buildings

Article

Developing an Inspector-Centric Blockchain-Enabled Conceptual Framework for BIM Management in Mars Buildings

Amirhossein Javaherikhah [1,*], Mercedes Valiente Lopez [1] and Saeed Reza Mohandes [2,*]

[1] Escuela Técnica Superior de Edificación, Universidad Politécnica de Madrid, 28040 Madrid, Spain; mercedes.valiente@upm.es
[2] Department of Engineering Management, University of Manchester, Manchester M13 9PL, UK
* Correspondence: amirhossein.javaheri@alumnos.upm.es (A.J.); saeedreza.mohandes@manchester.ac.uk (S.R.M.); Tel.: +34-664632040 (A.J.)

Abstract: Due to the unique atmospheric conditions on Mars, the management of essential information in Mars buildings is of great importance. Even the smallest error or manipulation of data can create irreparable risks for residents. Martian buildings require a strong security shield to ensure accurate and unaltered data processing. In this article, the factors affecting the buildings of Mars and the lives of the inhabitants of Mars were identified and analyzed, and seven key factors were identified. These factors were then integrated into Mars building information systems using blockchain technology, defining four distinct alert levels for specific building conditions. This research is based on the simulation of Martian buildings, and there has been no laboratory case to test the proposed method until now. The findings showed that the proposed framework for Martian buildings was better than similar studies based on Earth, and there was no similar case to compare the results in Martian buildings. The ground-breaking integration of blockchain and building information modeling (BIM) on Mars opens up new opportunities for extraterrestrial building control methods and marks the beginning of the evolution of this field, but given that there is still no construction in the field of buildings on Mars, organizations and bodies that work in this field can use the results of this research to check the compatibility of the proposed method with Martian buildings.

Keywords: building information modeling (BIM); blockchain technology; building of Mars; building information security; building management

check for updates

Citation: Javaherikhah, A.; Valiente Lopez, M.; Mohandes, S.R. Developing an Inspector-Centric Blockchain-Enabled Conceptual Framework for BIM Management in Mars Buildings. *Buildings* **2023**, *13*, 2858. https://doi.org/10.3390/buildings13112858

Academic Editors: Salvatore Antonio Biancardo and Jun Wang

Received: 25 September 2023
Revised: 28 October 2023
Accepted: 13 November 2023
Published: 15 November 2023

1. Introduction

Mars is the fourth planet from the sun in our solar system. Due to Mars' identical rotation period and tilt of its rotation axis relative to the plane of the ecliptic, its days and seasons closely resemble those of Earth. These characteristics of Mars, as well as its distinctive geography and landforms, have sparked a lot of interest in Mars exploration and the possibility of future Martian migration. The Mars exploration missions of many nations will continue to advance in the future with the goal of gaining a deeper understanding of the planet's outward climatic conditions and interior structure and laying the groundwork for a future human journey to Mars [1]. Therefore, Mars' structures are crucial for developing information management and its administration. because these studies are only starting their journeys. Consequently, building information management in various structures will change. Building Information Modeling (BIM) is a combination of regulations, procedures, and interoperating technology that generates a way for managing the fundamentals of a building's design and project data throughout its life cycle [2].

It may give a single presentation, data frame, and structure. The architecture of construction automation allows information and communication technology (ICT) to manage the life cycle information of structures. During the lifespan of a building, the fundamental characteristics of BIM may be summed up in four aspects: integration with various databases, facilitation of document management, analysis and simulation of sustainability, as well as visualization of analytical procedures and outcomes. The most recent application of ICT architecture for BIM is conventional client-server architecture, some of which is based on existing systems [3].

The impact of BIM on the architectural, engineering, construction, owner, and operator (AECOO) business has shifted [4]. BIM information transmission varies based on the kind of model and time period used and introduces risks for participating parties, such as issuer responsibility, information susceptibility to infiltration, and information abuse. Consequently, these risks cause a slew of contractual, legal, security, and system issues that stymie the growth and convenience of BIM adoption at the industry level [5]. According to the usage of BIM in Mars buildings, there is a need to offer information security. Due to the high level of security provided by blockchain, these two approaches may be integrated to ensure the security and correctness of BIM information in the building. Mars made sure. Blockchain is a distributed, digital, public record of data, assets, and all associated transactions that network members perform and share. Although blockchain is most commonly associated with digital currencies such as Bitcoin, it is seen as an emerging technology with the potential to transform the digital working environment and business practices in virtually every industry. transform [6]. The primary idea behind blockchain is to create a distributed digital agreement that ensures data is decentralized across several nodes exchanging similar information and that no user has complete control over the network. This improves activity transparency and data security. While blockchain was initially designed only for financial transactions, with the goal of creating a system that allows secure data transfer between two parties without the need for an intermediary, the tremendous destructive potential of blockchain has become clear in recent years with the exponential growth of various cryptocurrencies [7].

Blockchain will restructure current workflow routes in any company where it is used, emphasizing trust and collaboration between members, and will provide several advantages, including collaborative learning, immediate data interchange, automated contract execution, and more [8]. By defining BIM transactions and storing them on a private blockchain, Mars buildings may be managed using this study. In addition, four normal levels, one emergency level, two emergency levels, and three emergency levels have been developed in an effort to create a framework for building control inspections. Following is a description of Mars' history. The integration of BIM and blockchain will then be evaluated based on previous studies. In the subsequent section of the used approach, the specified transactions and four inspector-focused levels are described. Then, the implementation's outcomes are described, followed by a concluding statement. By conducting studies and research in the field of blockchain and its integration with BIM, similar research and studies have not been conducted in the field of integration of these two technologies in Martian buildings, and in general, no research has been conducted in the field of information management in Martian buildings.

Thus, the following research question is addressed in this paper:

How could blockchain technology and BIM be integrated to improve the information management of buildings on Mars?

To answer this question, the following objectives were determined:

Enhancing BIM security to maintain information security;

Using BIM for Mars buildings; and

Integration of BIM and blockchain.

The biggest gap in this research is that, due to the fact that construction has not yet started on Mars, it is possible that the security and accuracy of information have not been addressed, which has a special place in Martian buildings. Is. Investigating Mars building information and its management is of particular importance because this importance is emphasized more with regard to weather conditions. Therefore, blockchain technology has been used as a suitable tool to provide security. Also, various aspects of using blockchain and its integration with BIM have been evaluated in the context of the work.

2. Research Literature

2.1. About the Planet "MARS"

The Soviet Union launched the first Mars probe, 1960A, in 1960, which failed but marked the beginning of human exploration of the Red Planet. The Mars missions from the 1960s to the 1990s were summarized by Ouyang et al. (2011) [1]. The United States (eight launches, six successes) and the Soviet Union (six launches, two successes) dominated Mars exploration (fifteen launches, one success) during that time. Mariner 9, part of the National Aeronautics and Space Administration's (NASA) Marine program, successfully reached Mars orbit for the first time in 1971, collected the first high-resolution images from Mars satellites, and functioned on Mars. It has been in orbit for more than a year. Near the end of the twentieth century, the Mars Orbiter was one of the most successful Mars exploration missions in history, providing in-depth studies of the Martian atmosphere, temperature, geology, and soil and rock composition [1].

By concentrating on morphological, geochemical, and mineralogical properties, the Mars rover gathered a body of information about the Martian soil. Compared with Viking, this mission used a lander with multispectral imaging capability. The extremely mobile rover, which was capable of performing studies on soil mechanics, was also equipped to analyze the elemental chemistry of soil and rock [9]. Table 1 provides information about the various minerals that are present in the soil on Mars. It summarizes the mineral composition of the soil and helps to understand the geological and environmental conditions on the planet.

Table 1. Mars soil mineralogy ([10]).

	Na_2O	MgO	Al_2O_3	SiO_2	SO_3	Cl	K_2O	CaO	TiO_2	Fe_2O_3
Pathfinder	2.2	7.5	8.3	48.6	5.4	0.6	0.3	6.3	1.1	17.5
Viking soil	-	6.0	7.2	43.4	7.4	0.8	-	5.8	0.6	18.2

Despite all the research and available information, the viability of the presented theories will not be thoroughly evaluated in real-world situations until a construction robot equipped with additive manufacturing technology arrives on Mars. NASA's aim to establish a livable habitat on the moon prior to launching the Mars mission is a smart strategy for researching the structural behavior of housing in interplanetary environments. In terms of productivity, speed, and affordability, additive manufacturing is the most durable building method.

