fire

Article

DEMATEL, AISM, and MICMAC-Based Research on Causative Factors of Self-Build Housing Fire Accidents in Rural Areas of China

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Abstract: In recent years, the fire safety problems in self-build housing in China's vast rural areas have become increasingly prominent. We analyzed the interaction of causative factors and logical structure of self-build housing fire accidents (SBHFAs) to find their key causes and reduce their occurrence. Using the 24Model, 30 SBHFA investigation reports were analyzed, and 44 SBHFA causative factors and 97 causal relationship codes were obtained. The causality and centrality degree of causative factors were analyzed using the decision-making trial and evaluation laboratory (DEMATEL) method to obtain the causal attribute and importance of causative factors. An adversarial hierarchical topology model of causative factors was conducted using the adversarial interpretive structural modeling (AISM) method, and the causal hierarchical relationships were obtained. Using the Matrices Impacts Croises-Multiplication Appliance Classement (MICMAC) analysis, the causative factors' dependency degree and driving force were calculated. Combining and comparing the results of DEMATEL, AISM, and MICMAC analyses, we found that the adversarial hierarchical topology model of causative factors was reasonable, and key direct causative factors, key transitional causative factors, and key root causative factors were mined. Controlling the key causative factors could effectively reduce the occurrence of SBHFAs and guide the fire safety management of self-build housings in rural areas of China.

Keywords: self-build housing; fire accident; causative factor; adversarial hierarchy topology; DEMATEL; AISM; MICMAC

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1. Introduction

With the rapid development of urban and rural construction in China in recent years, the construction of self-build housing has increased, resulting in a large number of regional fire safety problems, especially in rural areas [1]. In 2021, China's Fire and Rescue Administration launched a new statistical system, adding the classification of self-build housing. According to statistics, 156,000 self-build housing fires occurred in 2021, accounting for 60.5% of all residential fires, resulting in 848 deaths or 58.1% of the total number of residential fire deaths [2]. These statistics suggest the necessity of studying the causes of self-build housing fire accidents (SBHFAs) in order to help reduce their incidence.

There are about 560,000 administrative villages, 3 million natural villages, and hundreds of millions of rural self-build houses in China. The fire safety concerns of individual rural self-build houses seem small, but the accumulation of hidden minor issues may lead to more serious problems. China's homestead management system has been implemented since the 1980s, and now the safety issues of rural self-build housing have come into focus [3]. On 25 June 2021, a major fire occurred in a self-built house in Beijie Village, Yuanxiang Town, Zhecheng County, Henan Province, China, resulting in 18 deaths and 11 injuries, with a direct economic loss of approximately 21.53 million yuan [4].

According to China's Fire and Rescue Administration data on the causes of residential fires in 2021, electrical fires accounted for 42.7% of fires, careless use of fire accounted for 29.8%, smoking for 4.6%, playing with fire for 1.9%, spontaneous combustion for 1.8%, arson for 1.3%, and other causes such as leftover kindling accounted for 17.9% of fires [2]. Statistical analysis of the fires from 1991 to 2010 showed that the main causes of residential fires were electrical failures and improper use of fire in daily life [5]. The data analysis of fires from 1997 to 2017 in China confirmed electrical factors and careless use of fire as their leading causes, with incidents of electrical fires increasing significantly. It was, therefore, proposed to increase investment in fire protection and improve public safety awareness to reduce the occurrence of fires [6]. The investigation and analysis of house fire accidents in rural areas in southwest China found that the problem of electrical fires in rural areas was serious. Strengthening the residents' fire prevention education was proposed to reduce rural electrical fire accidents [7]. A questionnaire assessment of the residents of Dong minority rural village in China found that their knowledge of electrical fire risk reduction was improved after educational intervention [8]. In rural areas of southern China, a large number of buildings using wooden materials were seriously threatened by fire. To ensure their fire safety, careful consideration should be given to providing safety education, building firefighting facilities, and developing housing designs [9]. In recent years, a large number of fires in residential areas in China were caused by electrical circuit failures of electric bicycles charging near residential stairs, in a direct violation of regulations [10]. Research conducted thus far has focused mainly on the statistical analysis of fire causes in residential areas, with only a few in-depth studies on the cause of self-build housing fires in China's rural regions. Further systematic, in-depth research on the fire cause and their relationships is needed, specifically on the interaction between the causative factors and the causal structure.

To that end, this paper analyzed the SBHFA investigation reports using the 24Model, identified SBHFA causes, and coded their relationships. The causal relationships between accident factors were analyzed using the DEMATEL method. An adversarial hierarchical topological network of causes was constructed using the AISM method, and the characteristics of their hierarchical structure were analyzed. The MICMAC method was used to classify the causative factors into groups to verify the rationality of the adversarial hierarchical topology network model. Finally, key causes were obtained through combined model analysis. Giving priority to addressing those causes has an important practical significance in reducing the incidence of SBHFAs in rural China.

2. Methodology

2.1. The Analytical Framework

This paper studied the interaction and logical relationship between the factors causing SBHFAs in order to find the key accident-contributing factors and take targeted control measures to improve the fire safety management of self-build housings. As shown in Figure 1, this study was mainly divided into six parts.

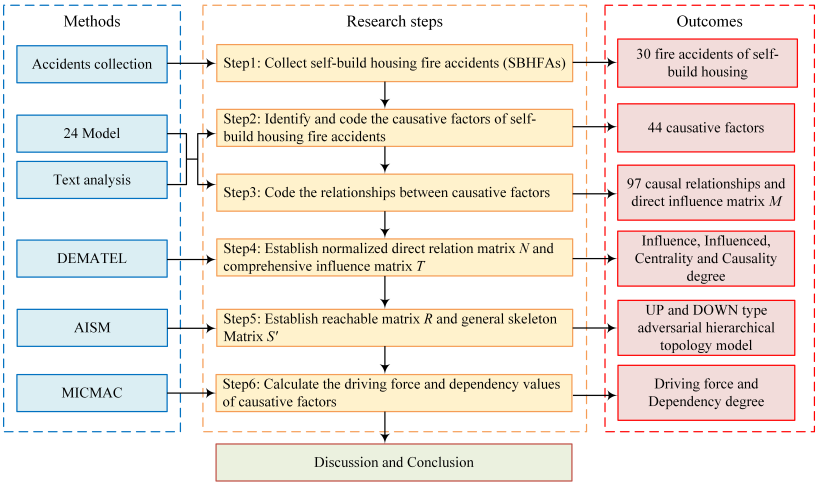


Figure 1. The analytical framework.

2.2. Data Collection

Using the advanced search function of the "Baidu" search engine, the search criteria were set to "self-build housing", "fire", and "accident investigation report". In order to ensure the accuracy and credibility of the reports, only accident investigation reports published on the official website of the government's emergency management departments at all levels were selected, and a total of 30 SBHFA investigation reports from 2014 to 2022 were screened. The 30 SBHFAs were coded from HZ01 to HZ30.

