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Spatial Planning Data Structure Based on Blockchain Technology

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Abstract: Spatial planning requires ensuring the legality, uniformity, authority, and relevance of data. Blockchain technology, characterized by tamper-proofing, complete record-keeping, and process traceability, may effectively organize and manage spatial planning data. This study introduces blockchain technology to address common spatial planning problems, such as planning overlaps and conflicts. We developed a block structure, chain structure, and consensus algorithms tailored for spatial planning. To meet the data management requirements of these structures, we devised a primary unit division method based on the space and population standards of the 15 min life circle, using the Point Cloud Density Tiler. The validation experiments were conducted using the Hyperledger Fabric 2.0 technology framework in Changsha City, Hunan Province, China, with the division method validated against the number and distribution of public service facilities. The validation results show that during the data storage process, the block size remains below 1.00 MB, the data redundancy is up to 21.30%, the consensus verification rate is 150.33 times per second, the block generation rate is 20.83 blocks per minute, and the equivalent data throughput is 12.21 transactions per second. This demonstrates that the proposed method effectively addresses the challenges of block size, data redundancy, consensus algorithm efficiency, and data throughput in blockchain technology. The findings demonstrate that the structures ensure legal, uniform, and authoritative spatial planning, and advance the application of blockchain technology in relevant fields. Additionally, we explored the application of a blockchain data structure in spatial planning monitoring and early warning. This technology can be further studied and applied in related fields.

Keywords: blockchain technology; spatial planning; data structure; consensus algorithm; 15 min life circle

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1. Introduction

Spatial planning has played a crucial role in China's rapid urbanization, promoting the sustainable use and adequate protection of national land. However, spatial planning in China faces challenges, such as excessive planning types, overlaps and conflicts, resulting from the involvement of multiple management entities [1]. To address these issues, spatial planning must ensure the legality, uniformity, authority, and relevance of data.

Spatial planning data consist of spatial and non-spatial elements. Spatial elements are structured data containing geometric information, such as points, lines, and polygons, as well as their planning attributes. The planning attributes must adhere to the control boundary standards set by related policies, such as the "three zones and three lines" regulatory policy in China. This policy specifies the agricultural zones, ecological conservation zones, and urban development zones, and delineates the permanent bare cropland protection boundaries, ecological conservation boundaries, and urban development boundaries. Non-spatial elements are stored as both structured and unstructured data in the form of files, including outcome texts (PDF), tables (MDB), raster maps (JPG at 300 DPI or higher resolution), and vector files (GDB with standardized attributes). They should meet the criteria for planning indicator transmission and maintain consistency between polygons and indicators. Non-spatial elements conflicting with their corresponding spatial elements should be eliminated. Since 2019, the Chinese government has been building a platform to store and manage basic territorial spatial information and an information system to implement and supervise spatial planning [2,3]. Spatial elements are stored in a relational database (e.g., PostgreSQL) and rendered using a spatial data engine (e.g., ArcSDE). Non-spatial elements are stored in a separate relational database. The platform and system are jointly used and managed by multiple levels of government. Although some challenges have been mitigated through rigorous management, overlaps and conflicts between polygons and indicators remain unsolved. Additionally, ensuring the security, integrity, and traceability of spatial planning data poses ongoing challenges.

Blockchain technology [4] is characterized by tamper-proofing, complete record-keeping, and process traceability [5,6]. It was initially used as the foundation for digital currencies such as Bitcoin. Gradually, it has been applied in many sectors such as financial insurance, digital copyright, the Internet of Things, logistics, public service, smart cities, and land management [7–11]. With the advancement of efficient interaction technologies, such as on-chain, off-chain, and cross-chain, the performance, scalability, and application of blockchain will significantly improve [12]. With continuous improvements in its applications, blockchain technology is gaining attention in the field of spatial planning. Employing blockchain technology in spatial planning may establish a unified, coordinated, and authoritative data system to provide a solid foundation for coordination among government bodies, addressing issues such as planning overlaps and indicators' inconsistency. Through a detailed examination of blockchain technology's applicability in spatial planning, a comprehensive concept of application has been proposed, which aims to enhance trust, intelligence, authority, and capability throughout the planning process [13]. A spatial planning application framework based on a consortium blockchain has been developed. This framework thoroughly explores the potential applications of blockchain technology in data management and data sharing [14]. Integrating blockchain into spatial planning can redefine legal status, enhance public involvement, and deter frequent planning modifications [15]. A blockchain-based data platform ultimately provides services to diverse data resources across regions, networks, departments, and entities, promoting government resource co-construction, co-governance, sharing, and supervision [16]. However, conventional blockchain applications face significant challenges, fundamentally restricting their adoption and scalability in spatial planning. These challenges include limited block size, data redundancy, insufficient consensus algorithm, and low data throughput [17]. Integrating blockchain technology into spatial planning data management, designing block structures, dividing primary units, and creating chain structures and consensus algorithms remain unclear. Therefore, the challenges and technological gaps mentioned above are the key research subjects of this study. This study focuses on introducing blockchain technology to spatial planning.

This study aims to design a spatial planning data structure using blockchain technology, to address the issues in typical blockchain applications effectively. First, we present the methodology. We developed a block structure tailored for spatial planning data and devised a method for dividing the primary units of structured spatial planning based on the space and population standards of the 15 min life circle. We also designed a chain structure for spatial planning data and constructed consensus algorithms based on statutory procedures and industry standards, enabling identification and verification via smart contracts. Second, we conducted validation experiments. All methods were validated using regulatory detailed planning data from the Changsha and the Hyperledger Fabric 2.0 technical framework. The findings show that these methods can reduce the necessary block size and decrease data redundancy, and enhance consensus verification efficiency and data throughput, thereby improving the precision and efficiency of data management and application. Finally, we discussed the application of the blockchain-based spatial planning data structure in the monitoring and early warning of illegal land use, the generalizability of the findings, and the limitations of our research. Considering advancements in blockchain technology, we outlined future research directions, including cross-industry data management and public data sharing, to extend the applications of this technology in spatial planning.

2. Methods

Blockchain technology employs a chain-based shared database structure with blocks as the primary units. In a blockchain, data must be stored in blocks and uploaded onto the chain after confirmation by all network nodes. The data permeates the entire network and creates backups on each node, making modification or deletion difficult. Any update to the data requires consensus confirmation. Upon successful storage, any update traces are maintained, resulting in tamper-proofing, complete record-keeping, and process traceability. This technology ensures secure data storage and verification through hash encryption algorithms, such as the SHA and SM3 algorithms, in a decentralized and trustless network environment. By doing so, the trust issues that often arise between network nodes are resolved. This study focuses on constructing block structures and their primary unit divisions for spatial planning data, as well as building chain structures and their consensus algorithms.

2.1. Block Structure

To enhance the utilization of existing spatial planning data and structures, this study proposes a framework to organize structured data blocks of polygon and attribute data, as well as unstructured data blocks of file-based data. By incorporating the corresponding original data into blocks, the framework guarantees data compliance, consistency, authoritativeness, and relevance while reducing data redundancy.

2.1.1. Block Structure of Structured Data

To enhance spatial planning data management and application, the research divides the entire area of data coverage into primary units that contain the spatial attribute data. These units exhibit strong spatial consistency, are of moderate size, and show a high compatibility with planning management, enabling them to be the basic units and spatial framework. At this scale, spatial partitioning and outcome mapping can be performed for spatial planning at different levels and types. Based on these primary units, a structured data block is constructed, compromising a block body and a block header (Figure 1).