2.2. Mars Building

2.2.1. Team Zopherus

Zopherus, built by a group of Arkansas residents (Figure 1), won NASA's 3D Printing Habitat Challenge. The "huts" are pieced together to form a close-knit society using a variety of materials from Mars. A 3D printer is used to complete the construction, removing the need for human engagement and ensuring that the structure is ready for human habitation upon arrival. A robot-built lander selects a good area to reside in the city and then installs a group of robots, which finally begin and end the design process [9].

2.2.2. Ai SpaceFactory: Marsha

The Ai Space Factory set out to develop the Marsha (Figure 2) when NASA launched its 3D-printed habitat competition in 2015. The double-insulated hub can withstand Martian atmospheric pressure, allowing all construction to be finished on Mars and eliminating the need to send completed structures aboard a space shuttle. Materials for this structure are readily available on Mars, with the team developing an emulsion of Martian basalt fibers and renewable bioplastics obtained from plantable plants. While these hubs are not shared places, they can easily accommodate 1–2 individuals and will provide those who migrate to Mars with their own space in the future [9].

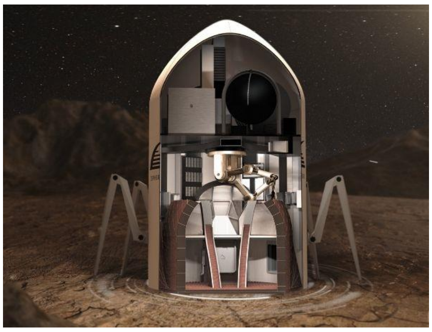

Figure 1. Zopherus.

Figure 2. Marsha.

2.2.3. Warith Zaki and Amir Amzar: Seed of Life

Malaysian designers Warith Zaki and Amir Amzar want to construct something like Ai Space with the seed of life (Figure 3). The plant is wrapped around a layer of ethylene tetrafluoroethylene (ETFE), and water is poured into the bamboo, freezing the structure and boosting protection by using robots to weave bamboo shoots (planted on Mars after locating a water source). Gives. The design of this pair is based on the idea of choosing against 3D printing, which is the theme of the building of most Martian structures, for the inhabitants of the planet's temperature. While bamboo alone may not be adequate to protect the construction, the researchers feel it is a more practical technique to build habitable structures on Mars than 3D printing [9].

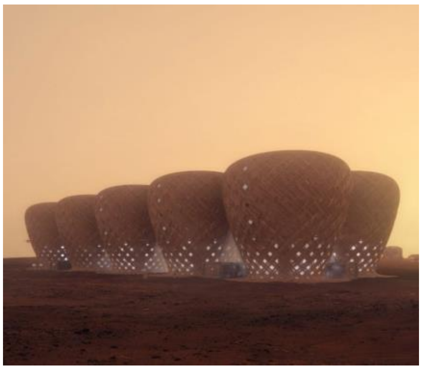

Figure 3. Seed of Life.

2.2.4. NASA, University of Arizona: Martian Greenhouse

While the majority of greenhouses on Earth are composed of glass, NASA and the University of Arizona Department of Agriculture have developed an inflatable greenhouse that grows vegetables on faraway planets (Figure 4). The 5 × 2-m design can allow air reclamation, water recycling, trash recycling, and even absorb the carbon dioxide inhaled by Repurpose astronauts to ensure astronauts and potential citizens may maintain a vegetarian diet in space. This greenhouse has been compared with many biological systems on Earth, and it will undoubtedly be used when people travel to Mars [9].

Figure 4. Martian Greenhouse.

2.3. Life on Mars

2.3.1. Water Drainage on Mars

Although the surface of Mars is currently cold and dry, there is ample evidence that the Red Planet was once partially covered with water. Researchers have theorized that life may have evolved on Mars when it was wet and could even be hiding there in the subsurface now. "On Earth, water means life", says Alberto Firen, an astrobiologist at the Spanish Center for Astrobiology and Cornell University in Ithaca, New York. The surface of Mars is extremely dry today, but there are many clues that point to a much wetter past. "Evidence of past water may be a clue to finding extinct life on Mars, and if some of that water still exists on Mars, the prospect of finding life will certainly increase". Water on Mars also has important implications for NASA's research areas beyond NASA's astrobiology program. Even if life no longer lives on Mars or never existed in the first place, water could still be vital to future life on Mars in the form of human colonies on the Red Planet. Water is not only useful for drinking but also for radiation protection and, when split into hydrogen and oxygen, as fuel. The prospect of past, present, and future life on Mars means that much of NASA's research on the Red Planet is focused on its water [8]. To address the issue of water drainage on Mars, researchers are actively exploring various methods. Optimal use of Mars resources is essential. One approach is to use existing subsurface water ice and recycle water into habitats. In addition, technologies for extracting water from the Martian atmosphere are being developed.

2.3.2. Establishing a Society on Mars

Humans are not made for Mars. Or, rather, Mars was not made for us. It is important to understand the sacrifices that a huge company requires in order to succeed. Building a Mars colony is on everyone's mind. SpaceX is testing the Mars rover prototype. Jeff Bezos is funding a lunar gateway for manned missions to Mars. Humans are certainly getting closer to setting foot on the Red Planet. The success of a Mars colony depends on how we decide to overcome these challenges. Building Mars to support human life will still take centuries. This causes immigrants to live in land-dependent habitats for the first few generations. Independence from Earth requires the use of purely Martian resources. The time scale required for deployment on Mars includes resource consumption considerations. Mars has even fewer usable resources than Earth. Using growth patterns on Earth as a model, Martians will soon encounter a problem we are only just beginning to see on Earth. They estimate that a Martian society will run out of resources in the next few centuries. This means that a truly independent Mars colony would likely have an expiration date unless we made fundamental changes [9]. The idea of having contractors on Mars means a more developed society. Establishing a Mars colony requires significant infrastructure, investment, and a sustainable source of income. This could be through scientific research, resource extraction, or even tourism in the future. This involves a gradual process, possibly starting with smaller research stations and expanding over time.

2.3.3. Revised Building Design

Given the unique challenges of Mars, such as its thin atmosphere and exposure to radiation, building designs must actually be adapted. Structures may need to be partially or fully underground for protection. Advanced materials and 3D printing technology are considered for construction. Designs should prioritize safety, radiation protection, and efficient use of resources [11].

2.4. Research Review

In his 1982 PhD thesis, Chaum was the first known person to propose a blockchain-like technology [11]. Haber and Stornetta described a cryptographically secure chain of blocks in 1991 [12]. Bayer et al. added Merkel trees to the method in 1993 [13]. Szabo created "bit gold", a decentralized digital currency mechanism, in 1998 [14]. Nakamoto introduced Bitcoin, an electronic currency with a completely peer-to-peer network, in 2008 [15]. In addition, the term blockchain was initially used to describe the distributed ledger that underpins Bitcoin transactions in 2008 [16]. Butrin proposed Ethereum in his white paper in 2013 [17]. Ethereum development was crowdfunded in 2014, and the Ethereum network became operational on 30 July 2015. The launch of Ethereum signaled the beginning of blockchain 2.0 because, unlike all of the previous block-chain projects that concentrated on the development of altcoins (currency comparable with Bitcoin), Ethereum allows individuals to connect to each other through trustless distributed applications on its own blockchain. The Linux Foundation introduced Hyperledger's block-chain frameworks, which differ from Bitcoin and Ethereum, in 2015. There are eight blockchain frameworks, Hyperledger Explorer, and four libraries available through Hyperledger [18]. A unique technique known as SDT is presented in the work by Xue and Lu (2020) to remove data redundancy in BIM by using blockchain. SDT tracks local alterations and incorporates them into a BIM contract. This analysis discovered that adding a block to the blockchain takes 0.02 s and that the amount of redundant data has decreased significantly [19]. A decentralized framework was established in the study by Dounas et al. (2021) integrating BIM elements on the blockchain platform. The findings revealed that the participants were satisfied with the level of security provided by the blockchain without any engagement in improving the blockchain's security or structure [20]. Research Using BIM (building modeling information technology), connected data, smart contracts, and blockchain, Ye et al. (2020) propose a system for automated payment. The billing model (BM) information model is created to connect data with the blockchain for automated payment [21]. Following research on a business tool named BIMCHAIN, Pradeep et al. (2020) investigate a blockchain-based approach for improving BIM data interchange trust. According to the findings of this study, there are eight fundamental functional requirements for a blockchain-based application to address BIM challenges [22]. Liu et al. (2019) investigate the roles and integrated strategies of BIM and blockchain in sustainable building design information management. The BIM user interface with blockchain technology is utilized for BIM transactions, while the BIM architecture and BC smart contract simplify the settlement of BIM challenges for sustainable design [23]. Integration of BIM and blockchain into the implementation of smart contracts was considered by Shojaei et al. (2020). A blockchain network is presented in this study to handle a prototype building project. The proposed design does not employ the cryptocurrency component of blockchain as a form of payment. The findings suggest that blockchain is an effective way for managing construction project contracts since it automates each transaction and keeps track of the project's progress [24].