2.3. 24Model and Causative Factor Coding

2.3.1. 24Model

The 24Model was based on the behavior theory developed by Chinese researchers on the basis of the accident cause chain proposed by Heinrich, Bird, and Reason [11]. The model divides the accident causes into two levels and four stages [12]. The organizational level is characterized by two stages of guiding behavior and operating behavior. At the individual level, there are conditions, two stages of habitual behavior, and one-off behavior. The guidance behavior includes the lack of safety culture, and the operation behavior includes the inadequacy in the safety management system. Habitual behaviors include a lack of safety knowledge, safety awareness, safety habits, safety psychology, and safety physiology. One-off behavior and conditions include unsafe acts and unsafe conditions [13]. The structure of the accident-causing 24Model is shown in Figure 2.

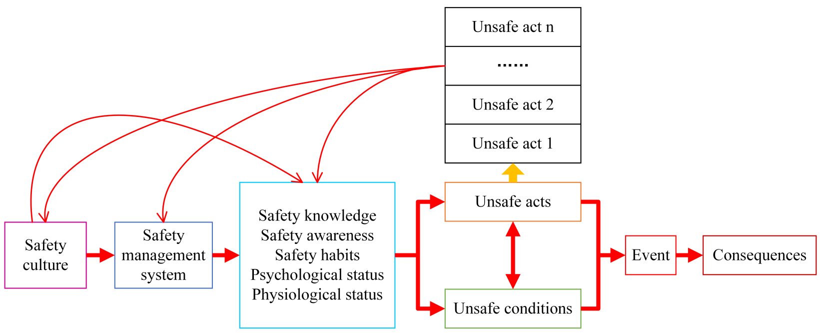


Figure 2. The latest version of 24Model and its application process in accident analysis [11].

2.3.2. Causative Factor Coding

Generally, qualitative research follows the logic of purposive sampling, with the goal of selecting the most appropriate and productive samples to effectively answer research questions and develop theories [14]. Too many research samples will likely waste public research funding and participants' time and energy. A small number of research samples may have the same outcome due to unreliable conclusions. Mason [15] analyzed 560 doctoral papers using qualitative research and summarized their sample size range; he found that the average sample size among various qualitative analysis methods ranged from 23 to 36 [15].

In this study, we used the qualitative analysis software NVivo 12 to conduct text analysis of fire accident investigation reports. We split three graduate students studying safety accidents into groups A (1 person) and B (2 people) and imported 30 accident investigation reports into NVivo 12. Then, using the 24Model and combined semantic analysis of 30 accident investigation reports, two groups identified accident causes and relationships and manually encoded them in NVivo 12. Finally, the encoding comparison function in NVivo 12 was used to compare the consistency of codes in groups A and B and calculate the Kappa coefficient. After obtaining an acceptable level of encoding consistency, we exported the coding book of causes and their relationships.

2.4. DEMATEL

The decision-making trial and evaluation laboratory (DEMATEL) is a complex system factor analysis method using graph theory and matrix tools [16]. System science believes that a system is an organic connection between elements. DEMATEL divides the system into elements and the relationship between them. Its essence is to treat the system as a directed graph with weights [17]. The analysis steps of DEMATEL are shown in Figure 3. The traditional DEMATEL method uses expert scoring to construct a direct influence matrix of factors with a strong subjectivity. This paper obtained a direct influence matrix by transforming the relationship coding book of causes, which was less subjective than the traditional expert scoring method.

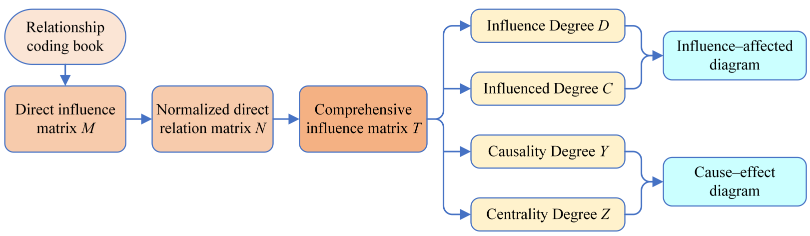


Figure 3. DEMATEL analysis flowchart.

- Step 1. Normalized direct relation matrix N

The direct influence matrix M was constructed according to the coding of causal relations. Then, according to Equation (1), the direct influence matrix M is processed and the normalized direct relation matrix N was established [18]:

$$N = \frac{M}{\underset{1\le i\le n}{max} \sum_{j=1}^{n} m_{ij}} \tag{1}$$

where *max* denotes the maximum value of the sum of elements in each row of the direct influence matrix M.

- Step 2. Comprehensive influence matrix T

The direct influence matrix reflects only the direct relationship between causes, and the indirect relationship between factors should also be considered. According to Equation (2), the comprehensive influence matrix T, which can reflect the comprehensive relationship between various factors, was obtained:

$$T = N(I - N)^{-1} \tag{2}$$

where I represents the identity matrix.

- Step 3. Influence, influenced, causality, and centrality degree

After obtaining the comprehensive influence matrix T, we calculated the influence degree D and the influenced degree C according to Equation (3):

$$D_i = \sum_{j=1}^{n} t_{ij}, \quad C_j = \sum_{i=1}^{n} t_{ij} \tag{3}$$

where D_i represents the comprehensive influence value of factor i on other factors, and C_j represents the total influence value of other factors on factor j.

The causality degree Y and centrality degree Z of factor i can be calculated according to Equation (4):

$$Y_i = D_i - C_i, \quad Z_i = D_i + C_i \tag{4}$$

Causality degree refers to the degree of influence of one factor on other factors. The causality degree greater than 0 indicates that this factor greatly influences other factors and is called a causal factor. The contrary is called the resulting factor. The centrality indicates the importance of this factor in the system.

2.5. AISM

2.5.1. ISM and AISM

The interpretive structural modeling (ISM) method was proposed by Professor Warfield in 1974 and is mainly used to analyze the constituent elements of complex systems, their interdependence, and mutual constraints [19,20]. Its basic principle is to decompose the constituent elements of a complex system into several subelements and, through a series of topological operations, obtain a single hierarchical graph guided by the results. Our hierarchical graph was arranged from top to bottom into a multilevel hierarchical structure to obtain a reachable causal sequence from cause to effect and express it in a hierarchically directed topological graph [21].

The adversarial interpretive structural modeling (AISM) method incorporates the idea of the generative adversarial network (GAN) into traditional ISM to include the idea of an adversarial game. Its core is establishing a set of adversarial hierarchy diagrams by adding to ISM the opposing reason priority hierarchy extraction rules [22]. Compared with the single extraction rule of ISM, AISM can more comprehensively reflect the hierarchy of factors [23]. The analysis steps of AISM are shown in Figure 4. The AISM method can effectively distinguish the degree of influence of various causative factors, thus dividing them into essential, transitional, and surface layer factors.