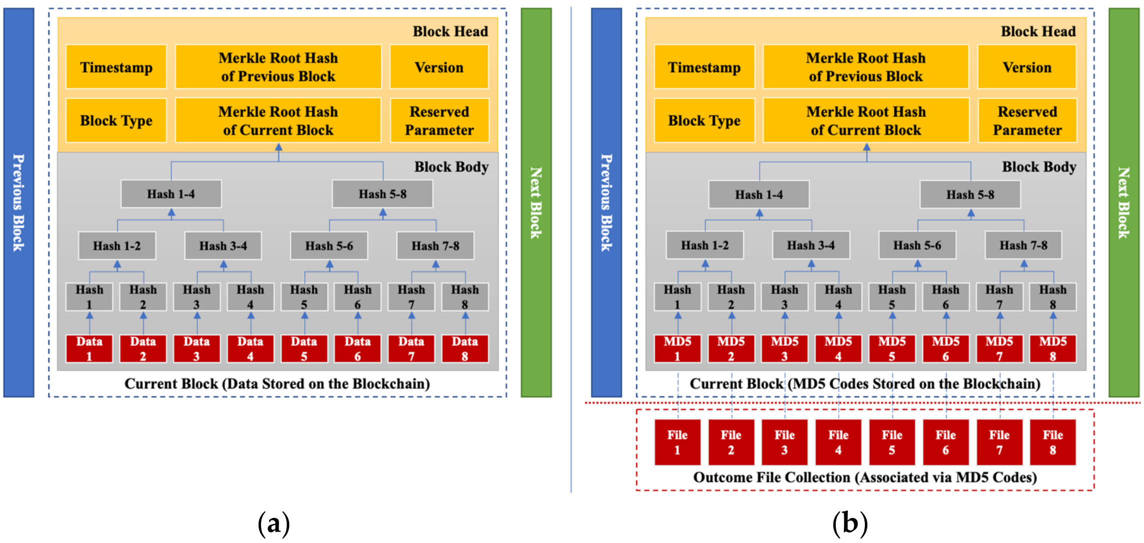

Figure 1. The block structure of (**a**) structured spatial planning data and (**b**) unstructured spatial planning data.

(1) Block Body of Structured Data

Map and organize the original data according to the spatial topology of the primary unit and the corresponding spatial planning layer and form a block body of structured data through the following steps. Initially, arrange the spatial planning polygon and attribute data in each primary unit into JSON data (JavaScript Object Notation, a lightweight data exchange format). Subsequently, group the JSON data corresponding to each 2^n primary units as a group. Here, n denotes a natural number, depending on the block size and chain cycle, and 2^3 is chosen for this study. After that, using the structure of the Merkle tree, apply the hash encryption algorithm level by level to construct the block body and record detailed data. Should the available primary units be fewer than eight, null values can be used to complete the structure.

(2) Block Header of Structured Data

Construct the block header of structured data to store summarized data, utilizing the Merkle Root Hash of the current block, the Merkle Root Hash of the previous block, the Timestamp, the Version, the Block Type, and the Reserved Parameter. The Reserved Parameter serves as a repository for ancillary information, including but not limited to the current block update information and primary unit ID.

(3) Primary Unit Division for Structured Data

The primary unit division methods of spatial planning include standard territorial statistical unit division, multi-level planning unit construction, and urban community life circle delineation. In China, spatial planning prioritizes a people-centered concept. When establishing basic management units, the government focuses on residents' daily lives. Therefore, urban community life circle delineation is adopted as the primary unit division method in this study. The 15 min life circle is a prominent example of this approach and is widely embraced in the field of spatial planning. The spatial planning departments in China have established standards and specifications for the 15 min life circle and have implemented pilot programs in cities such as Shanghai and Changsha. These circles are defined by subdistrict administrative boundaries, communities, and towns, centered around residential areas, with a walking distance of 15 min (about 800–1000 m) and a service population of 50,000 to 100,000 people. Many studies have been conducted on the primary unit division of the 15 min life circle, focusing on travel distance, travel time, population size, resident activities, geographic environment, and administrative boundaries. Different methods have been used to delineate the 15 min life circle in Beijing [18], Shanghai [19–21], Xi'an [22], and in other places for urban upgrading and facility optimization [23–27]. However, these methods do not incorporate blockchain data structure. This research proposes a method to divide spatial planning data into primary units corresponding to the 15 min life circle for the application of blockchain technology. The method has the following five steps:

Step 1—defining regional classes: Divide the study area into areas within and outside urban development boundaries. These two areas are further analyzed using regulatory detailed planning polygons and village planning or village administrative boundaries.

Step 2—extracting minimum elements: Inside the boundaries, the regulatory detailed planning polygons are extracted as minimum elements to form primary units. Outside the boundaries, the polygons outlined in village planning or administrative boundaries are extracted as minimum elements, which are also the primary units. By overlaying these minimum elements and linking them with population and land area information, a comprehensive set of minimum elements spanning the entire region is established.

Step 3—combining minimum elements: Inside the boundaries, some minimum elements cross subdistrict administrative boundaries or major urban roads. This study introduces urban road aggregation and administrative boundary aggregation techniques to address this. Urban road aggregation uses the central lines of various levels of urban roads in regulatory detailed planning to combine the minimum elements initially. Administrative boundary aggregation uses the subdistrict administrative boundaries to refine the combined minimum elements. Subsequently, these combined minimum elements are linked with the population and land area information. This process can reduce the calculation load in subsequent steps. Additionally, the minimum elements are further modified to exclude invalid data that are too small or have an area-to-perimeter ratio less than 1. Outside the boundaries, we use the original minimum elements, rather than combining them.

Step 4—dividing primary units: Extract the centroids of the combined minimum elements inside and outside the boundaries, which are then converted into point clouds with attribute data. The region is subdivided using the Point Cloud Density Tiler method. Iteratively calculate the area and population of each subdivided area until all meet the standards of the 15 min life circle. The area of a point cloud or set of point clouds is the primary unit.

Step 5—calibrating and optimizing primary units. The division results are calibrated in terms of area and population, ensuring the area is <5 square kilometers and the residential population is $<100,000$. Optimize the primary units crossing mountains and rivers. Manual assistance is needed to refine the division rules.

2.1.2. Block Structure of Unstructured Data

Per the spatial planning data catalog and file guidelines, each involved spatial planning outcome file should serve as a primary unit. Each unit stores the file's MD5 codes, according to which the files are arranged and selected to create an unstructured data block (Figure 1), containing a block body and block header.

(1) Block Body of Unstructured Data

Group every eight primary units sequentially and calculate each level using the hash encryption algorithm according to the Merkle tree's structure to form the block body of unstructured data. The block body records the MD5 codes of the corresponding spatial planning outcome files. Should the available primary units be fewer than eight, null values can be used to complete the structure.

(2) Block Header of Unstructured Data

Construct the block header of unstructured data to store summarized data, utilizing the Merkle Root Hash of the current block, the Merkle Root Hash of the previous block, the Timestamp, the Version, the Block Type, and the Reserved Parameter. The Reserved Parameter serves as a repository for ancillary information, including but not limited to the version and type of spatial planning.