According to research conducted and a study of various works on this subject, the need for information monitoring through blockchain has not been highlighted. Blockchain monitoring does not imply that blockchain as an authority supervises the proper execution of transactions, since this technology is incapable of doing so. The meaning of blockchain is to monitor the correct execution of transactions; the central and intermediate role of blockchain is to ensure that the information sent from actor x to actor y matches the transaction history information stored in the blockchain; and simply storing the information in the blockchain is a logical and efficient method for enhancing security. Consequently, the purpose of using blockchain is to improve information transit and data security.

3. Research Methods

In the framework presented in this research, we have a non-exclusive public blockchain in which all buildings and residents can become members, create smart contracts, and exchange information. One of the conditions for membership in this blockchain is to have sensors for all members of the building, which is both expensive and difficult to install. These sensors are the responsibility of the customer and then must be approved by the construction company. These sensors are different depending on the type of contract with the company; for example, if the type of contract is only to adjust the oxygen of the residence, the oxygen control sensors are installed in suitable places to reduce the oxygenation of the place. Send this information to the manufacturing company. Sensor information is stored in the cloud, and this information is then hashed and its hash placed in the non-exclusive public blockchain. Every contract that is made creates a ledger in the blockchain, and from now on, all transactions related to this contract are chained together in this ledger. And the hash of each block is stored in the next block, and this causes that if the smallest change is made in the hash of one block, the hash of other blocks will also change, and all the blocks in the network will notice this change, and this will make the information in the blockchain. Each client has a private and public key and a digital signature to authenticate them. Customers can have a different public key to communicate with each company to increase the security of their anonymity.

3.1. Negotiation Stage and User Contract Request

At first, the client becomes a member of the public, non-exclusive blockchain. Customers can obtain the company's public key through the company's website or through Certification Authorities (CAs). The customer negotiates with the desired company about the terms, costs, and other matters of the contract, and then the customer requests the contract for the transaction. The company sends The structure of this transaction is as follows:

"T_ID || Request_Smart_Contract || SP_PK || User_PK || Sing" (1)

As shown in Table 2, in a blockchain network, transactions are processed and recorded as blocks, which are then added to the existing chain of blocks in a linear and immutable manner. Each transaction within a block is identified by a unique number called a transaction ID (T_ID). This ID serves as a reference to the specific transaction and allows users to easily trace the history and status of their transactions. When a customer requests a smart contract from a construction company, they submit their request to the blockchain network as a transaction. The details of the request, including the terms and conditions of the contract, are encoded in a data structure called Request_Smart_Contract. To ensure the security and authenticity of the transaction, the customer signs the request with their private key and attaches their public key (User_PK) to the transaction. The construction company also attaches their public key (SP_PK) to the transaction. The customer's signature (Sign) serves as proof of their identity and authorization for the transaction. When the transaction is submitted to the network, it is processed and verified by the nodes in the network. If the transaction meets the necessary criteria and is approved by the network, it is added to the blockchain as a new block, which includes the transaction ID, the customer's request, and the signatures from both parties.

Table 2. Summary of transactions.

Transaction	Details
T_ID	The unique number and hash of the current transaction
Request_Smart_Contract	The customer's smart contract request to the construction company
SP_PK	Company's public key
User_PK	Customer's public key
Sign	Customer's signature

3.2. The Stage of Entering into a Smart Contract

The construction company prepares the contract and sends it to the customer. After receiving the contract, the customer signs it and then sends it to the desired company; the company also signs the contract and sends it to the blockchain, and the construction company's signature is the creation of a new block. It is on the blockchain. The structure of this transaction is as follows:

"T_ID | | P_T_ID | | User_PK | | User_Sign | | SP_PK | | SP_Sign | | Rfe.contract.ID" (2)

As shown in Table 3, in order to conclude contracts on the public blockchain, there are specific conditions that must be met. One of these conditions is that the contracts must involve sensors, which are provided by the customer and installed by the construction company. Once the sensors are installed, the customer adds them to their cloud and defines a new key, which allows the sensor data to be sent to the cloud. However, before the contract can be finalized, the construction company must confirm the correctness of the customer's sensors. This is typically done through a physical inspection of the sensors, which may include checking the accuracy of oxygen or temperature sensors, for example. The construction company will inform the customer of when the inspection will take place. Once the contract is signed and the sensors are verified, the sensor data must be stored on the blockchain platform. This includes data from sensors used to control oxygen, temperature, and air exchange in the building's structure and side walls. This data is stored in a block on the public blockchain, which creates a tamper-proof record of the sensor readings. By using the blockchain to store sensor data, it is possible to ensure the integrity and accuracy of the data, as well as the security and transparency of the contract. This can help reduce the risk of fraud or error in the sensor readings while also providing a clear record of the contract terms and sensor data for monitoring and analysis.

Table 3. Summary of transactions with Details.

Transaction	Details
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
User_PK	Customer's public key
User_Sign	Customer's signature
SP_Sign	Public key and signature of the construction company
Rfe.contract.ID	Field of contracts related to sensors

3.3. Sensors

There are many sensors in the discussion of intelligent building management using sensors. The number of building sensors can vary greatly depending on several factors, such as the size of the building, the purpose of the sensors, and the specific needs and goals of the residents or building managers. For this research, we have used six types of sensors, as shown in Table 4.

Table 4. Sensors used.

Sensor
Oxygen
Temperature
Control
Celling
Wall
Facilities

3.4. Oxygen Sensor Control

At this stage, the sensors measure the oxygen in the surrounding environment at certain time intervals (a time clock), and after the approval of the inspector, the data is stored on the blockchain platform. The structure of this transaction is as follows:

$$\text{"T\_ID || P\_T\_ID || S\_ID || Oxygen\_content"} \tag{3}$$

As shown in Table 5, in a blockchain-based system, T_ID (Transaction ID) refers to the unique identifier of the current transaction that is being recorded in the blockchain. Each transaction in the blockchain has a unique ID, which is generated using a hashing algorithm. Hashing is the process of converting the input data into a fixed-size output that is unique to that data. The hash function used to generate T_ID ensures that it is virtually impossible to modify the transaction data without changing the ID. P_T_ID (Previous Transaction ID) refers to the hash of the previous transaction that was recorded in the blockchain. In a blockchain, each block contains a reference to the previous block in the chain, which creates a linked list of blocks. This linked list ensures the integrity and security of the blockchain, as any attempt to modify a previous transaction would invalidate all subsequent transactions in the chain. S_ID (Sensor ID) is a unique identifier of the sensor that is being monitored in the system. In the context of intelligent building management using sensors, S_ID may refer to the ID of a particular sensor that measures the oxygen content in the environment. Oxygen content is a measure of the amount of oxygen present in the environment. In the context of intelligent building management using sensors, measuring oxygen content can be important for ensuring the health and safety of occupants. For example, if the oxygen content falls below a certain threshold, it could indicate a ventilation problem or the presence of harmful gases, which could pose a risk to human health. By monitoring the oxygen content using sensors and recording the data in a blockchain-based system, building managers can ensure that they have an accurate and tamper-proof record of the environmental conditions in the building.

Table 5. Summary of transactions with details.