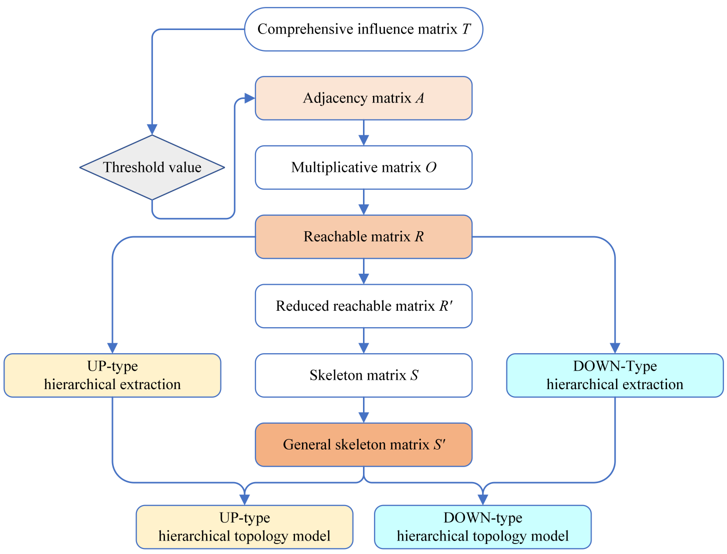


Figure 4. AISM analysis flowchart.

2.5.2. Matrix Construction in AISM

- Step 1. Adjacency matrix

In this paper, threshold λ was introduced, and its value was calculated using Equation (5):

$$\lambda = \alpha + \beta \tag{5}$$

where α is the average value of all elements of the comprehensive influence matrix T, and β is the standard deviation.

Based on the comprehensive influence matrix $T = [t_{ij}]_{n\times n}$ and Equation (6), the adjacency matrix $A = [a_{ij}]_{n\times n}$ was constructed:

$$\begin{cases} If\ t_{ij} \geq \lambda, a_{ij} = 1 \\ If\ t_{ij} < \lambda, a_{ij} = 0 \end{cases} \tag{6}$$

where 1 represents a strong relationship between the two factors, and 0 represents no relationship or weak relationship between the two factors.

- Step 2. Reachable matrix

The multiplicative matrix O was calculated according to the adjacency matrix A and Equation (7), and the reachable matrix R was calculated according to Equation (8):

$$O = A + I \tag{7}$$

$$O^{k-1} \neq O^k = O^{k+1} = R \tag{8}$$

where I is the identity matrix.

- Step 3. General skeleton matrix

The reachable matrix R was used to reduce the points and edges, that is, the loop in the reachable matrix was regarded as a point, and the reduced reachable matrix R' was obtained after reduction. We calculated the skeleton matrix S according to Equation (9) and then substitute the simplest link form between the loop elements into S to obtain the general skeleton matrix S' [24]:

$$S = R' - \left(R' - I\right)^2 - I \tag{9}$$

where I is the identity matrix.

2.5.3. Hierarchical Extraction

For a reachable matrix, there were reachable set K, antecedent set X, and common set G, where G = K ∩ X. In the reachable matrix R, the reachable set of factor i (all elements whose row value of factor i was 1) was recorded as K(R_i). The antecedent set of factor i (all elements whose column value of factor i was 1) was recorded as X(R_i). The intersection set of factor i was G(R_i), that is, K(R_i) ∩ X(R_i).

For the UP type of hierarchical extraction—the hierarchical division of the priority of the results—extraction rule was G(R_i) = K(R_i). The extracted features were placed above each time, and the extracted features were placed from top to bottom in sequence.

For the DOWN type hierarchical extraction—the hierarchical division of the priority of causes—extraction rule was G(R_i) = X(R_i). The extracted features were placed below each time, and the extracted features were placed from bottom to top in sequence.

2.5.4. Adversarial Directed Topology Hierarchy Diagram

According to the relationship between the factors in the general skeleton matrix S' and the level extraction results, we drew a group of directed topological hierarchy diagrams of antagonism. Directed line segments were used to represent the accessibility relationship between factors and double arrows were used to indicate the formation of loops, representing the mutual accessibility relationship. The lower level indicated that the factor was the root cause, and the higher level indicated that the factor was a direct cause.

2.6. MICMAC

The Matrices Impacts Croises-Multiplication Appliance Classement (MICMAC) method uses the reachable paths and hierarchical loops between factors to analyze the influence and dependency between various factors in the system and clarify the role and status of each factor in the system [25]. In order to verify the rationality of the hierarchical division of causative factors in SBHFAs using the AISM model, MICMAC was used to analyze the dependence and driving force of each causative factor.

Driving force is the influence of one factor on other factors, and dependence is the degree of the influence of one factor over another [26]. According to Equation (10), the driving force value Q and the dependency value P of each factor were calculated from the reachable matrix R. According to the driving force and dependency values, causative factors could be divided into four categories, namely linkage, dependency, autonomous, and independent factors [27]:

$$Q_i = \sum_{j=1}^{n} r_{ij}, P_j = \sum_{i=1}^{n} r_{ij} \tag{10}$$

where r_{ij} is the value of the element in row i and column j of the reachable matrix R.

3. Results

3.1. Basic Information on SBHFAs

As shown in Figure 5, the sizes of nodes for the year, city, number of deaths, and number of injuries represent the number of associated accidents; the larger the node, the more accidents associated with it. It can be seen from Figure 5 that Fuyang City had the largest number of SBHFAs in this study. Most of the accidents occurred in 2020 and 2021. From the distribution of casualties, the number of accidents with five deaths was the highest, as was the number of accidents with one injured. The maximum number of deaths in a single accident was 18, and the maximum number of injuries in a single accident was 38. These results indicate that the SBHFAs in China seriously threaten the life and safety of the people.

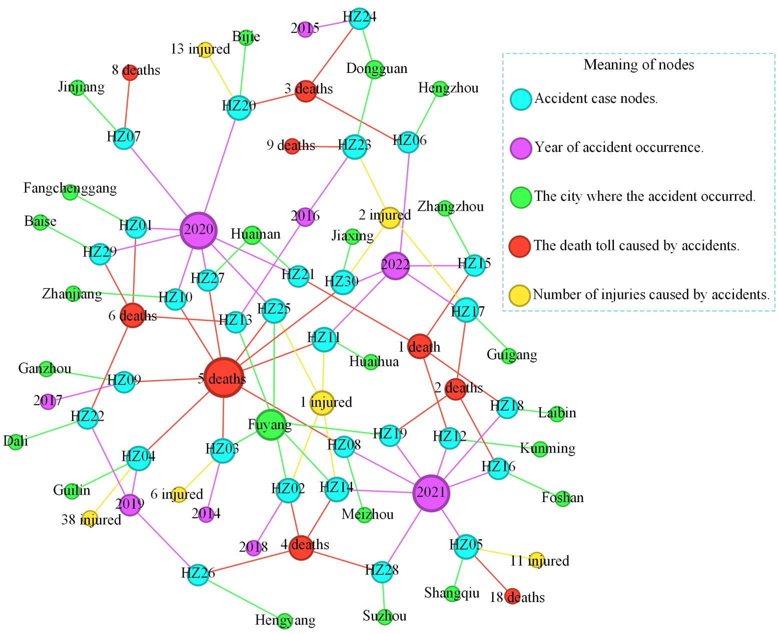


Figure 5. Basic information map of accident cases.