The unstructured data block is constructed solely for the MD5 codes of the spatial planning outcome files. This block connects with spatial planning outcome files and maintains distributed storage and management. Therefore, it eliminates data redundancy and conforms to the directory and file specifications of spatial planning outcomes.

2.2. Chain Structure

In a blockchain, blocks are arranged in a chronological sequence and connected tightly using hash pointers, composed of the Merkle Root Hash of two neighboring blocks. Constructing the chain structure involves initialization and updating. Once a chain is constructed, altering block information requires recalculating and replacing all Merkle Root Hashes from the current block to the genesis block along the chain. In addition, such modifications must be performed simultaneously in the copies stored in all network nodes, making data tampering nearly infeasible. By verifying the Merkle Root Hash of the last block on any node, we can detect data tampering, ensuring the integrity of the chain.

2.2.1. Initializing the Chain Structure of Spatial Planning Data

Before being stored on the blockchain, structured and unstructured data blocks are distributed to all network nodes. Once verified by the smart contracts, which include verification conditions integrated into the current blockchain, all blocks, including the genesis block, can be stored sequentially on the blockchain, forming a chain (Figure 2). These blocks, ordered by timestamp, are linked to each other by hash pointers.

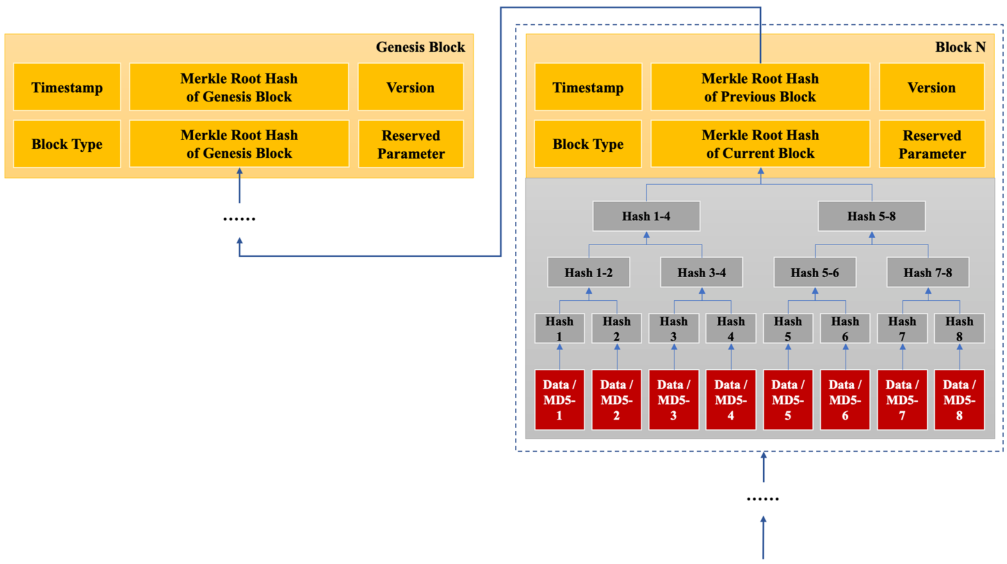

Figure 2. The chain structure of spatial planning data.

2.2.2. Updating the Chain Structure of Spatial Planning Data

Once a chain is established, all updates and modifications should follow the set guidelines. For the primary units that require updates or modifications, new blocks should be created for both structured and unstructured data. After verification by all network nodes, these new blocks are distributed and stored on the current chain, with their hash pointer pointing to the last block of the chain. Then, the updating or modification of the blockchain is finished.

2.3. Consensus Algorithms

In applications, consensus algorithms such as Proof of Work (PoW), Proof of Stake/Delegated Proof of Stake (PoS/DPoS), and Practical Byzantine Fault Tolerance (PBFT) are used [28,29]. Network nodes establish consensus by competing with their computational capabilities, leading to low efficiency and high energy consumption.

In spatial planning, achieving consensus should follow strict legal approval procedures and planning standards set by government departments. Government departments can provide credit endorsements in the process of reaching consensus, replacing the need to compare network nodes' computational capabilities. In this case, consensus is achieved in two ways. First, analyze the spatial topology of related results to achieve spatial unification consensus. This involves checking spatial elements against topological regulations to ensure that the spatial planning data are consistent with the existing administrative boundaries, central urban area boundaries, industrial park boundaries, historical and cultural protection areas, etc. Second, compare related indicator data to achieve index transmission consensus. Indicator values from various levels and types of spatial planning are extracted and compared to meet the indicator transmission requirements [30–32]. This process clarifies the transmission relationships of indicators and ensures a hierarchical and rigorous transmission process. In master planning, indicators such as the area of ecological conservation zones, permanent bare cropland protection zones, and arable land reservation zones are compared. In detailed planning, indicators such as land use, land area, floor area ratio, building density, building height control, and greening rate are compared. In special planning, key indicators are primarily extracted based on the outcomes and then compared with the corresponding indicators in master planning and detailed planning.

Based on the above two ways, the consensus algorithms can be divided into quality inspection, spatial detection, and indicator transmission models (Figure 3). These models are coded as smart contracts and integrated with the blockchain for spatial planning data. All new blocks are automatically identified and validated before being added to the chain.

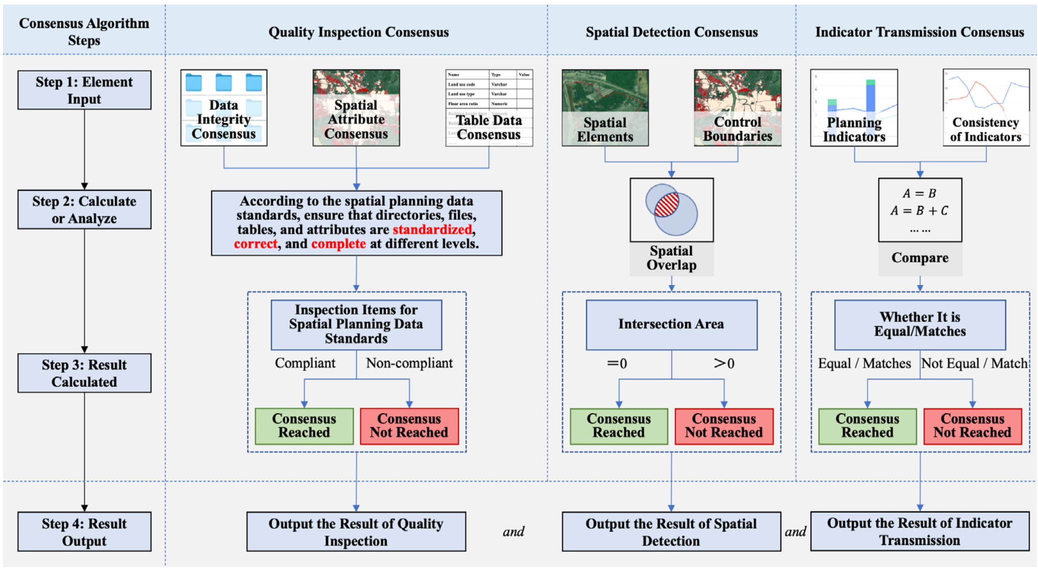

Figure 3. The consensus algorithms for spatial planning based on blockchain technology.