Transaction	**Details**
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
S_ID	Desired sensor number
Oxygen_content	Amount of oxygen in the environment

3.5. Temperature-Control Sensor

This sensor shows the temperature of the environment, which can be used to control the temperature of a building in different places such as the commuter area, bedroom, living room, etc. The structure of this transaction is as follows:

$$\text{"T\_ID || P\_T\_ID || S\_ID || temperature"} \tag{4}$$

As shown in Table 6, in a blockchain-based system, T_ID (Transaction ID) is a unique identifier of the current transaction that is being recorded in the blockchain. This identifier is generated using a hashing algorithm that transforms the transaction data into a fixed-size, unique code. P_T_ID (Previous Transaction ID) refers to the hash of the previous transaction that was recorded in the blockchain. In a blockchain, each block contains a reference to the previous block in the chain, which creates a linked list of blocks. The P_T_ID ensures that the integrity of the blockchain is maintained, as any attempt to modify a previous transaction would invalidate all subsequent transactions in the chain. S_ID (Sensor ID) is a unique identifier of the sensor that is being monitored in the system. In the context of intelligent building management using sensors, S_ID may refer to the ID of a particular sensor that measures the ambient temperature in a specific zone or area of the building. In the context of intelligent building management using sensors, temperature sensors may be used to monitor the ambient temperature in different zones or areas of a building. By recording the temperature readings in a blockchain-based system, building managers can track changes in temperature over time and identify patterns or anomalies that may indicate issues with the heating, ventilation, and air conditioning (HVAC) system or other factors affecting the indoor environment.

Table 6. Summary of transactions with details.

Transaction	Details
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
S_ID	Desired sensor number
temperature	Temperature is related to the ambient temperature

3.6. Control Sensor

The sensor being discussed is related to monitoring the air exchange between a building and the environment, and it is important for this exchange to be zero. In other words, the sensor is designed to detect any air movement that may occur between the inside of the building and the outside. This is important because it helps to maintain a stable and comfortable environment inside the building, which is essential for the occupants. However, the sensor's importance becomes even more critical when considering a location like Mars. On Mars, the atmospheric pressure is very low, and any air pressure that enters the walls can be damaging. Therefore, it is essential to monitor the resistance of the external walls and ensure that they are able to withstand the pressure exerted by any air currents. To achieve this, two different sensors and transactions are required. The first sensor is an air exchange control sensor, which is used in areas where there is a higher possibility of air entering and exiting. This sensor will detect any air movement and alert the control system if there is a breach in the building's envelope. The second sensor is a wall resistance control sensor, which is used in areas where there is the greatest pressure against air currents. Typically, this is in the upper parts of the building. This sensor will detect any pressure exerted on the walls and alert the control system if there is any damage to the walls. Also, a sensor should be added to control the facilities so that it can be used to control the facilities and the place of their failure. Therefore, a transaction is added to the previous transactions to control the facilities. These transactions can be shown in a generalized form in a transaction that includes items such as sensor type, control type, and sensor values, as shown below:

"T_ID | | P_T_ID | | S_ID | | Type_Sensor | | Type_Control | | Amount" (5)

As shown in Table 7, in a blockchain network, transactions are recorded in blocks, and each block contains a hash of the previous block, creating a chain of blocks, hence the name blockchain. In the context of the sentence you provided, T_ID refers to the hash of the current transaction, which is a unique identifier for that particular transaction. It helps to ensure the integrity and security of the transaction by providing a unique identifier that can be used to verify the transaction's authenticity. P_T_ID, on the other hand, refers to the hash of the previous transaction. It is used to create a link between the current transaction and the previous transaction in the blockchain, which ensures the immutability and transparency of the network. S_ID is a variable that relates to the desired sensor number. It is used to identify the specific sensor that is being controlled or monitored by the transaction. Type_Sensor indicates the type of sensor being controlled or monitored by the transaction. There are three types of sensors: air exchange control, pressure control, and facility control. Type_Control indicates the type of control that the sensor is subject to. There are two types of controls: sensitive and non-sensitive. Sensitive controls are for air and pressure exchange, while non-sensitive controls are for facility control. Finally, the amount refers to the values that the sensors show, which are controlled or monitored by the transaction. These values could be anything from temperature to humidity, and they are used to trigger various actions in the blockchain network, such as opening or closing air vents or adjusting pressure levels in a controlled environment.

Table 7. Summary of transactions with details.

Transaction	Details
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
S_ID	Desired sensor number
Type_Sensor	Type of sensor
Type_Control	Type of control sensor
Amount	Values sensor

3.7. Components of Buildings

In this part, the components of the building whose information is stored in the blockchain by sensors have been discussed. This part includes three parts of walls, ceilings, and facilities, each of which is described in detail below.

3.8. Ceiling

The roof is one of the most important factors in building components, especially in Mars buildings. According to this point, the roofs in Mars buildings, in addition to determining the level of each floor of the building, should include things such as air conditioning and temperature control. Air control and the prevention of air flow between the floors are controlled using the air exchange control sensor, and temperature control is determined using the temperature sensor. Also, the height of the ceilings should be such that it leads to the circulation of air containing oxygen and temperature control. Therefore, the information that can be stored in the blockchain as building management for roofs is the type of roof, the type of material, the height of the roof, and the amount of load that each roof bears. Hence, this transaction is shown below:

"T_ID | | P_T_ID | | R_ID | | Roof_type | | Material | | Height | | Load amount | | Description" (6)

As shown in Table 8 and Figure 5, in a database management system, a transaction identifier (T_ID) is a unique identifier assigned to a transaction, which is a series of database operations that are executed as a single logical unit of work. The T_ID helps in tracking the progress of a transaction and in managing concurrency control. The previous transaction identifier (P_T_ID) is the identifier of the transaction that was executed immediately before the current one. It helps in maintaining the consistency of the database and in detecting conflicts that may arise due to concurrent transactions. A roof identifier (R_ID) is a unique identifier assigned to a roof in a database that stores information about roofs on Mars (Figure 5). The type of roof is classified as sloping, flat, or dome-shaped, and each type may have an outer and inner roof. The material used in the roof depends on the type of soil on Mars. The height of the roof is an important parameter that determines its suitability for a particular application. The load amount refers to the amount of weight that the roof can support without collapsing or failing. This parameter is important in designing roofs for different purposes, such as residential, commercial, or industrial use. Finally, the description of the roof map includes information such as the size of the roof, the purpose for which it is intended, and any other relevant details. This information helps in managing and maintaining the database of roofs on Mars.

Table 8. Summary of transactions with details.

Transaction	Details
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
Roof_type	Type of roof
Material	Material used in the roof
Height	Height of the roof
Load amount	Amount of load placed on the roof
Description	Description of the roof map

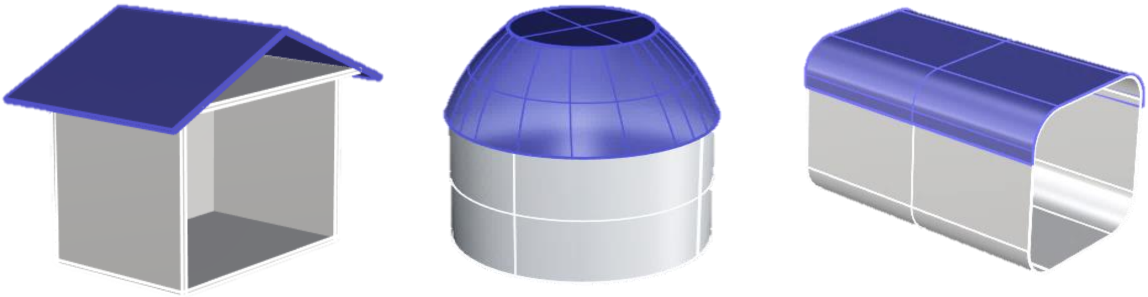

Figure 5. Type of Ceiling.

3.9. Wall

The second most important factor in Mars buildings is the wall. Walls are divided into several types. He pointed out the side wall, internal wall, retaining wall, shear, and opening shear. But there is a kind of wall on the surface of Mars called the Guard Wall, which prevents meteorites from hitting the surface of Mars. Also, the thickness of the walls, the materials used in them, and the height of the walls can be added to the blockchain as building management information. This transaction is described below:

"T_ID || P_T_ID || W_ID || Wall_type || Material || thickness || Load amount || Description" (7)

As shown in Table 9, a transaction identifier (T_ID) is a unique identifier assigned to a transaction that helps in tracking the progress of the transaction and managing concurrency control. The T_ID is used to ensure that the database remains in a consistent state even when multiple transactions are being executed concurrently. The previous transaction identifier (P_T_ID) is the identifier of the transaction that was executed immediately before the current one. It helps in maintaining the consistency of the database and detecting conflicts that may arise due to concurrent transactions. A wall identifier (W_ID) is a unique identifier assigned to a wall in a database that stores information about walls on Mars. The type of wall is classified as simple, parallel arrangements with grids, solid parallel arrangements, empty and unreinforced parallel arrangements, and each type may have an outer and inner wall (Figure 6). The type of material used in the wall depends on the type of soil on Mars, and the thickness of the wall depends on its application. The load amount refers to the amount of weight that the wall can support without collapsing or failing. This parameter is important in designing walls for different purposes, such as residential, commercial, or industrial use. Finally, the description of the wall map includes information such as the size of the wall and any other relevant details. This information helps in managing and maintaining the database of walls on Mars.