3.2. Analysis of the SBHFA Causes

According to 24Model, the SBHFA causative factors were divided into five categories: unsafe acts, unsafe conditions, habitual unsafe behaviors, safety management system, and safety culture. By analyzing the 30 collected SBHFA investigation reports, 44 causative factors were finally obtained, classified, and coded. Those that fall into the categories of unsafe acts, unsafe conditions, habitual unsafe behaviors, safety management system, and safety culture are, respectively, represented by letters "UA, UC, HUB, SMS, and SC" and serial numbers, as shown in Table 1. By encoding the relationships of 44 causative factors, 97 relationships were obtained. Comparing the coding results of groups A and B using NVivo 12 software, it was found that the kappa coefficients of the codes were all greater than 0.75, indicating that the coding for the SBHFA causative factors was consistent within an acceptable range [28]. The directed edge list between the encoded SBHFA causative factors is shown in Table A1 in Appendix A.

Table 1. Causative factors of self-build housing fire accidents in rural areas of China.

Category	No.	Factor Coding	Accident Causation
Unsafe acts	1	UA01	Improper fire extinguishing measures and escape methods
	2	UA02	Careless use of fire in life
	3	UA03	Improper use of an electric heater
	4	UA04	Illegal business activities
	5	UA05	The illegal setting of the accommodation area
	6	UA06	Charging of electric vehicles parked illegally
	7	UA07	The owner did not implement the main responsibility of fire safety
	8	UA08	Leftover kindling
	9	UA09	Improper use of fire, electricity, or gas
	10	UA10	Illegal expansion and reconstruction of original buildings
	11	UA11	Insufficient fire safety education for family members
Unsafe conditions	12	UC01	A large number of flammable materials not stored properly
	13	UC02	Battery failure, spark, or explosion
	14	UC03	The electrical circuit installation is not standardized
	15	UC04	Electrical circuit fault
	16	UC05	The shared building not equipped with required firefighting facilities and equipment
	17	UC06	The shared building not equipped with independent evacuation facilities or auxiliary evacuation facilities
	18	UC07	The residential and non-residential parts of the shared building not separated by fire protection
	19	UC08	Low fire resistance rating of building materials
	20	UC09	Hidden dangers in the building structure
	21	UC10	The outer window of the building set with a metal fence difficult to open from the inside
	22	UC11	The fireproof spacing of civil buildings not meeting the requirements of national standards
	23	UC12	The position of the gas cylinder not standard
	24	UC13	Gas leakage
	25	UC14	The setting of the evacuation door not meeting the escape requirements
	26	UC15	The evacuation passage blocked
	27	UC16	Insufficient emergency rescue equipment at the fire station or untimely maintenance
Habitual unsafe behaviors	28	HUB01	Safety physiological defect
	29	HUB02	Lack of fire safety common sense
	30	HUB03	Poor living habits
	31	HUB04	The phenomenon of unauthorized connection of wires is serious
	32	HUB05	Weak awareness and ability to escape and self-rescue
	33	HUB06	Weak awareness of fire safety
	34	HUB07	Fire safety hidden danger investigation and rectification not in place
	35	HUB08	Insufficient vocational skills
Safety management system factors	36	SMS01	Inadequate implementation of the fire safety responsibility system
	37	SMS02	Failure to set up a full-time fire brigade according to regulations
	38	SMS03	No emergency plan for firefighting and evacuation
	39	SMS04	No fire safety management system

Table 1. *Cont.*

Category	No.	Factor Coding	Accident Causation
Safety culture factors	40	SC01	Not attaching importance to job responsibilities
	41	SC02	Not paying no attention to daily fire safety management
	42	SC03	Not attaching importance to fire safety meetings
	43	SC04	Neglecting fire safety regulations
	44	SC05	Inadequate fire safety awareness and education

We sorted the 30 accidents into T01–T30 in order of occurrence. As shown in Figure 6, the horizontal coordinate position corresponding to the color block is the case where the causative factor first appears. Once the causative factor appeared, it was fixed at the position where it first appeared. Although the factor appeared in subsequent cases, it was no longer displayed in the figure. When a factor appeared again in subsequent cases, its frequency increased by 1 in the position where it first appeared. When it occurred several times, its frequency increased by several times. Figure 6 shows that most causative factors emerged in the first 15 cases, few emerged in the last 15 cases, and no new factors emerged in the last two cases. Therefore, the coding of causative factors in this paper ensured the reliability of the study.

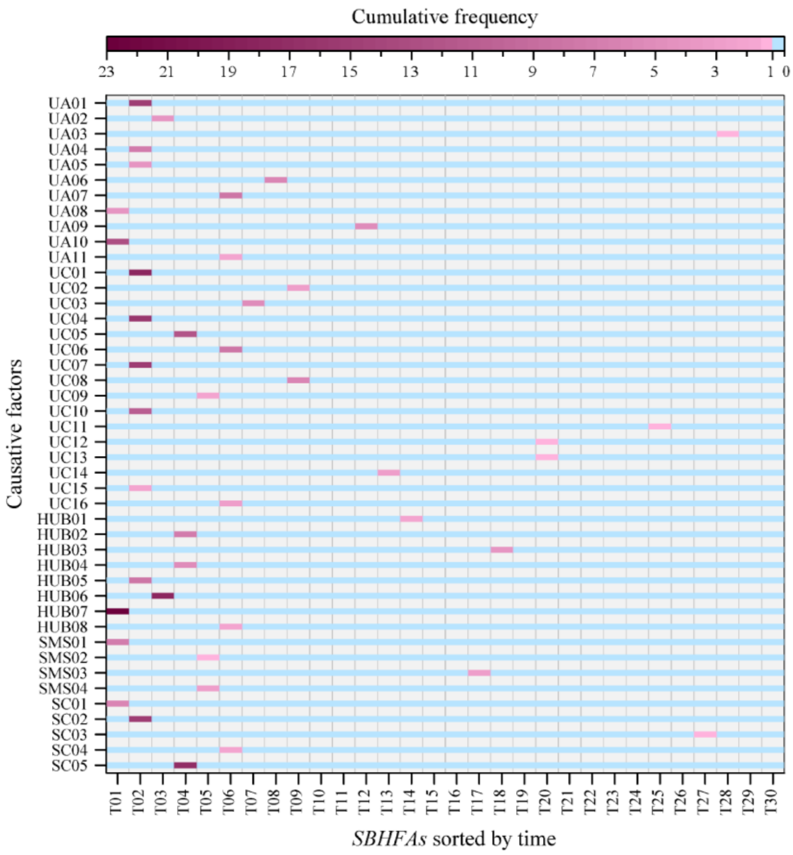


Figure 6. *SBHFA* causative factors emergence chart.