3. Experiments

3.1. Data

(1) Spatial Planning Data

The attribute data, graphic data, and supporting files of Changsha's regulatory detailed planning were employed in the experiments. These datasets were derived from spatial planning outcomes that had been reviewed and approved according to statutory procedures. Both spatial and non-spatial elements were standardized in terms of the coordinate system and planning attributes, then stored in a geospatial information data management platform, which enabled us to access related spatial planning data for consensus verification, such as for the "three zones and three lines". These data included 77 regulatory detailed planning attributes and boundary point data, such as vector polygons, land use information, land area, floor area ratio, and building density. As village planning was still pending approval, null values were assigned to the corresponding primary units.

(2) Current Spatial Data

Changsha's community-level administrative boundary graphic data were employed in the experiments. These datasets were derived from the spatial planning data, standardized in terms of the coordinate system and planning attributes, and stored in the same platform to ensure strict spatial alignment with the spatial planning data. These data include vector polygons, district names, and land area.

(3) Other Data

Data from the Changsha Statistical Bulletin of National Economic and Social Development 2022 was used to verify the population scale in the experiments, including the total permanent population of Changsha (10.4 million at the end of 2022), the per capita built area of urban residents' self-owned housing (41.7 square meters), and the per capita built area of rural residents' self-owned housing (61.3 square meters). Additionally, Changsha's POI data from January 2023, including 14 categories, 144 subcategories, and 406,700 data items, were used to evaluate the rationality of the primary unit division. These POI data were also derived from the spatial planning data, updated with the latest information, standardized in terms of the coordinate system and planning attributes, and stored in the same platform. This ensured strict spatial alignment with the spatial planning data, as well as their validity and usability in the experiments.

3.2. Experimental Procedures

3.2.1. Primary Unit Division for Structured Data

This research focused on Changsha, the capital city of Hunan, China, which spans 11,819 square kilometers. A step-by-step calculation process is presented as follows.

(1) Defining Regional Classes and Extracting Minimum Elements

Utilizing classification criteria, we extracted 25,769 regulatory detailed planning polygons with an average land use area of 0.04 square kilometers inside the boundaries for urban development. Additionally, 1047 village planning or village administrative boundaries, with an average area of 10.31 square kilometers, were identified outside the boundaries. Together, these make 26,816 minimum elements, covering the full extent of Changsha.

(2) Combining Minimum Elements

Within the urban development boundaries, we initially used the centerline of urban roads in regulatory detailed planning to combine the minimum elements. Then, the subdistrict administrative boundaries were used to correct narrow or fragmented parts. The population and land area information from planning land polygons were calculated and connected. We obtained 7754 combined minimum elements, each with an average area of 0.13 square kilometers. Outside the boundaries, the 1047 original minimum elements did not require further combination and were used in subsequent research steps. Together, the two sets together made 8801 combined minimum elements, covering the whole city. Verification showed that these units do not cross major urban roads or subdistrict administrative divisions.

(3) Dividing, Calibrating, and Optimizing Primary Units

We extracted the centroids of the 8801 combined minimum elements to create a point cloud and linked them with attribute information. The data were processed using the Point Cloud Density Tiler method and iterative optimization, resulting in the formation of 261 primary units inside the boundaries, averaging 3.93 square kilometers in area and with an average population of 88,572, and 864 primary units outside the boundaries, averaging 12.49 square kilometers in area. Combining the two sets generated a total of 1125 primary units (Figure 4). Verification confirmed that these primary units do not cross major urban roads or subdistrict administrative divisions.

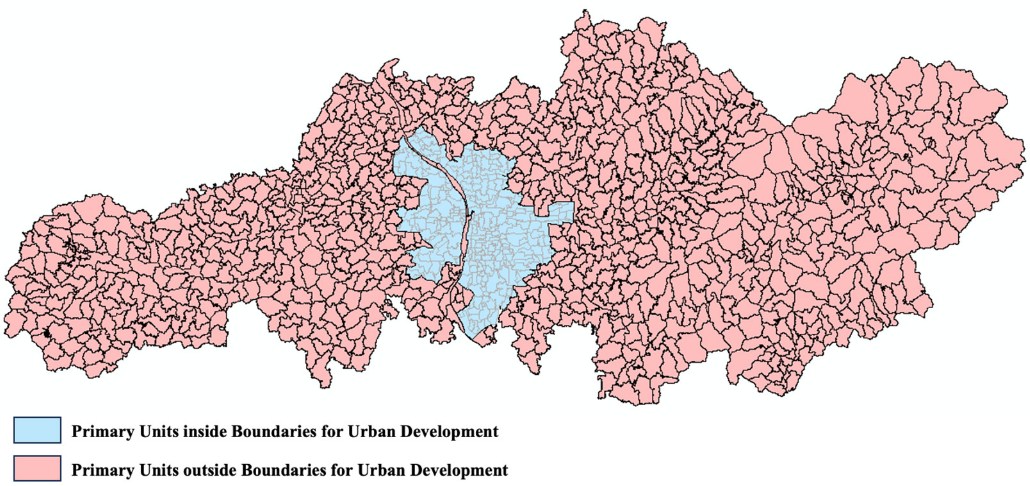

Figure 4. The primary units based on the 15 min life circle in Changsha obtained by the proposed method.

3.2.2. Spatial Planning Data Structures

This study used the Changsha Natural Resources Network and Hyperledger Fabric 2.0 to establish a blockchain network of 11 network nodes (Figure 5). The network includes one orderer node and ten peer nodes. The orderer node, referred to as the O_0 node for Changsha, is tasked with organizing and packaging blocks. The peer nodes, named from P_1 to P_{10}, correspond to the municipality and its nine districts. These peer nodes generate, validate, and upload blocks.

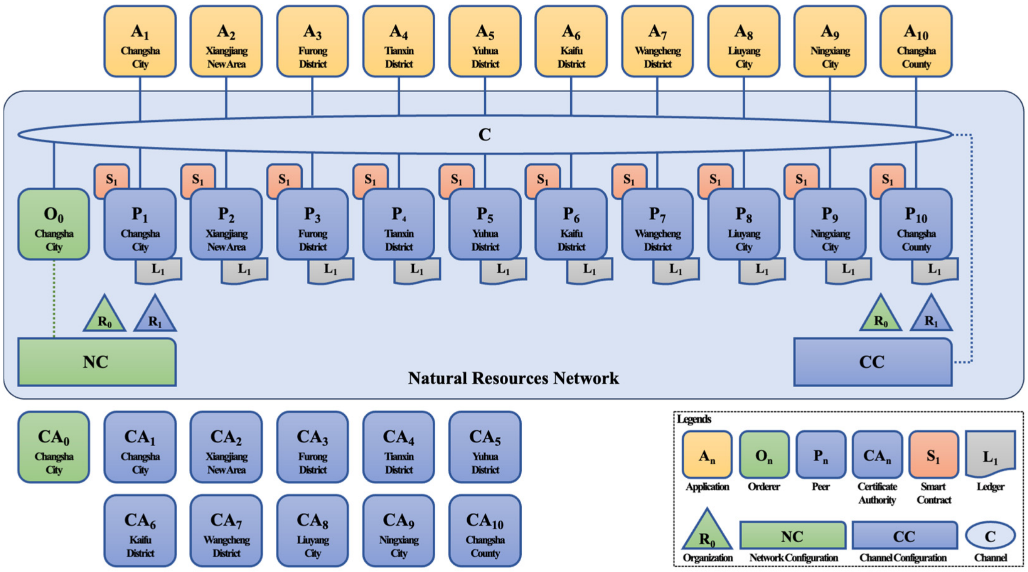

Figure 5. The blockchain network for Changsha's spatial planning data management.