Table 9. Summary of transactions with details.

Transaction	Details
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
W_ID	wall ID
Material	Type of materials used in the wall
thickness	Thickness of the wall
Load amount	The amount of load placed on the wall
Description	Description of the wall map

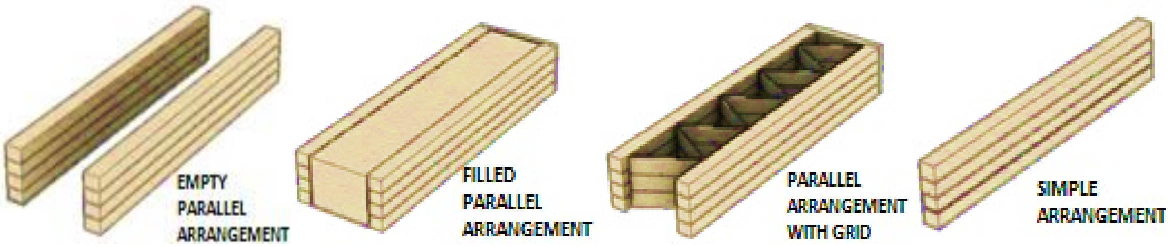

Figure 6. Type of wall.

3.10. Facilities

Building facilities are crucial components that give life to a building and enable people to continue living and working in it. They are the infrastructure and equipment that support a safe, comfortable, and functional environment for the occupants. When it comes to Mars buildings, the types of facilities required are significantly different from those needed on Earth due to the harsh conditions on the planet. The first critical facility in a Mars building is the water supply system. This system must be able to provide hot and cold water for drinking, cooking, and sanitation. The water supply pipes must be designed to withstand the low-pressure environment on Mars, which is significantly different from Earth's atmospheric pressure. Additionally, the water system must include a way to purify and treat water for reuse to ensure sustainability. Another essential facility is the sewage collection system. To prevent contamination and health hazards, waste products must be collected and disposed of properly. Airtight pipes that can withstand pressure changes, extreme temperatures, and radiation exposure must be used for proper sewage collection and disposal. The waste must also be treated and processed safely for the environment and the occupants. Ventilation is also critical in a Mars building. It helps regulate the temperature and air quality in the building, preventing the buildup of harmful gases and allowing for the flow of fresh air. Vent pipes must be designed to withstand extreme temperatures and pressures while providing efficient airflow to prevent the spread of airborne illnesses. Fire safety is another crucial concern in any building, including Mars buildings. Fuel and fire extinguishing pipes must be installed throughout the building to provide quick access to fire suppression materials. These pipes must be designed to withstand the extreme temperatures and pressures of Mars, and the fire suppression materials must be carefully chosen to be effective in the low-pressure environment. Finally, electrical piping is essential for a Mars building's efficient operation. The electrical system must provide reliable power despite the harsh environmental conditions. Electrical piping in the form of ducts must be installed to protect the wiring from radiation exposure and extreme temperatures. There is a center in the Mars buildings, and the corresponding transaction is to store the docket information. This information includes the location of the docket, the size of the docket, and the description of the docket, which is generally stored in the blockchain. The types of facilities that can be used in a Mars building are cold and hot water pipes, sewage collection pipes, vent pipes, fuel and fire extinguishing pipes, and electrical piping.

$$\text{“T\_ID} \mid\mid \text{P\_T\_ID} \mid\mid \text{D\_ID} \mid\mid \text{Location} \mid\mid \text{Size} \mid\mid \text{Description”} \tag{8}$$

As shown in Table 10 a transaction identifier (T_ID) is a unique identifier assigned to a transaction, which helps in tracking the progress of the transaction and managing concurrency control. The T_ID is used to ensure that the database remains in a consistent state even when multiple transactions are being executed concurrently. The previous transaction identifier (P_T_ID) is the identifier of the transaction that was executed immediately before the current one. It helps in maintaining the consistency of the database and detecting conflicts that may arise due to concurrent transactions. A docket identifier (D_ID) is a unique identifier assigned to a docket in a database that stores information about dockets. The location of the docket indicates where the docket is currently located, such as a warehouse or a distribution center. The size of the docket indicates the physical dimensions of the docket, which can be important in determining how much space it will occupy during transportation or storage. The description of the docket map includes information about the items that have passed through the docket, such as the type of products, quantities, and any special handling requirements. In summary, the docket information is used to track the movement of goods through the supply chain and to maintain an accurate inventory of products in storage. The information can be used to optimize logistics processes, improve order fulfillment accuracy, and reduce errors and delays.

Table 10. Summary of transactions with details.

Transaction	Details
T_ID	Unique number and hash of the current transaction
P_T_ID	Hash of the previous transaction
D_ID	Docket ID
Location	Location of the docket
Size	Size of the docket
Description	description of the docket map

4. Suggested Methods of Measurement

As mentioned in the previous sections, three categories of general information can be stored in the blockchain: smart contracts, information collected by sensors, and information used as building information management to control roofs, walls, and building facilities, along with the description of each. Therefore, transactions are considered for each part, and these transactions are stored in the blockchain after completion. In the proposed method, an inspector is considered a controlling element. This system includes an inspector that has four levels: normal, emergency 1, emergency 2, and emergency 3. The normal state is when all components of the building work properly and the state of the building is considered normal. The system is designed to identify any problems that may arise and classify them at the appropriate levels. If a problem occurs in any of the facilities, it will be evaluated and included in emergency level 1. This could include a malfunctioning sensor or a damaged sensor. Even if a sensor reaches the end of its life, it is considered a problem, and a warning is sent to the manufacturer. Technicians are given the opportunity to solve the problem before someone's life is endangered. In emergency level 2, temperature level control, oxygen level, and air exchange level are controlled. Emergency level 2 is activated if part of the building collapses, resulting in reduced oxygen levels, increased temperatures, and ultraviolet radiation. At this point, the robot rescue team is given a limited amount of time to enter the damaged part and repair it. However, human life is not threatened at this level. If the problem continues and human lives are in danger, the situation will reach emergency level 3. Emergency level 3 is the most critical level and is activated when a part of the building is damaged by factors such as earthquakes, meteorites, or other factors. Any other type of damage at this level, the robot rescue forces are immediately sent to the place to save people's lives.

As it is clear from Figure 7, at first, the data of Martian buildings is sent to it for storage on the blockchain platform. At the same time, the data is also sent to the supervisor, and after receiving the information, the supervisor compares it with the data stored in the blockchain, and if the data is correct, the alarm level of that house is determined. After determining the warning level, if necessary, a message is sent to the rescue robots to refer them to the desired location for assistance.

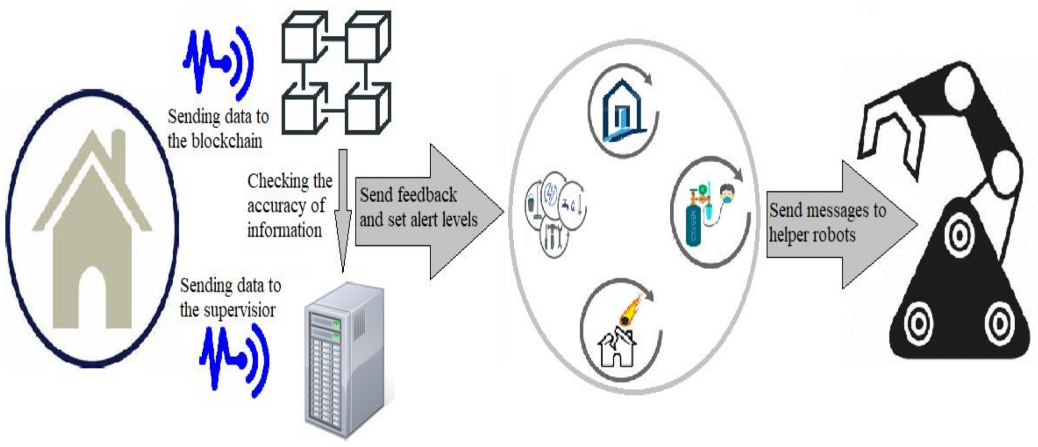

Figure 7. Proposed method and framework.