The frequency of SBHFA causative factors was counted to obtain the causative factors' frequency distribution, as shown in Figure 7. Figure 7a indicates that the top three causes were HUB07 (frequency 23), UC01 (18), and HUB06 (18). UA01 (15) in unsafe actions, UC01 (18) in unsafe conditions, HUB07 (23) in habitual behaviors, SMS01 (7) in the safety management system, and SC05 (17) in safety culture have the highest frequency in corresponding categories. Figure 7b shows that the number of causative factors with low frequency was higher than those with high frequency. The frequency of most causative factors was 1–8.

Therefore, it is necessary to strengthen the control of high-frequency causative factors, especially those for investigating and rectifying fire safety hazards.

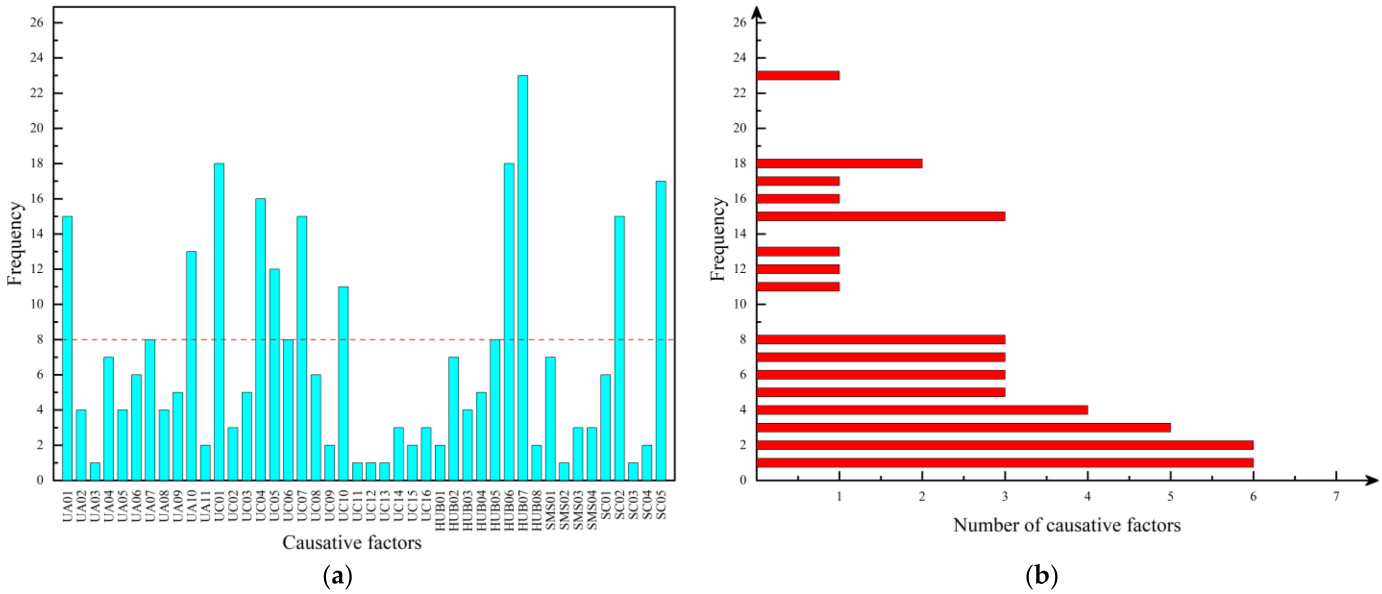


Figure 7. Frequency distribution of causative factors. (**a**) Frequency of causative factors; and (**b**) the number of causative factors corresponding to the frequency.

3.3. DEMATEL Analysis Results

3.3.1. Direct Influence Matrix

We obtained SBHFA causative factors' direct influence matrix M using the directed edge list transformation, as shown in Figure 8. The relationships with greater influence strength were SC05 → HUB06 (influence strength is 11), HUB07 → UC01 (11), SC02 → HUB07 (9), and HUB07 → UA10 (8).

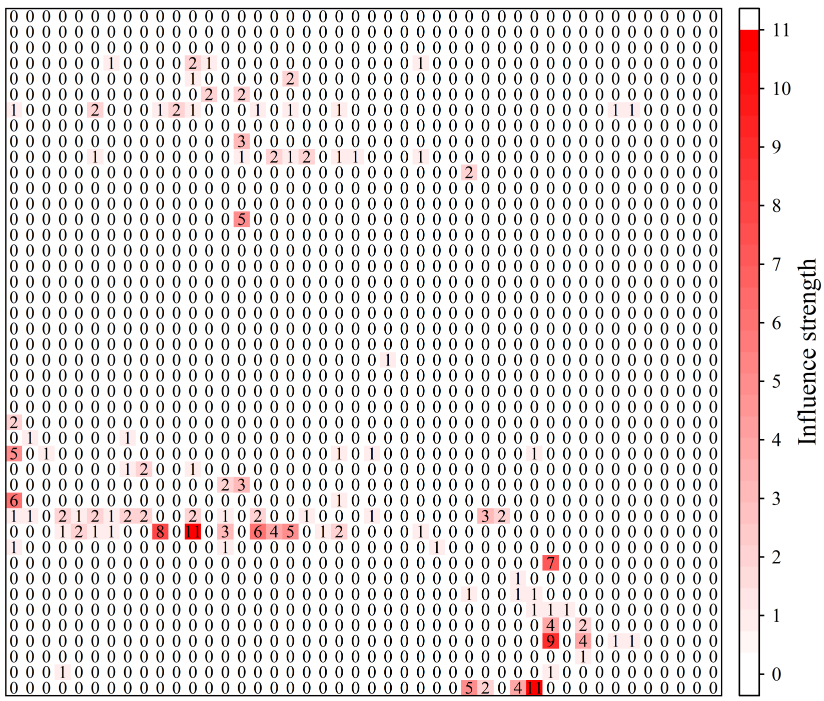
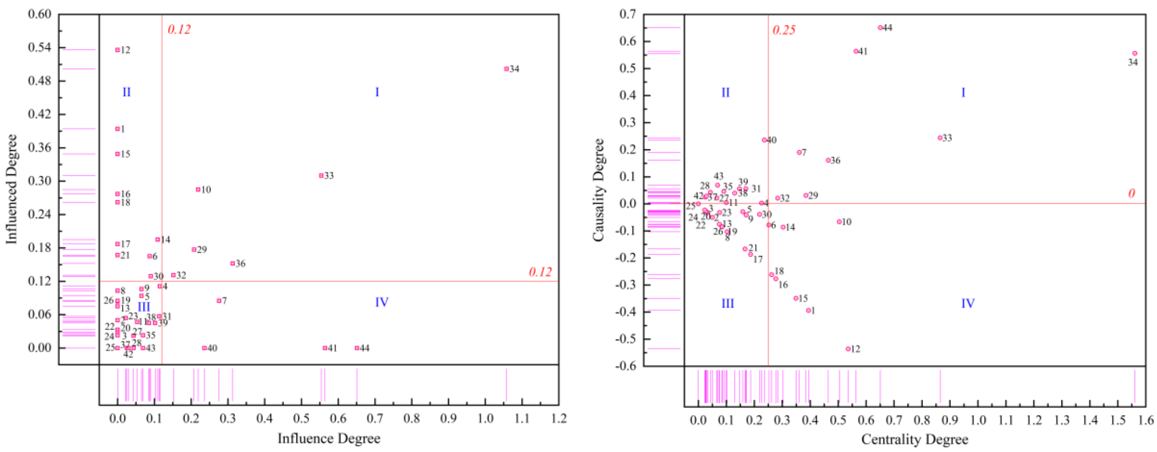