The process of storing spatial planning data on the blockchain was completed in four steps, as depicted in Figure 6.

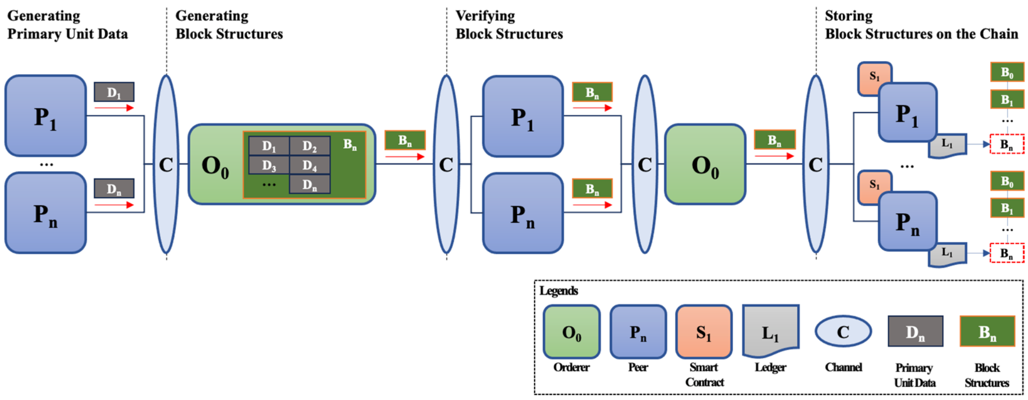

Figure 6. The process of storing spatial planning data on the blockchain.

(1) Generating Primary Unit Data

For the structured spatial planning data, we extracted 17 core attributes and data from boundary points (Table 1) from 77 regulatory detailed planning attributes and the boundary point data of each primary unit. These data were used to generate JSON data by the corresponding peer nodes, stored in primary units, and submitted to the orderer node. For the unstructured data, we extracted their MD5 codes from the outcome files by the corresponding peer nodes, stored them in primary units, and submitted them to the orderer node.

Table 1. The core attributes and planning boundary point data in regulatory detailed planning.

Field Name	Field Code	Field Type	Field Length
Land use code	YDCode	Varchar	50
Land use type	YDType	Varchar	10
Land use name	YDName	Varchar	50
Regulatory detailed planning code	GHCode	Numeric	38
Regulatory detailed planning name	GHName	Varchar	100
Floor area ratio	Capability	Numeric	38
Building height limit	BLDHLimit	Numeric	38
Building density	BLDDensity	Numeric	38
Greening rate	GreenRate	Numeric	38
Total area	AreaTotal	Numeric	38
Land area	AreaYD	Numeric	38
Road area	AreaRoad	Numeric	38
Green area	AreaGreen	Numeric	38
Building area	AreaBuild	Numeric	38
Population size	PopNum	Numeric	38
Population density	PopDensity	Numeric	38
Supporting service facilities	PubEstab	Varchar	200
Planning land boundary point	Shape	Binary	Indefinite Length

(2) Generating Block Structures

Upon receiving the primary units, the orderer node packaged the structured or unstructured primary unit data into blocks according to the order of receipt, considering the preset block size and uploading interval. In this study, the block size is set to 8 primary units, and the uploading interval is set to 1 s. Additionally, if the time exceeded the uploading interval and the primary units were fewer than 8, null values could be used.

(3) Verifying Block Structures

Once a block was generated, it was distributed to all connected peer nodes by the orderer node. Peer nodes verified the block utilizing the smart contracts containing quality inspection, spatial detection, and indicator transmission consensus algorithms, replacing traditional consensus algorithms like PoW, PoS/DPoS, and PBFT, to enhance the efficiency of consensus verification. Peer nodes output the verification results back to the orderer node. To clarify the validation process of primary unit data in blocks, a pseudocode is provided as follows. The functions and classes in the pseudocode should be defined and implemented according to specific requirements.

(4) Storing Block Structures on the Chain

The verified block was then distributed by the orderer node to all connected peer nodes for storage. Otherwise, it was rejected. In this study, using the above method, we created 141 blocks for the 1125 primary units of structured data and 766 blocks for the 6127 primary units of unstructured data to store Changsha regulatory detailed planning data. To address the uncertain Shape field length in the structured data blocks, the SM3 algorithm was used in hash processing to standardize and compress the corresponding JSON data, minimizing redundant storage.

The Pseudocode for Consensus Verification of Primary Unit Data in Blocks

```
//Pseudocode for Hyperledger Fabric 2.0 Chaincode, compliant with Java 8 Standard
@Transaction(intent = Transaction.TYPE.SUBMIT)
public Response validatePrimaryUnitData(Context context, String type, String key, String value) {
    try {
        //Parse the input data into a list of data entries
        List<Map<String, Object>> inputDataList = parseInputData(value);
        //Iterate over each data entry in the data list
        for (Map<String, Object> dataEntry: inputDataList) {
            String dataType = dataEntry.get(“dataType”).toString();
            //Validate based on data type
            Response result;
            if (“structured”.equals(dataType)) {
                result = validateStructuredData(dataEntry);
            } else if (“unstructured”.equals(dataType)) {
                result = validateUnstructuredData(dataEntry);
            } else {
                //Unknown data type case
                return new Response(Response.Status.FAILURE, “Unknown data type.”);
            }
            //If any validation fails, return a failure response
            if (result.getStatus() == Response.Status.FAILURE) {
                return result;
            }
        }
        //All validations passed
        return new Response(Response.Status.SUCCESS, “All data entries are valid.”);
    } catch (Exception e) {
        //Handle exceptions generically
        return new Response(Response.Status.ERROR, “Validation error.”);
    }
}
//Method to validate structured data
private Response validateStructuredData(Map<String, Object> dataEntry) {
    //Perform quality, spatial, and indicator validations for structured data
    boolean valid = ConsensusValidator.validateQuality(dataEntry).SUCCESS
                    ConsensusValidator.validateSpatial(dataEntry).SUCCESS
                    ConsensusValidator.validateIndicator(dataEntry).SUCCESS;
    return valid ? new Response(Response.Status.SUCCESS, “Structured data valid.”)
                 : new Response(Response.Status.FAILURE, “Structured data validation failed.”);
}
//Method to validate unstructured data
private Response validateUnstructuredData(Map<String, Object> dataEntry) {
    //Perform MD5 validation for unstructured data
    boolean valid = ConsensusValidator.validateMD5(dataEntry).SUCCESS;
    return valid ? new Response(Response.Status.SUCCESS, “Unstructured data valid.”)
                 : new Response(Response.Status.FAILURE, “Unstructured data validation failed.”);
}
//Example input data structure for validation
String value = “{ \”id\”: 202407270001, \”data\”: [ { \”dataType\”: \”structured\”, \”floorAreaRatio\”: 2.0,
\”planningLandBoundaryPoint\”: \”MULTIPOLYGON(((lat1 lon1, lat2 lon2, . . .)))\”, . . . }, { \”dataType\”:
\”unstructured\”, \”fileMD5\”: \”D56D71ECADF2137BE09D8B1D35C6C042\”, . . .} ] }”;
```