5. Results of Analysis

In this part, two important and fundamental factors in blockchain are examined. These two factors include the amount of memory consumed and the duration of adding a new block to the blockchain, which are evaluated using the following two criteria for the transactions used. All these things have been performed in the Python programming language and implemented on Google Collaborate. So, the proposed system for this research is the servers used by Google to run Python programs. In the following, each transaction has been evaluated.

5.1. Contract

The first stage of the platform presented is the stage of signing a contract with customers, which should be conducted using a smart contract. These steps are as follows: first, the customer sends a request for a contract to the construction company, and the company sends and signs the contract after checking the profiles of the people or customers. The stages of the contract are shown in the figure below. It is worth noting that all the steps include the transactions presented in the previous section. Therefore, in these operations, no transaction should remain incomplete and should be completed. In fact, either a transaction or a step is completed and stored in the blockchain, or no transaction is made.

As it is clear from Figure 8 below, all movements are forward, and if the desired transaction is stopped at any stage, that transaction is lost and must be restarted from the beginning. In the first stage, each customer has a public token and a private token, where the private token of each person is the digital signature of that person. At this stage, the customer, having the public token of the desired company, sends his request and specifications to the company and signs the contract. After this step, the customer's request is sent to the desired company in the form of a JSON file (Figure 9). After checking the structure of the desired house and the customer's profile, the company signs the contract with the company's private token, sends the final contract to be stored in the blockchain, and also sends the final version of the smart contract to the customer.

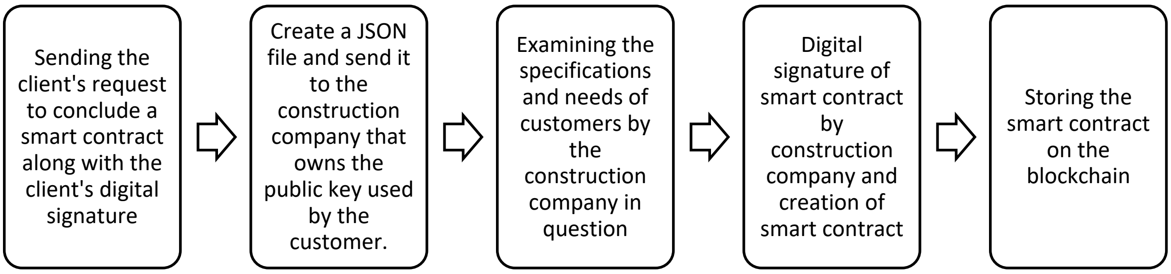

Figure 8. The stages of the contract between the customer and the manufacturer.


```
{
    "System": "{'Linux'}",
    "Node Name": "{'749a3b916e97'}",
    "Release": "{'5.10.147+'}",
    "Version": "{'#1 SMP Sat Dec 10 16:00:40 UTC 2022'}",
    "Nat_Code": "3258747698",
    "name": "Amirhossein",
    "family": "Javaheri",
    "Address": "Madrid",
    "user_sing": "30254780",
    "timestamp": "2023-01-11 09:50:12.361892"
}
```


Figure 9. Customer request specifications.

As it is clear from the above figure, the profile of a customer has been sent to the company along with the system profile. The diagram below also shows the amount of memory consumed and the duration of creating and adding a block to the blockchain, as well as the chain from one block to 10,000 blocks (Figure 10).

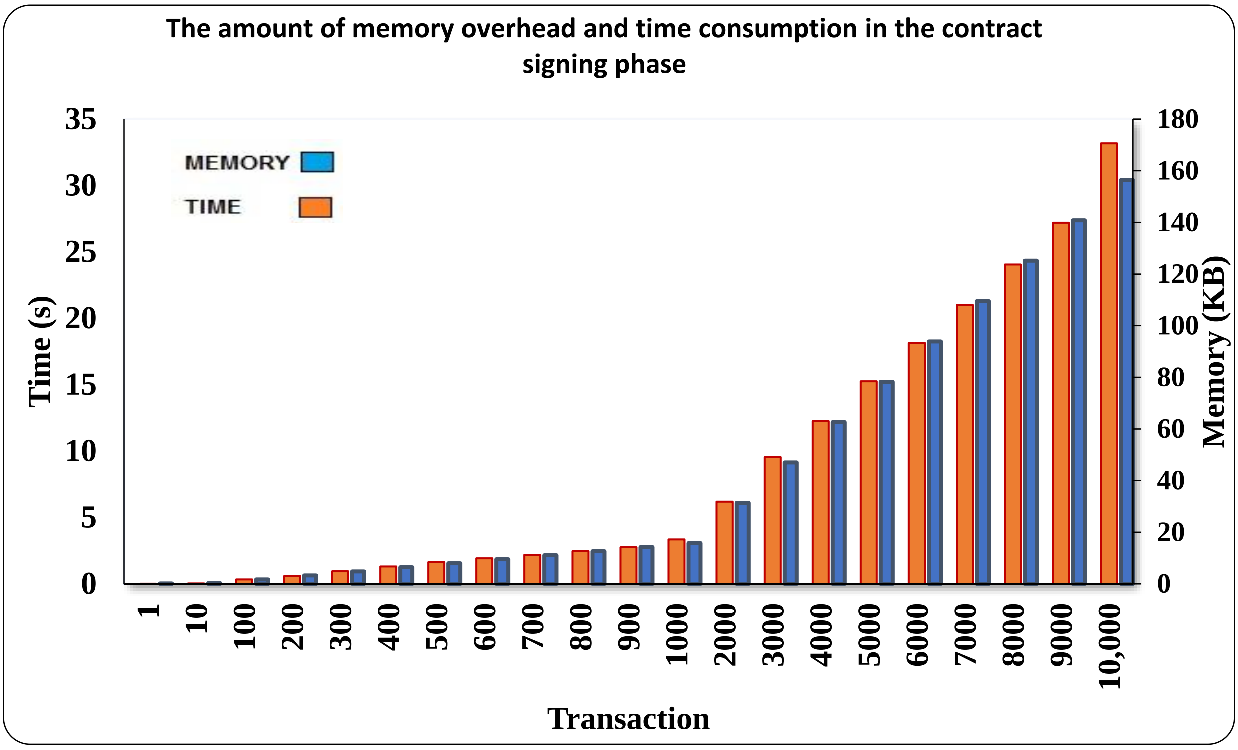

Figure 10. The amount of memory consumed and the duration of creating the contract.

5.2. Check the Proposed Method

In this part, a platform is designed to send data to the central server to check the warning level that was discussed in Part 4. First of all, information is collected from sensors that are installed in the environment. Considering that this system has an intranet, this information is sent to the central server in the form of an XML file so that the inspector system can determine the warning level by checking the receipt of the XML files and matching them with the information stored in the blockchain. The flowchart of this system is shown in the figure below (Figure 11).

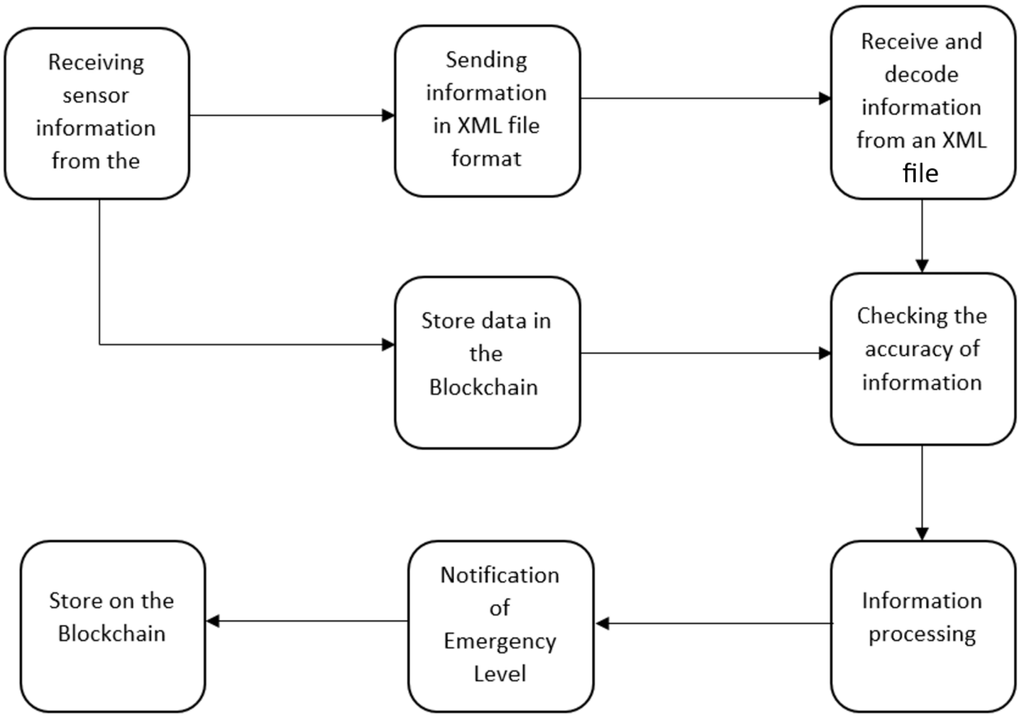

Figure 11. Flowchart for sending data to the central system.

