., 2019). It aims to create a decentralized ledger to track and trade water entitlements, enhancing transparency and efficiency in water markets. Decision support systems can leverage this Blockchain-based platform to facilitate informed decision-making regarding water allocation and trading.

Last but not least, the SmartH2O project (Novak, et al., 2016), funded by the European Commission, is focused on utilizing Blockchain and decision support systems to improve water management in urban areas. The project aims to develop a Blockchain-based platform for monitoring water quality, consumption, and infrastructure performance. Decision support systems integrated with this platform can provide real-time insights and recommendations for an efficient water management.

While these examples provide a glimpse into the potential of Blockchain and decision support systems in water management, it's important to note that this field is still evolving, and further research and implementation are needed to fully realize their benefits.

2.4 Crowdsensing and Serious Gaming

The integration of crowdsensing and serious gaming in water management has gained significant attention in recent years, with several studies focusing on specific aspects of these technologies (Predescu et al., 2021b; Mittal, Scholten & Kapelan, 2022; Predescu et al., 2021a). This section presents a selection of relevant studies that highlight the application of crowdsensing and serious gaming in water monitoring and decision support systems.

A previous study (Predescu et al., 2021b) explored the use of crowdsensing for water quality assessment. The researchers developed a mobile crowdsensing platform that allowed citizens to contribute water quality data using their smartphones. The study demonstrated the potential of crowdsensing in enhancing spatial and temporal coverage of water quality monitoring and engaging the public as active participants in environmental monitoring efforts.

In (Minkman, van Overloop & van der Sanden, 2015) the conducted research on crowdsensing-based water quality monitoring in the Netherlands highlights the overall citizen interest and involvement. The study is based on a framework that integrates crowd-sensed data with scenarios identified by representatives of Dutch water boards. The study demonstrated the feasibility of crowdsensing as a valuable tool for real-time water quality monitoring and highlighted its potential in improving the overall understanding of water resources.

Mittal, Scholten & Kapelan (2022) conducted a systematic review on serious games for decision support in water management. The study examined a range of serious games designed for water-related applications, including flood management, water allocation, and water governance. The findings indicated that serious games offer valuable platforms for stakeholder engagement, collaborative decision-making, and scenario analysis, enhancing participants' understanding of complex water management challenges.

The potential of serious games to solve water problems was covered in a special issue of the Water Journal (Medema et al., 2019), which focused on the complexity of water management, addressed through a social learning approach supported by innovative instrumentation and tooling. The research directions emphasize the potential of serious gaming in improving stakeholders' awareness, knowledge, and decision-making skills related to water management.

These studies collectively highlight the diverse applications and potential benefits of integrating crowdsensing and serious gaming in water management. The integration of these technologies holds great promise for improving water monitoring practices and facilitating sustainable water resource management.

3. The Proposed Solution

The proposed solution introduces an innovative approach for event reporting within the context of urban water infrastructure, employing crowdsensing scenarios.

The designed reporting system encompasses the integration of a crowdsensing model into a serious game-based interactive platform, augmented with Blockchain support.

Within the realm of location-based serious game architecture, characterized by the dissemination of reporting tasks across a geographical map, an incentive mechanism has been devised in previous research work with the primary objective of attaining an optimal distribution of participants, thereby fostering effective collaboration in the context of crowdsensing-based reporting. This complex challenge can be conceptualized as an allocation optimization problem, which necessitates the seamless integration of a reward-based incentive mechanism. (Predescu & Mocanu, 2019)

The initial application developed within the Watergame project (UEFISCDI, grant number PN-III-P2-2.1-PED-2019-4993, Smart Urban Water-Based on Community Participation Through Gamification - Watergame Project) included various features for a water distribution network in an urban environment and provided a bridge to educate customers to improve their consumption and also become aware of the impact that they may have by reporting possible incidents in the water infrastructure.

Figure 1, which shows the graphical user interface for event reporting leverages the functionality of Google Maps, wherein the spatio-temporal distribution of reports is visually presented through the utilization of markers.

3.1 Blockchain Integration

The proposed architecture embraces a contemporary approach that leverages the latest features of Blockchain technology. This includes integrating decentralized principles, incorporating Web 3.0 concepts, and adhering to token standards such as ERC-20 and ERC-1155.

Ethereum has emerged as the most popular platform for creating digital currencies and decentralized apps (dApps).

Therefore, the decentralized component for user interactions was implemented using Ethereum Blockchain infrastructure. This component was based on an ERC-20 token named Water Game Token (WGT) and was designed to facilitate the following scenarios:

- The user will receive WGT after reporting a valid incident;
- The user will be able to donate WGT to other users directly from his/her crypto wallet;
- The user will be able to buy or trade WGT (directly from crypto wallet, exchanges, or other platforms);
- Users will be allowed to participate in initial coin offerings (ICO);
- Any customer has the possibility to buy discount tokens (saved also as decentralized tokens) with the accumulated WGT;
- By selling their discounts on secondary markers or directly from their wallets, the contracts will be automatically changed without any human intervention.