3.3. Results Evaluation

3.3.1. Evaluating the Rationality of Primary Unit Division

To assess the rationality and reliability of the primary units, we compared them with the spatial and population standards of the 15 min life circle defined in this study. We utilized Changsha’s POI data of January 2023 to evaluate the livability of each unit

(Formula (1)). We analyzed the number and distribution of public service facilities. Starting from the unit's centroid, we employed the Neighbor Finder method to calculate the sub-indicator coverage in each primary unit. This included seven dimensions relating to education facilities, government services, public culture, sports facilities, medical health, welfare care, and daily life, and 24 specific indicators (Table 2). The Analytic Hierarchy Process (AHP) hierarchical analysis method was employed to obtain the weights of each dimension and indicator (Table 2). Finally, we evaluated the livability of each primary unit by calculating its indicator values, weighted according to the AHP analysis. This further ensures that the primary unit division results are both reasonable and scientifically sound for spatial planning applications.

$$\begin{aligned} I_{Livability} = {} & A_{Education} \times 0.138 + B_{Government} \times 0.115 + C_{Public} \times 0.241 \\ & + D_{Sport} \times 0.122 + E_{Medical} \times 0.132 + F_{Welfare} \times 0.115 \\ & + G_{Daily\text{-}Life} \times 0.137 \end{aligned} \tag{1}$$

Table 2. The factors of livability for spatial planning primary units based on public service facilities.

Dimension	Dimension Weight	Specific Indicators	Indicator Weight
Education facilities (A)	0.138	Kindergarten coverage (A1)	0.393
		Primary school coverage (A2)	0.321
		Middle school coverage (A3)	0.286
Government services (B)	0.115	Community public service center coverage (B1)	0.354
		Subdistrict administrative management coverage (B2)	0.314
		Police station coverage (B3)	0.332
Public culture (C)	0.241	Community cultural activity room coverage (C1)	0.186
		Cultural activity center coverage (C2)	0.152
		Regional level or above cultural venues coverage (C3)	0.127
		Street green space coverage (C4)	0.191
		Community park coverage (C5)	0.180
		Comprehensive park coverage (C6)	0.164
Sports facilities (D)	0.122	Community multi-function sports field coverage (D1)	0.393
		National fitness activity center coverage (D2)	0.324
		Regional level or above sports facilities coverage (D3)	0.283
Medical health (E)	0.132	Community health service station coverage (E1)	0.376
		Subdistrict health service center coverage (E2)	0.321
		Hospital coverage (E3)	0.303
Welfare care (F)	0.115	Home care service station coverage (F1)	0.529
		Day care center coverage (F2)	0.471
Daily life (G)	0.137	Nursing home coverage (G1)	0.282
		Farmers' market coverage (G2)	0.372
		Public toilet coverage (G3)	0.209
		Garbage collection station coverage (G4)	0.137

As the calculation result shows, the primary units adhere to the public service facility allocation system of city–district–subdistrict–community in terms of educational facilities, government services, public culture, sports facilities, medical health, welfare care, and daily life (Figure 7). The livability is very high inside the urban development boundaries of Changsha, gradually decreasing outward. Some high values scattered outside the boundary are from developed towns. This distribution is consistent with the actual situation of Changsha's urban development and aligns with the overall layout of spatial planning and the actual application requirements.

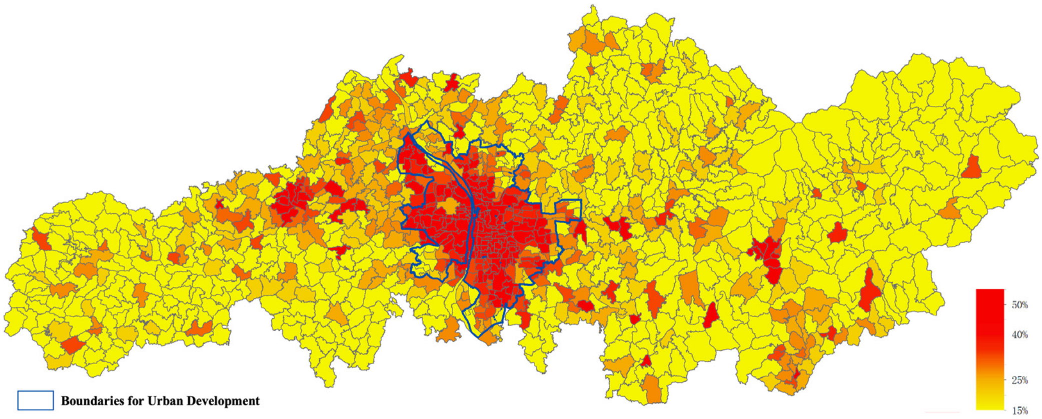

Figure 7. The result of livability for spatial planning primary units based on public service facilities.

3.3.2. Efficiency Assessment of Spatial Planning Data Structure

Using the proposed method, this study successfully stored Changsha's regulatory detailed planning data on the blockchain. The data included 25,769 structured data polygons, consuming a storage space of 461.13 MB (70.98 MB for attribute data and 390.16 MB for planning boundary point data), along with 6127 unstructured data files occupying 42.06 GB. To assess the efficiency of the proposed method, the block size, data redundancy, consensus algorithm efficiency, and data throughput were evaluated.

(1) Block Size and Data Redundancy Evaluation

After storing all experimental data on the blockchain, we obtained 907 blocks. Among them, 141 structured blocks occupied 124.80 MB per peer node, averaging 0.89 MB per block. The 766 unstructured blocks occupied 3.74 MB per peer node, averaging nearly 5.00 KB per block. The average sizes of both block types can effectively address the challenge of limited block size.

When initializing the chain of spatial planning data, the structured data, which contain 17 core attributes and one hashed boundary point datum, had a redundancy rate of 21.30%, equating to 124.80 MB per peer node. In contrast, the unstructured data, which stored only MD5 codes from outcome files, had a redundancy rate of approximately 0.01%, amounting to 3.74 MB per peer node. The total data redundancy was only 128.54 MB per peer node, with a redundancy rate of approximately 0.29%, meeting the actual application requirements.

When updating Changsha's 2021–2023 regulatory detailed planning data on the chain, 1160 polygons required modification. Considering the data redundancy during the initialization of the chain, the annual data redundancy for updating is approximately 5.78 MB per peer node. This also meets the actual application requirements.

(2) Consensus Algorithm Efficiency and Data Throughput Evaluation

The blockchain initialization was completed in 43 min and 32 s, producing 907 blocks (7252 primary units including 450,327 attribute data and 25,769 planning boundary point data) and performing 392,662 consensus verifications. On average, the consensus verification rate was 150.33 times per second, the equivalent data throughput was 12.21 transactions per second (calculated using the number of polygons and files successfully stored on the blockchain), and the block generation rate was 20.83 blocks per minute. In particular, the core of the consensus algorithm, which involves comparing indicators and performing topological analysis of polygons, meets the needs of practical application and shows significant potential for improving both consensus algorithm efficiency and data throughput without vast computational resource requirements.