As it is clear from the figure above, since the exchange of information is within the company's internal network, by using the XML file (Figure 12), the information can be sent to the main source of the company, and the received information is compared with the information inside the blockchain. After the correctness of the information is determined, the amount and level of warning should be issued. In this section, if the alarm level is at level 1, no message is sent to the technician and rescue robots, and if it is at the 1st to 3rd alarm level, depending on the alarm level, robots specific to each alarm level are activated, and according to the ID of the sensors, they refer to the location of the accident.


```
▼<Round>
   <Round/>
   <Sensor>974 = 27</Sensor>
   <Sensor>450 = 21</Sensor>
   <Sensor>793 = 1</Sensor>
   <Sensor>957 = 0</Sensor>
   <Sensor>825 = 2</Sensor>
   <Sensor>136 = 0</Sensor>
   <Sensor>time = 2023-01-25 14:52:04.496617</Sensor>
 </Round>
```


Figure 12. Sensors XML file.

As you know, in the buildings on Mars, due to the importance and sensitivity of the matter of life, the information and the accuracy of the information must be checked to make sure which sensor and which house need the attention of the rescue team and if the information undergoes transformation and changes. and penetrate into the system, the costs of maintaining robots and using them will be heavy. Therefore, information processing is a very important step, and before leaking information to the central system using blockchain, the accuracy of this information must be evaluated. The reason for using the XML file is to use a public blockchain because it is not possible to de-hash the information in the public blockchain, and according to the law, this should not be done. Based on this, according to the results of the research, from 1 to 12,000 pieces of data were created in the blockchain, and it is inserted that the two variables of cost and time were evaluated.

As shown in Figure 13, the longest time to receive a response from the center is for 12,000 data points, which takes about 60 s. Thus, it can be said that the time it takes to send data and receive a response from the destination is an average time, which, although it may be effective to respond to some failures, may be dangerous for some other factors. One of the factors that may be dangerous for this period of time is related to the oxygen in the environment, for which, of course, solutions can be provided. For example, a separate framework can be created for the oxygen sensor so that the response speed can be increased and the response time can be reduced based on it, which, of course, with the increase in the number of oxygen sensors in the environment, is not much different from the designed framework. The weakness of blockchain work can be expressed as follows: with the increase in the number of transactions, adding a block to the previous blockchain takes more time, and this is dangerous for checking the oxygen level of the environment.

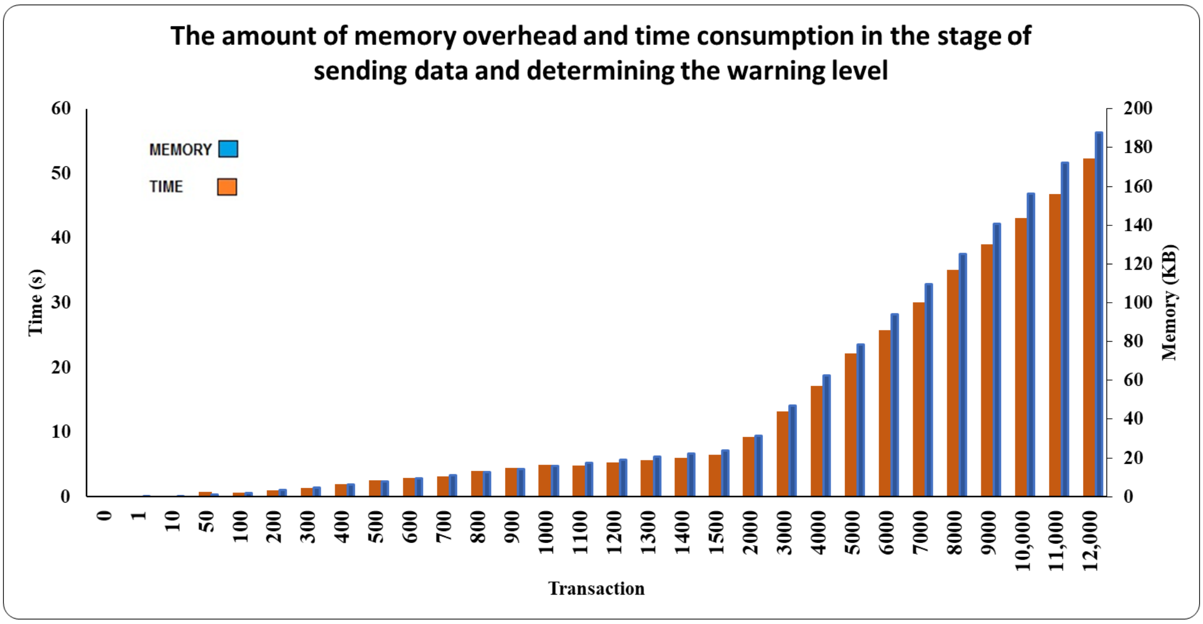

Figure 13. The amount of memory consumed and the duration of creating warning levels.

6. Discussion

Considering that this issue and life on the planet Mars still have hidden dimensions and points, this research can be a precursor to the integration of BIM and blockchain for the information management of Mars buildings, which can be done by considering other limitations and expanding these models to finally reach a standard model. According to Xingyu et al. (2022), blockchain is an emerging distributed technology that ensures data integrity by providing decentralized, immutable, and traceable data storage. However, the direct integration of BIM with blockchain reduces the risk of leaking sensitive data, but the risk remains because blockchain is a transparent network to the extent that shared information (including sensitive data) can be disclosed to all members without access control [25]. Therefore, in order to deal with such possible risks, an inspection to check the data and the accuracy of the received information has been explained in the proposed framework so that, in case of sabotage or information leakage, the system has the ability to detect it. Therefore, the proposed framework in this field has an improvement in guaranteeing the quality of data and information compared with other similar methods.

According to Celik et al. (2023), recent advances in building information modeling have shown new ways to integrate processes and data with open data formats. In construction projects that generate and share multiple streams of BIM data, mechanisms to define priority, provenance, and appropriateness of information become necessary for consistent and traceable use of the data [26]. Therefore, in this research, by entering into a smart contract and determining the location of each sensor, the method of sending information and the origin of sending information are calculated in a completely accurate manner. Also, prioritization has been determined at four warning levels, which is in line with the results. Also, the literature has shown that several weaknesses of BIM, including the trust issue, the asset ownership issue, and the data reliability issue, can be addressed by incorporating blockchain into its processes [27–29]. Therefore, the first issue, which is data trust in Mars, must be verified with high accuracy; the issue of property ownership has also been reliably observed using smart contracts on the blockchain platform; and the issue of data reliability, in addition to considering the capacity of the blockchain, has also been verified by an inspector.

7. Conclusions

Finding another environment for the continuation of human life due to the exhaustion of the earth and the loss of its natural resources is an issue that will be addressed more in the coming years. One of the prerequisites of human life is to have a safe shelter, which is a little easier on earth due to the presence of sufficient oxygen, proper light, and water. So far, the closest and most similar planet to Earth for life is Mars, and due to its environmental conditions, more controls are needed for human vital elements. In this study, it has been tried to manage the information about Mars buildings by combining BIM and blockchain. In two main frameworks, eight main transactions were designed. The first framework is related to the conclusion of a smart contract between the customer and the support company for the construction of Mars buildings. The second framework is related to providing an inspector for building control, and by sending data from sensors and checking their accuracy, four warning levels were determined. The results of the research showed that in the first stage, which is the contract, for the number of 12,000 records, a duration of 30 s and a memory amount of 175 kilobytes are required. For this purpose, it can be shown that the duration of adding a block to the blockchain is a suitable value. And the amount of memory used is also suitable. In the second stage, which is the determination of the warning level, 12,000 records of 60 s duration and 180 kilobytes of memory are required, which can be said to be suitable for other events and transactions except oxygen control. Control. Considering that this issue and life on the planet Mars still have dimensions and hidden points, this research can be a precursor to the integration of BIM and blockchain for the information management of Mars buildings, which can be done by considering other limitations. Did. One of the limitations of this research was that the use of blockchain technology in BIM in Mars buildings has not been investigated. However, the use of blockchain technology in the context of Mars buildings is unique and requires specialized approaches. There are also various areas that can be further explored in this research, such as the development of specific protocols and standards for BIM management in Mars buildings, the integration of various sensors and IoT devices for real-time monitoring and control of facilities, and the development of artificial intelligence-based algorithms. For predictive maintenance and abnormality detection. This is an exciting area of research that could help develop sustainable and safe habitats on Mars and other planets. This requires interdisciplinary collaboration between experts in BIM, blockchain, space engineering, and other related fields to create a comprehensive and effective solution.