Figure 8. Direct influence matrix M.

Therefore, it is necessary to carry out public fire safety awareness and education to improve residents' fire safety. The safety management departments need to pay attention to the daily fire safety management, conduct fire safety hidden danger inspections and rectification, promote standardized storing of flammable materials, and reduce illegal reconstruction.

3.3.2. Causality and Centrality Analysis of Causative Factors

The direct influence matrix M of SBHFA causative factors was normalized according to Equation (1) to obtain the normalized direct relation matrix N (Figure A1 in Appendix B). Then the comprehensive influence matrix T (Figure A2 in Appendix B) of SBHFACFs was obtained according to Equation (2). From Equations (3) and (4), influenced factors, as well as the influence, causality, and factors' degree of centrality (Table A2 in Appendix A), were obtained and shown in Figure 9.



(**a**) (**b**)

Figure 9. Index relation diagram of SBHFA causes. (**a**) Influence–affected diagram, and (**b**) cause–effect diagram.

Figure 9a shows the relationship between influencing and affected factors of SBHFA. The two red lines are the average values of the degree of influencing and affected factors, both of which are 0.12. The distribution of factors in the third quadrant is relatively concentrated, and both the degree of influence and of being influenced are relatively low. Figure 9b shows the relationship between centrality and causality. The two red lines show the average centrality value of 0.25 and the causality value of 0. The distribution of factors with a centrality of less than 0.25 and causality of −0.1 to 0.1 is relatively concentrated, indicating that the centrality and causality of most causative factors were small.

In Figure 9a, factors 34 (HUB07), 33 (HUB06), 10 (UA10), 36 (SMS01), 29 (HUB02), and 32 (HUB05) in the first quadrant show a high degree of influence and being influenced, indicating that these factors had a strong impact on other factors, were affected by other factors, and had a strong intermediary role in the causal transmission. In the second quadrant, factors 12 (UC01), 1 (UA01), 15 (UC04), 16 (UC05), 18 (UC07), and 14 (UC03) had a low degree of influence, but a high degree of being influenced, indicating they were strongly affected by other factors. In the fourth quadrant, factors 44 (SC05), 41 (SC02), 7 (UA07), and 40 (SC01) were less influenced but showed a high degree of influence on other factors, indicating their strong impact.

As shown in Figure 9b, the above factors were distributed in the first and fourth quadrants except for 40 (SC01), indicating that these factors had high centrality and importance. Among them, the causality degree of factors 44 (SC05), 41 (SC02), 34 (HUB07), 40 (SC01), 33 (HUB06), 7 (UA07), 3601), 29 (HUB02), and 32 (HUB05) was positive, meaning that they had a significant impact on other factors and were important root causes of accidents. The causality degree of factors 10 (UA10), 14 (UC03), 18 (UC07), 16 (UC05), 15 (UC04), 1 (UA01), and 12 (UC01) was negative, which means they were result factors and important direct factors that caused accidents.

From these results, we can conclude that the most critical factors in fire prevention and fire safety management of China's rural self-built housing requiring long-term commitment are actively raising fire safety awareness and education 44 (SC05), carrying out the daily fire safety management 41 (SC02), and conducting the fire safety hidden danger inspections and rectifications 34 (HUB07). In the short term, the most important direct factors that require immediate attention include the standardized storage of flammable substances 12 (UC01), adopting correct fire extinguishing measures and escape methods 1 (UA01), and regularly inspecting and repairing circuits 15 (UC04).

3.4. AISM Analysis Results

3.4.1. Adversarial Hierarchy Extraction

The average value α of all elements of the comprehensive influence matrix T was 0.0028, the standard deviation β was 0.0147, according to Equation (5), and the threshold value λ was 0.0175. According to Equation (6), the comprehensive influence matrix T was processed to construct the adjacency matrix A (Figure A3 in Appendix B). The multiplicative matrix O (Figure A4 in Appendix B) was obtained according to Equation (7), and the reachable matrix R was finally obtained according to Equation (8), as shown in Figure 10.

1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0	1	1	0	0	0	0	0
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1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0	1	1	0	0	0	0	1

Figure 10. Reachable matrix R.

The reachable set K, the antecedent set X, and the intersection set G (Table A3 in Appendix A) were obtained by analyzing the reachable matrix R. Using the extraction method of UP and DOWN types of hierarchies, two hierarchical division results were obtained, as shown in Table 2.

Table 2. Adversarial hierarchy extraction results.

Level	Result First—Type UP	Reason First—Type DOWN
1	UA01, UA02, UA03, UA08, UC01, UC02, UC04, UC05, UC06, UC07, UC08, UC09, UC10, UC11, UC13, UC14, UC15	UA01, UC02, UC04
2	UA05, UA06, UA09, UC03, UC12, UC16, HUB01, HUB05	UA06, UA08, UA09, UC01, UC03, UC06, UC07, UC08, UC10, UC11, UC13, UC15, UC16
3	UA10, HUB03, HUB04, HUB08, SMS02	UA02, UA03, UA05, UA10, UC05, UC09, UC12, HUB03, HUB04, HUB05, HUB08
4	UA04, UA07, UA11, HUB02, HUB06, HUB07, SMS03, SMS04	UA04, UA07, UA11, HUB02, HUB06, HUB07, SMS03, SMS04
5	SMS01, SC04, SC05	SMS01
6	SC01, SC02, SC03	SC01, SC02, SC03, SC04, SC05, SMS02, HUB01, UC14

3.4.2. Matrix Topology Operation Results

Factors UA04, UA07, UA11, HUB02, HUB06, HUB07, SMS03, and SMS04 showed strong connection in the reachable matrix R. Only the factor UA04 was retained to form the reduced reachable matrix R' (Figure A5 in Appendix B). According to Equation (9), we obtained the skeleton matrix S (Figure A6 in Appendix B) and then, according to the method in AISM, obtained the general skeleton matrix S', as shown in Figure 11. It can be seen that the causal relationship between factors was sparse.