The Ethereum architecture, from a technical perspective, consists of a chain of blocks, each of which contains a list of transactions, the Ethereum virtual machine, which serves as the runtime environment (in the form of a secure sandbox) for executing smart contracts written in Solidity, the proof-of-stake algorithm, and the native ETH token, which is used for both transactions (regardless of their type) and fees. The adoption

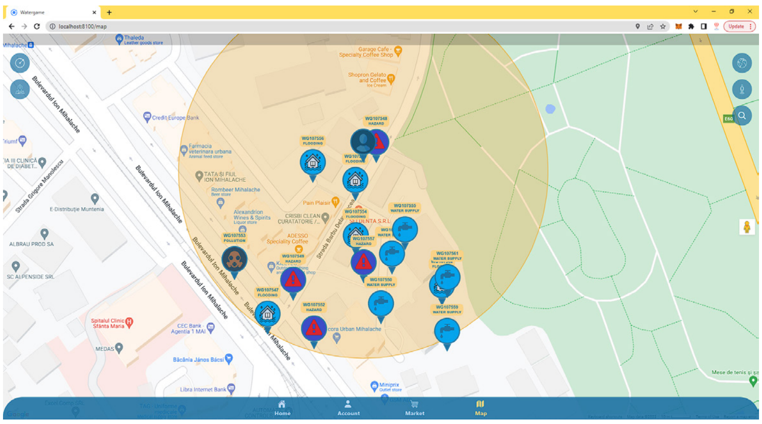

Figure 1. Event Reporting mechanism

of these concepts naturally defined better ways of writing the code in the Blockchain field and the ERC standards.

All these technical aspects and ready-to-use features determined the use of Ethereum Blockchain as the first candidate when implementing our decision support system decentralized solution.

3.2 User Interactions

The solution was designed for optimizing the distribution network incident reporting mechanism. In this sense, the registered users can report water distribution issues, and the reports are rewarded with application tokens.

After the issue is reported, there are a lot of actions that need to be performed by the water provider and these actions require a lot of time.

First, each incident needs to be inspected by validators and approved by them in order to be actively handled by the dedicated persons from this field.

The validation process consists in checking data accuracy, verifying if there are sufficient details in the reported incident, and checking the complexity of the details. After the issue is validated, the ticket is taken by the intervention team.

In order to optimize this process, the decision support system was designed to facilitate (A) the detection, and (B) the validation of the incidents.

A. Incident Detection

The incident will be parsed by the decision support system according to the following flow:

- Allocate the reported incident and interrogate Ethereum-based Blockchain system for reporter rating;
- Calculate the rating based on the information recorded on Blockchain and provide recommendations for the validator.

B. Incident Validation

The validator receives the incident processed by the DSS and can perform the following actions:

- Confirm the DSS decision (approve/reject incident);
- Inspect the reported incident;
- Assign new rating to the reporter.

From the technical point of view, an ERC-1155 Ethereum contract is used in order to save user ratings. Each user will have one rating assigned per reported incident. When the decision support system calculates the average user ratings in order to determine the recommended actions, it will retrieve the existing records from Blockchain and perform the necessary calculations.

4. Results

The proposed application provides a decision support system for verifying and facilitating the exchange of virtual currencies into tangible benefits, particularly in the domain of service provision within the water distribution network.

Figure 2 illustrates the interface of the Blockchain system employing the MetaMask extension, thereby enabling users to engage in various operations utilizing the WGT (Water Game Token) virtual currency.

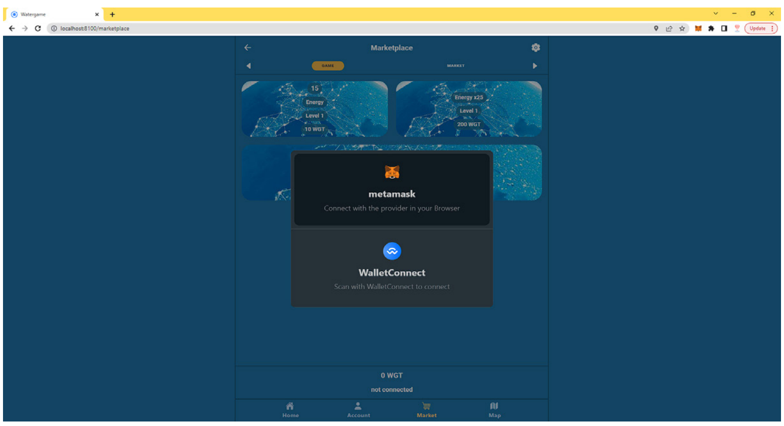

Figure 2. Authentication using MetaMask

Upon successful authentication on the Blockchain network, relevant account details of the user, including the account identifier and balance, are promptly retrieved, and presented within the application interface.

For managing user ratings, the ERC-1155 token standard was used, with the following decentralized file system as it is depicted in Figure 3.