Author Contributions: Conceptualization, A.J.; Methodology, A.J.; Software, A.J.; Validation, A.J.; Formal analysis, A.J.; Investigation, A.J.; Resources, A.J.; Data curation, A.J.; Writing—original draft, A.J.; Writing—review and editing, A.J., M.V.L. and S.R.M.; Visualization, A.J.; Supervision, M.V.L. and S.R.M.; Project administration, A.J.; Funding acquisition, S.R.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by [saeedreza mohandes] grant number [2657981].

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Liu, J.; Li, H.; Sun, L.; Guo, Z.; Harvey, J.; Tang, Q.; Lu, H.; Jia, M. In-situ resources for infrastructure construction on Mars: A review. *Int. J. Transp. Sci. Technol.* **2022**, *11*, 1–16. [CrossRef]
2. Babalola, A.; Musa, S.; Akinlolu, M.T.; Haupt, T.C. A bibliometric review of advances in building information modeling (BIM) research. *J. Eng. Des. Technol.* **2023**, *21*, 690–710. [CrossRef]
3. Zheng, R.; Jiang, J.; Hao, X.; Ren, W.; Xiong, F.; Ren, Y. bcBIM: A Blockchain-Based Big Data Model for BIM Modification Audit and Provenance in Mobile Cloud. *Math. Probl. Eng.* **2019**, *2019*, 5349538. [CrossRef]
4. Wong, J.-Y.; Yip, C.-C.; Yong, S.-T.; Chan, A.; Kok, S.-T.; Lau, T.-L.; Ali, M.T.; Gouda, E. BIM-VR Framework for Building Information Modelling in Engineering Education. *Int. J. Interact. Mob. Technol. (iJIM)* **2020**, *14*, 15–39. [CrossRef]
5. Erri Pradeep, A.; Yiu, T.; Amor, R. Leveraging blockchain technology in a BIM workflow: A literature review. In *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving Data-Informed Decision-Making*; ICE Publishing: London, UK, 2019; pp. 371–380.
6. Gupta, S.; Sinha, S.; Bhushan, B. Emergence of blockchain technology: Fundamentals, working and its various implementations. In Proceedings of the International Conference on Innovative Computing & Communications (ICICC), Delhi, India, 20–22 February 2020.
7. Saini, H.; Bhushan, B.; Arora, A.; Kaur, A. Security vulnerabilities in Information communication technology: Blockchain to the rescue (A survey on Blockchain Technology). In Proceedings of the 2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT), Kannur, India, 5–6 July 2019; pp. 1680–1684.
8. Nawari, N.O.; Ravindran, S. Blockchain technology and BIM process: Review and potential applications. *J. Inf. Technol. Constr.* **2019**, *24*, 209–238.
9. Reedie, J. Building for Mars: Four Designs to Support a Colony on the Red Planet. 2023. Available online: https://www.architectureanddesign.com.au/news/four-creations-for-life-on-mars (accessed on 12 November 2023).
10. Banin, A.; Clark, B.C.; Wänke, H. Surface chemistry and mineralogy. *Mars* **1992**, 594–625.
11. Chaum, D.L. *Computer Systems Established, Maintained and Trusted by Mutually Suspicious Groups*; Electronics Research Laboratory, University of California: Riverside, CA, USA, 1979.
12. Haber, S.; Stornetta, W.S. *How to Time-Stamp a Digital Document*; Springer: Berlin/Heidelberg, Germany, 1991.
13. Bayer, D.; Haber, S.; Stornetta, W.S. Improving the Efficiency and Reliability of Digital Time-Stamping. In *Seq II: Methods in Communication, Security, and Computer Science*; Springer: Berlin/Heidelberg, Germany, 1993; pp. 329–334.
14. Sharma, R. Bit Gold, Investopedia. 2021. Available online: https://www.investopedia.com/terms/b/bit-gold.asp (accessed on 12 November 2023).
15. Nakamoto, S. Bitcoin: A Peer-to-Peer Electronic Cash System. Bitcoin. 2008. Available online: https://bitcoin.org/bitcoin.pdf (accessed on 12 November 2023).
16. Sheldon, R. A Timeline and History of Blockchain Technology. 2021. Available online: https://www.techtarget.com/whatis/feature/A-timeline-and-history-of-blockchain-technology (accessed on 12 November 2023).
17. Buterin, V. Ethereum White Paper. *GitHub Repos.* **2013**, *1*, 22–23.
18. Groetsema, A.; Sahdev, N.; Salami, N.; Schwentker, R.; Cionca, F. *Blockchain for Business: An Introduction to Hyperledger Technologies*; The Linux Foundation: San Francisco, CA, USA, 2019.
19. Xue, F.; Lu, W. A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. *Autom. Constr.* **2020**, *118*, 103270. [CrossRef]
20. Dounas, T.; Lombardi, D.; Jabi, W. Framework for decentralised architectural design BIM and Blockchain integration. *Int. J. Arch. Comput.* **2021**, *19*, 157–173. [CrossRef]
21. Ye, X.; Sigalov, K.; König, M. Integrating BIM- and Cost-included Information Container with Blockchain for Construction Automated Payment using Billing Model and Smart Contracts. In *ISARC, Proceedings of the International Symposium on Automation and Robotics in Construction, Kitakyushu, Japan, 26–30 October 2020*; IAARC Publications: Oulu, Finland, 2020; Volume 37, pp. 1388–1395.
22. Pradeep, A.S.E.; Amor, R.; Yiu, T.W. Blockchain Improving Trust in BIM Data Exchange: A Case Study on BIMCHAIN. In Proceedings of the Construction Research Congress, Tempe, Arizona, 8–10 March 2020; American Society of Civil Engineers: Reston, VA, USA, 2020; pp. 1174–1183.
23. Liu, Z.; Jiang, L.; Osmani, M.; Demian, P. Building Information Management (BIM) and Blockchain (BC) for Sustainable Building Design Information Management Framework. *Electronics* **2019**, *8*, 724. [CrossRef]
24. Shojaei, A.; Flood, I.; Moud, H.I.; Hatami, M.; Zhang, X. An implementation of smart contracts by integrating BIM and blockchain. In Proceedings of the Future Technologies Conference (FTC) 2019, San Francisco, CA, USA, 14–15 November 2019; Springer: Berlin/Heidelberg, Germany, 2020; Volume 2, pp. 519–527.

25. Tao, X.; Liu, Y.; Wong, P.K.-Y.; Chen, K.; Das, M.; Cheng, J.C. Confidentiality-minded framework for blockchain-based BIM design collaboration. *Autom. Constr.* **2022**, *136*, 104172. [CrossRef]
26. Celik, Y.; Petri, I.; Barati, M. Blockchain supported BIM data provenance for construction projects. *Comput. Ind.* **2023**, *144*, 103768. [CrossRef]
27. Tan, J.H.; Loo, S.-C.; Zainon, N.; Aziz, N.M.; Rahim, F.A.M. Potential functionality and workability of blockchain within a building information modelling (BIM) environment. *J. Facil. Manag.* **2023**, *21*, 490–510. [CrossRef]
28. Li, X.; Lu, W.; Xue, F.; Wu, L.; Zhao, R.; Lou, J.; Xu, J. Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. *J. Constr. Eng. Manag.* **2022**, *148*, 04021195. [CrossRef]
29. Huang, H.; Zeng, X.; Zhao, L.; Qiu, C.; Wu, H.; Fan, L. Fusion of Building Information Modeling and Blockchain for Metaverse: A Survey. *IEEE Open J. Comput. Soc.* **2022**, *3*, 195–207. [CrossRef]