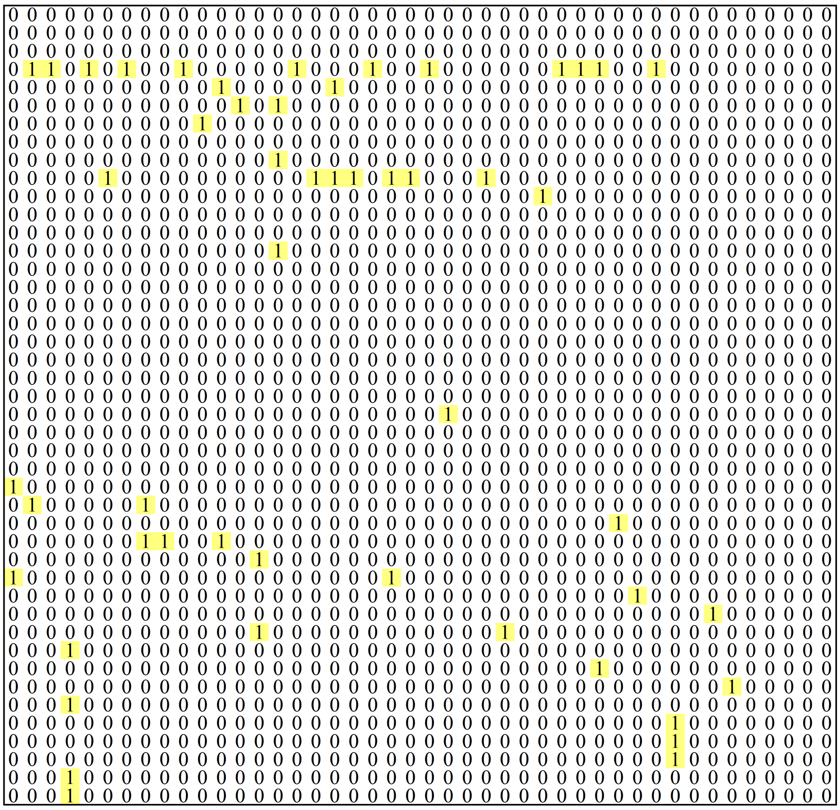
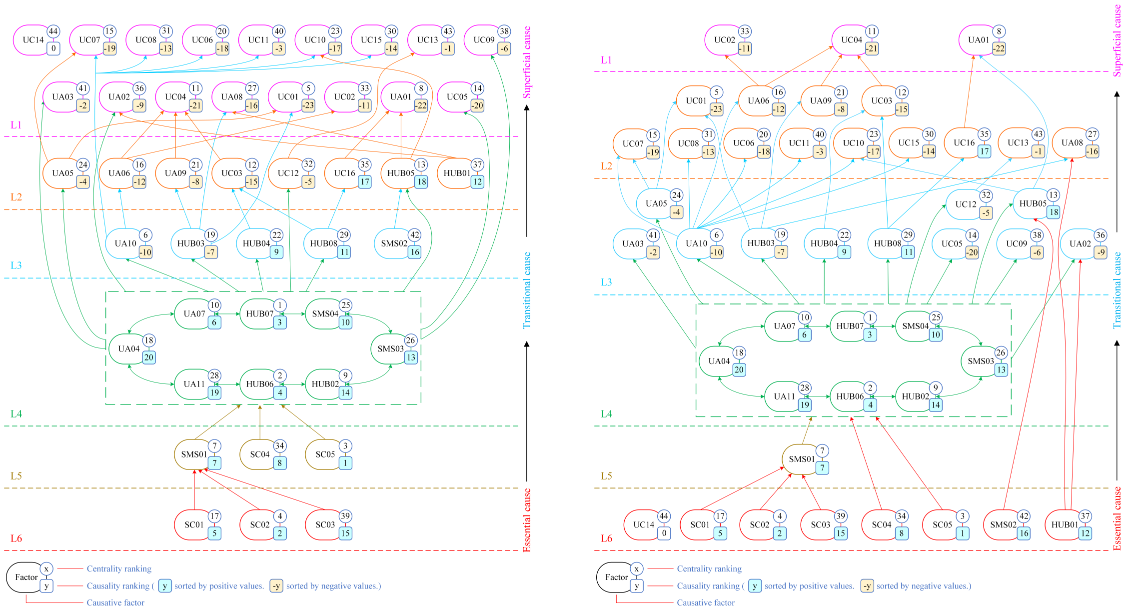


Figure 11. General skeleton matrix S′.

3.4.3. Adversarial Multi-Level Hierarchical Structure Model Analysis

On the basis of the association between factors in the general skeleton matrix S' and the hierarchical extraction results of UP type and DOWN type, the hierarchical structure diagrams of UP-type and DOWN-type were obtained, as shown in Figure 12. After comparing these hierarchical diagrams, we found that the directional line segments of each factor pointed in the same direction, and the hierarchy division was essentially the same.



(**a**) (**b**)

Figure 12. Adversarial-directed topology hierarchy diagram. (**a**) UP-type-directed topology hierarchy, and (**b**) DOWN-type-directed topology hierarchy.

- Activity system of extension

The system with active factors is called an activity system. The system without active factors is called a rigid system or topological rigid system. As shown in Figure 12, many factors jump between different system levels; for example, the factor HUB01 transitions from L2 to L6. These are active factors, and the system is an extension variable system.

- Loop analysis

The circuit is also called a strong connection. We found loops in the antagonism level topology diagram of UA04, UA07, UA11, HUB02, HUB06, HUB07, SMS03, and SMS04 closely related to each other that could be divided into a subsystem. Therefore, when conducting SBHFAs control, the above loop factors should be controlled by integrated management to improve management effectiveness.

- Analysis of isolated factors

It can be seen from Figure 12 that no directed lines connect UC14 and other factors; that is, UC14 was not influenced and did not affect relationships with other factors. From the perspective of comprehensive impact matrix T, the values of the row and column corresponding to UC14 should be less than the threshold value λ. It can be seen from the confrontation hierarchy that the interaction between UC14 and other factors in the system was the weakest, and so was the impact.