3.3.3. Comprehensive Assessment of Results

This study designed and constructed a blockchain-based data structure for storing spatial planning data. It also provided methods for primary unit division and consensus algorithm construction. In the experiments, we derived primary units with a strong spatial consistency, moderate size, and high compatibility with planning management. This provides a solid framework for the storage and management of spatial planning data. Using Bitcoin as a benchmark, we compared the quantitative indicators of our experimental data with those of typical blockchain applications. Specifically, in our experiments, the average block size was controlled at approximately 0.89 MB, while Bitcoin's average is approximately 1.00 MB. The data redundancy was up to 21.30%, while Bitcoin uses complete redundancy for storage. The consensus algorithm achieved a rate of 150.33 times per second, and the block generation rate was 20.83 blocks per minute, in contrast to Bitcoin's consensus and block generation, which occurs every 10 min with a computational power consumption of 8.32 quintillion hashes per second. Additionally, the equivalent data throughput was 12.21 transactions per second, compared to Bitcoin's 6.67 transactions per second.

From the evaluation indicators above, the experiment demonstrated significant advantages over Bitcoin in terms of block size, data redundancy, consensus algorithm efficiency, and data throughput. These findings effectively address the challenges in typical blockchain applications and could be applied to the data storage needs of spatial planning. In terms of actual data storage performance, we verified that the spatial planning data storage on each network node achieved 100% data consistency. Complete records of data storage or modification were maintained, meeting the requirements for constructing a unified and coordinated spatial planning data system. Additionally, by leveraging the tamper-proofing, record-keeping, and process traceability characteristics of blockchain technology, we ensured the legality, uniformity, authority, and relevance of spatial planning data.

4. Discussion

4.1. The Applications in Monitoring and Early Warning

Using blockchain technology to build a unified, authoritative, and trustworthy shared data system for spatial planning ensures a consistent and authoritative database for spatial planning management. This system allows for the establishment of rules for spatial boundaries and planning indicators, linking them to related management data, such as land use approval and planning permission. This approach enables real-time monitoring and early warning of illegal land use (Figure 8), thereby improving the efficiency of supervising spatial planning.

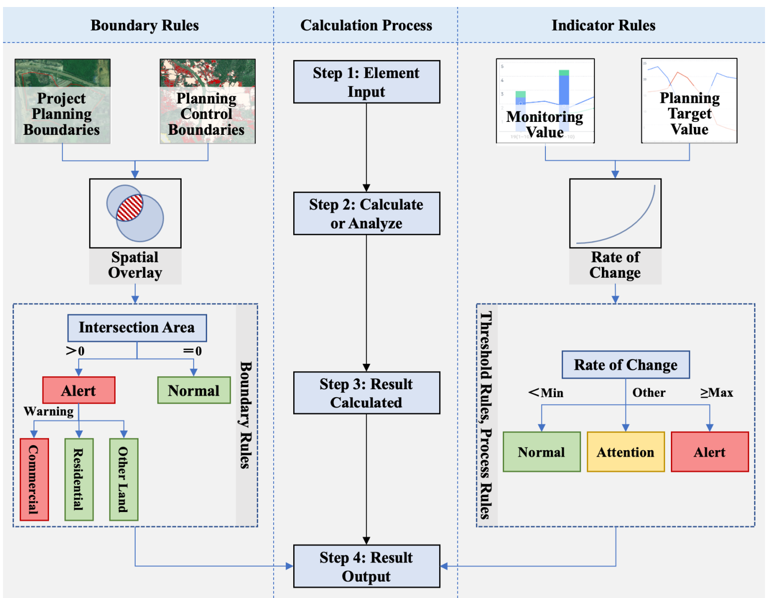

Figure 8. The monitoring and early warning models for spatial planning boundaries and indicators.

4.1.1. Spatial Monitoring and Early Warning

The spatial data of planning control boundaries are obtained and verified in the blockchain data structure through hash pointers and Merkle trees. After verification, these boundaries are compared with those outlined in the project planning to promptly track boundary encroachment and violations, issuing warnings according to rules (Table 3). This process can be divided into four steps:

(1) Inputting Elements:

Extract planning control boundaries S_1 and project planning boundaries S_2.

(2) Calculating Intersections:

Perform intersection calculation on S_1 and S_2, and output S_3.

(3) Calculating and Outputting Results:

Calculate the area of S_3, and assess the warning situation according to the rules. Take the monitoring of the ecological conservation zones as an example. If $S_3 > 0$, the project planning boundaries have invaded the boundaries, and a warning is issued. If $S_3 = 0$, the project planning boundaries have not invaded the boundaries, and no warning is issued. Finally, output the warning result R_S (Formula (2)).

$$R_S = \begin{cases} \textbf{\textit{Alert}} & : S_3 > 0 \\ \textbf{\textit{Normal}} & : S_3 = 0 \end{cases} \tag{2}$$

Table 3. The monitoring and early warning rules for spatial planning control boundaries.

Control Boundaries	Reference Data	Monitoring and Early Warning Rules
Urban development boundaries	Various boundaries, complete survey maps, and aerial photo enforcement polygons	Prohibit crossing. Construction must be confined within the urban development boundaries. A red warning will be issued if crossing is detected.
Permanent bare cropland protection boundaries and ecological conservation boundaries		Prohibit occupation. A red warning will be issued if occupation is detected.
Nature reserve boundaries		Prohibit occupation. The core protection areas and general control areas are managed separately. A red warning will be issued if occupation is detected.
Historical protection zone boundaries, urban green space boundaries, urban surface water protection and control zone boundaries, and urban infrastructure land control zone boundaries		Strictly controlled occupation. A red warning will be issued if occupation or land misuse is detected.

4.1.2. Indicator Monitoring and Early Warning

We can obtain the constraint planning indicators of master planning and detailed planning and verify them through hash pointers and Merkle trees. These indicators serve as critical metrics for urban development progress. After verification, we can compare them with the indicators in the project planning to monitor issues of exceeding limits or rapid progression in urban construction development, issuing warnings according to the rules (Table 4). This process can be divided into four steps.

(1) Inputting Elements

Extract the constraint planning indicators, including the planning target value I_0, planning period Y, and the monitoring value I_{n} of the nth planning year.

(2) Analyzing Trends

Calculate the ratio of the monitoring value to the target value of the constraint planning indicators, denoted as R_n (Formula (3)), representing the indicator's achievement rate. Then, calculate the monitoring value's annual change rate, denoted as V_n (Formula (4)), which represents the indicator's development rate.

$$R_n = \frac{I_n}{I_0} \tag{3}$$

$$V_n = \frac{I_n - I_{n-1}}{(I_1 - I_0)} \times Y \tag{4}$$

(3) Calculating and Outputting Results

The warning levels are defined by the value of R_n, which is between 0.9 and 1.0. The warning levels include green ($R_n < 0.9$), yellow ($0.9 \leq R_n \leq 1.0$), and red ($R_n > 1.0$), corresponding to normal, nearing the planning limit, and surpassing the planning limit, respectively. A larger R_n value implies higher warning levels. The warning levels can also be defined by the value of V_n, which is between 1.2 and 1.5. Green ($V_n < 1.2$), yellow ($1.2 \leq V_n \leq 1.5$), and red ($V_n > 1.5$) warnings correspond to normal, accelerating, and the over-speedy development of indicators, respectively. Finally, output the warning result W_n (Formula (5)).

$$W_n = \begin{cases} \textbf{\textit{Normal}} & : R_n < 0.9 \ \ or \ \ V_n < 1.2 \\ \textbf{\textit{Attention}} & : 0.9 \leq R_n \leq 1.0 \ \ or \ \ 1.2 \leq V_n \leq 1.5 \\ \textbf{\textit{Alert}} & : R_n > 1.0 \ \ or \ \ V_n > 1.5 \end{cases} \tag{5}$$

Table 4. The monitoring and early warning components and guidelines for spatial planning constrained indicators.