To integrate the DSS with the Blockchain domain, the *DSSManager* smart contact was defined. Based on the information retrieved from the Blockchain, the centralized component of the Decision Support System analyzes the ratings and provides recommendations for the validators. The contract therefore exposes the following functionalities:

- Integrates with ERC-1155 Ratings Contract and is able to retrieve the data from that contract for each user;
- Exposes a method named "getAccountAverageRating" that parses and returns the average rating for a given user address;
- Exposes a method named "getAccountRatingsHistory" that returns all the previous ratings for a given user address.

Based on the information retrieved from Blockchain DSSManager, the centralized component of the Decision Support System makes a decision for: incident confirmation, incident rejection, or incident passed to human validator, based on the user rating returned from Blockchain.

Following this logic, in the first two cases, the human validator is just informed about the actions taken by DSS, and in the third case, the human validator evaluates the received information, takes a decision regarding the reported incident and at the end inserts a new rating in Blockchain.

The diagram in Figure 4 presents the incident validation flow, from the perspective of the DSS domain, Blockchain domain, and validator domain, showing the interactions between the solution components. The recommendation system can provide decision support for automating incident validation based on user ratings registered in Blockchain, which would be the subject of future work regarding the integration of AI (artificial intelligence) algorithms to improve the overall effectiveness in real operating conditions.

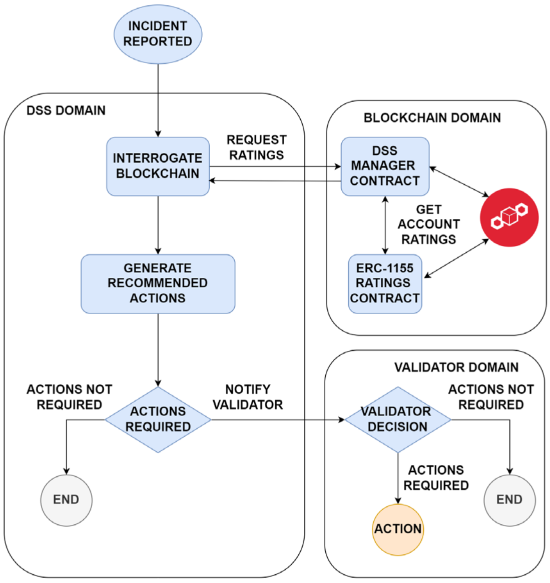

Figure 4. Incident validation flow

5. Conclusion

This study reveals that there are several ideas in the field of water management that support both the demands of customers and water distribution flows.

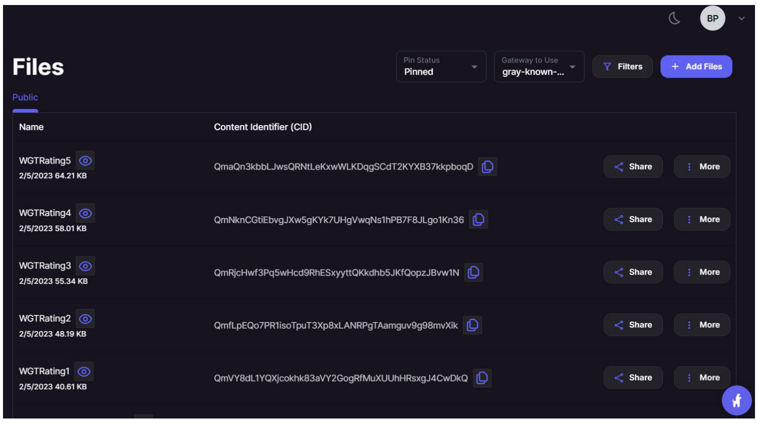

Figure 3. ERC-1155 Rating Token in Pinata

On the other hand, the development of technologies like Blockchain, Crowd-Sensing, Decision Support Systems, and Serious Gaming has significantly changed this field by enabling architects to create solutions that are more intricate and dynamic.

The proposed solution extends the domain of Cyber-Physical Systems for water management with a decentralized architecture that facilitates the participant incentives and incident validation flows and helps the water suppliers to manage reported incidents in large-scale water distribution networks.

The role of this paper in the water management field is very important because it offers a solution that improves the water provider internal validation workflows with the support of a Blockchain decentralized architecture.

By combining these technologies, this paper brings novelty to this field, by utilizing their unique qualities, and most importantly by integrating Blockchain on top of the proposed architecture to improve solution security, transparency, and trust. The practical novelty brought about by this solution lies in defining the support for automating incident validation process using smart contracts.

Finally, the proposed solution can bring a significant improvement in this field and could be a game changer for the industry of water supply companies.

As further developments, the proposed solution shall be deployed on a larger scale to evaluate its overall performance in the context of a Cyber-Physical System with a Crowdsensing component for water management, which requires an extensive validation of the proposed validation schemes to achieve overall effectiveness in real operating conditions.

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