Indicators	Indicator and Data Source	Monitoring and Early Warning Rules
Master planning indicators	(1) Base year indicator value (from planning outcomes) (2) Target year planning value in the near term (from planning outcomes) (3) Target year planning value in the long term (from planning outcomes) (4) Historical current value (from annual change survey) (5) Dynamic monitoring value (from approval and management data)	The corresponding warning rules can be developed based on the actual application of each indicator. The rules provided in this research are for reference only. (1) Green warning (normal): 110% of the lower limit < indicator value, or indicator value <90% of the upper limit, and there are no other abnormalities. (2) Yellow warning (attention): the lower limit < indicator value <110% of the lower limit, or 90% of the upper limit < indicator value < upper limit. (3) Red warning (alert): if the monitoring value of an indicator exceeds the upper or lower limit of its target value, or if there is a more severe situation than the yellow warning.
Detailed planning indicators	(1) City-level planning indicators, such as the number of regulatory detailed planning regions, total planning area (from planning outcomes) (2) District-level planning indicators, such as planning area, total planning construction land area, and population scale (from planning outcomes) (3) Polygon-level planning indicators, such as land use, land area, floor area ratio, and building density (from planning outcomes)	Each indicator follows the corresponding early warning rules. The following are some indicator rules: (1) Total construction land area (city-level): a red warning is triggered when the monitoring value surpasses the total planning construction land area. (2) Public service facilities (district-level): a yellow warning is triggered when planning modifications lead to a rise in population and facility demands; a red warning is triggered when the required facility area exceeds the planning value, or when the facility land reduces. (3) Floor area ratio (polygon-level): a red warning is triggered if the planning modification of the floor area ratio exceeds the upper limit, or if the conditions for granting do not comply with the planning.

4.2. Generalizability, Limitations, and Future Research Considerations

In this study, the block and chain structures are designed to handle both structured and unstructured data, covering all kinds of data in spatial planning. The primary unit division method and consensus algorithms align with mainstream standards and application requirements. The validation experiments were conducted using Changsha's regulatory detailed planning within Hyperledger Fabric 2.0. The results demonstrated that the research findings can ensure the legality, uniformity, authority, and relevance of spatial planning data.

Compared to traditional spatial planning data storage methods, our findings enable automatic data verification, significantly reducing uncertainties caused by human intervention. Additionally, compared to typical blockchain applications, our methods address issues associated with blockchain technology, facilitating efficient data verification and management. Furthermore, the findings are adaptable and can be adjusted according to actual needs, industry policies, and regulatory requirements. For example, the primary unit division method can be customized based on factors like space and population standards. Likewise, the consensus algorithms can also be adjusted and extended according to the provided pseudocode, including rules for indicator verification, standard verification, and spatial topology.

This study offers technical solutions and robust support to address common challenges in spatial planning applications based on blockchain technology, demonstrating broad applicability in data management. Experimental validation shows that these solutions can be adapted and extended to other types of spatial planning outcomes, and implemented in different cities, regions, and nations. The findings facilitate the development of similar applications and hold practical significance for related fields. However, this research focused on the applications for spatial planning departments, with relatively clear target users and a uniform network environment. As the applications advance, several areas for further research should be explored, as listed below.

(1) Enhancing Cross-Industry Coordination and Expanding Users Using Cross-Chain Technology

In China, for example, spatial planning is coordinated nationally by natural resource departments. However, other government departments and industries often develop their own spatial management policies, deploy monitoring devices (such as IoT sensors), and collect data (such as sensing images). Integrating these diverse data sources with spatial planning could greatly enhance monitoring and provide valuable data support. The challenge lies in their storage across different entities and network environments, which can affect completeness, timeliness, and relevance. By adopting the method described in this study, the policies, data, and distribution of devices can be stored in their respective blockchain networks based on a unified primary unit system. Utilizing cross-chain technology to foster connectivity and data sharing among these blockchains, and ensuring a tight integration with spatial planning, can markedly improve their interactivity and collective efficacy.

(2) Providing Public Disclosure and Verification Services Using Off-Chain Interaction Technology

Spatial planning data are typically stored in isolated networks, making public access challenging. To address this, government departments and professional institutions frequently create public versions of spatial planning data. However, ensuring their accuracy, timeliness, and completeness can be difficult, and tracing their origins is often problematic. Additionally, when the public requires more detailed information based on these versions, conflicts occur. By integrating blockchain technology to manage spatial planning data, we can use off-chain interaction technologies (such as offline verification and hash comparison) to solve these issues. This approach can establish a robust mechanism for verifying the consistency of different spatial planning versions across various network environments, even offline. This, in turn, enhances public engagement and transparency in spatial planning, promoting a more informed and involved public in the urban development process.

5. Conclusions

This study investigates common issues in organizing and managing current spatial planning data. Based on blockchain technology, we proposed a block structure to organize and manage spatial and non-spatial element data. Considering the 15 min life circle, we developed a primary unit division method for spatial planning. A chain structure tailored for blockchain initialization and subsequent updates were established. Quality inspection, spatial detection, and indicator transmission consensus algorithms based on smart contracts were explored. The entire procedure was validated in the experiments conducted in Changsha, which demonstrated its practicality and viability for addressing planning data challenges such as overlaps and conflicts. The assessment of the proposed method also showed that it overcame blockchain technology's limitations in block size, data redundancy, data throughput, and consensus algorithm efficiency. The method can establish a robust data foundation for creating a unified and coordinated spatial planning data system, ensuring legality, uniformity, authority, and relevance. This advances blockchain technology research in this field and enables its application in spatial planning. Moreover, we discussed spatial monitoring, indicator monitoring, and their early warning systems, providing a feasible way to realize spatial planning monitoring, early warning, and dynamic assessment. The proposed method can be used for other research in related domains. In the future, with the continuous development of technologies like cross-chain, on-chain, and off-chain interaction, this research can be applied to deeper and broader scenarios, such as cross-industry data management and public data sharing.

6. Patents

Inventor: Minwen Tang, Wujiao Dai, Changlin Yin
Title: A Method and Device for Storing Detailed Spatial Planning Based on Blockchain
Patent Number: ZL 2023 1 1654854.7
Filing Date: 4 December 2023
Grant Date: 11 June 2024

Abstract: The invention provides a method and device for storing detailed planning data based on a blockchain. The method includes obtaining detailed planning data from a database, creating a blockchain tailored to these data with pre-set consensus algorithms, and storing the data on the blockchain if they meet the consensus algorithms. Using blockchain technology to store detailed planning data ensures tamper-proofing, complete record-keeping, and process traceability for detailed planning. It fosters mutual trust and data sharing among multiple parties under joint maintenance, ensuring their legality, uniformity, authority, and relevance.

Author Contributions: Conceptualization, Minwen Tang, Wujiao Dai, and Changlin Yin; methodology, Minwen Tang and Wujiao Dai; software, Minwen Tang, Jun Chen, and Haoming Liu; validation, Minwen Tang; investigation, Bing Hu; resources, Bing Hu; data curation, Bing Hu; writing—original draft preparation, Minwen Tang; writing—review and editing, Minwen Tang, Wujiao Dai, and Changlin Yin. All authors have read and agreed to the published version of the manuscript.

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

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