- Hierarchical analysis and full-series causal analysis

The system was a six-level topological structure in which the directed line segment was the cause and the result. After removing the isolated factors in Figure 12, the remaining factors corresponding to the level constituted the whole causal series. The two complete causal series were inconsistent, which was also characteristic of the activity system.

- Analysis of essential layer factors, transition layer factors, and surface layer factors

The essential layer factors affected other factors and were at the lowest level. From the topological view, the essential layer only emits directed segments. Therefore, the united lowest level factors that removed the isolated factors in the confrontation hierarchy were the essence factors, {SC01, SC02, SC03} ∪ {SC01, SC02, SC03, SC04, SC05, SMS02,

HUB01} = {SC01, SC02, SC03, SC04, SC05, SMS02, HUB01}. The set of factors at the essence level, located at the highest level of the system, could directly or indirectly affect other factors in the system. Essential factors played a leading role in the system and were the most important in SBHFAs. In particular, SC01, SC02, and SC03—three safety culture factors—were always at the intrinsic cause level in the directed topology hierarchy model. These three factors were critical in the entire fire accident causal system and should be controlled.

The transition layer factors sent an upward arrow to affect the upper layer factors and were also affected by the essential layer. There were many factors at the transition layer in the system, covering four levels, with a total of 21 factors. The transition layer factors were the core causes of SBHFAs. They were located in the middle of the increasing level of the whole system and played the role of connecting links between the levels. They need to be given priority in the prevention of SBHFAs.

The characteristics of the surface factors at the top level did not affect other factors. Therefore, the union of the uppermost factors, excluding isolated factors in the confrontation hierarchy, were {UA01, UA02, UA03, UA08, UC01, UC02, UC04, UC05, UC06, UC07, UC08, UC09, UC10, UC11, UC13, UC15} ∪ {UA01, UC02, UC04} = {UA01, UA02, UA03, UA08, UC01, UC02, UC04, UC05, UC06, UC07, UC08, UC09, UC10, UC11, UC13, and UC15}. Surface factors had the most direct influence on SBHFAs, directly causing fires. Other factors could affect the whole system through the surface factor layer, leading to accidents. In particular, UA01, UC02, and UC04 were three individual factors that were always in the surface cause in the directed topology hierarchy model and were important direct factors that led to the SBHFAs. Strengthening the control of these factors would rapidly and significantly reduce the accident rate.

3.5. MICMAC Analysis Results

From the reachable matrix R and Equation (10), we obtained the driving force and dependency degree of SBHFA causative factors (Table A4 in Appendix A). The greater the driving force, the greater the impact of one factor on the others, and the greater the impact, the greater the dependency. As can be seen from Figure 13, SBHFACFs could be classified based on driving force and dependency.

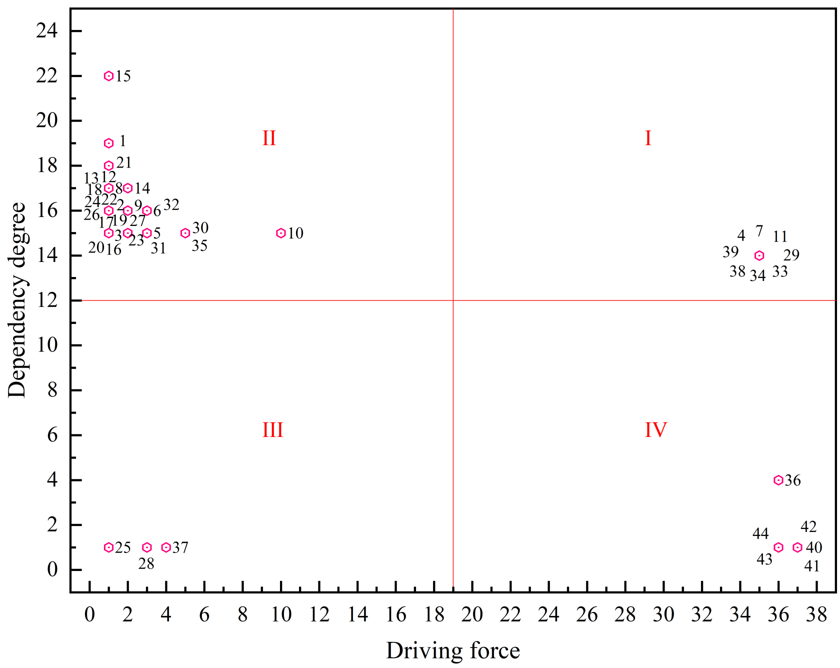


Figure 13. SBHFACFs classification based on driving force and dependency.

- Linkage factors

The linkage factors (the first quadrant) include 4 (UA04), 7 (UA07), 11 (UA11), 29 (HUB02), 33 (HUB06), 34 (HUB07), 38 (SMS03), and 39 (SMS04), all of which had a strong driving force and dependency. They showed high instability and were difficult to control.

- Dependency factors

In the second quadrant, the factors with greater dependency degree included 15 (UC04), 1 (UA01), 21 (UC10), 13 (UC02), 12 (UC01), 18 (UC07), 8 (UA08), 14 (UC03), and others. These factors were the most direct causes of SBHFAs. Their occurrence was dependent on whether other factors were controlled. They could be improved with the resolution of other factors.

- Autonomous factors

The autonomous factors (the third quadrant) included 25 (UC14), 28 (HUB01), and 37 (SMS02), which had a small degree of dependency and driving force, but played a role in connecting the surface and essential layer factors. The relationship between them and other factors was simple and targeted risk control strategies should be proposed.

- Independent factors

The independent factors (fourth quadrant) included 36 (SMS01), 40 (SC01), 41 (SC02), 42 (SC03), 43 (SC04), and 44 (SC05). These factors had a high driving force and were the root causes of SBHFAs. They were not easily constrained by other factors and could not be eliminated by addressing them. Therefore, taking the lead in addressing such factors would be more conducive to managing the others.

4. Discussion

In this study, we used the 24Model to identify causative factors and their relationships. Using DEMATEL analysis, we obtained SBHFA causal and outcome factors, as well as the causative factors' attributes and the rank of their importance in the entire causal system. The adversarial hierarchical topology of SBHFA causative factors was obtained using AISM analysis, and the set of root causative factors in the essential layer, the set of intermediate causative factors in the transition layer, and the set of direct causative factors in the surface layer were analyzed. The role and status of SBHFA causative factors in the system were analyzed through MICMAC. From the results of the above analyses, reasonable key causative factors could be obtained, and targeted measures could be selected to control them to effectively reduce the occurrence of accidents.

Comparing the results of DEMATEL and AISM, it was found that there was a significant relationship between the factor's causality degree factor and its hierarchy. The greater the factor's positive causality degree, the lower its position in the hierarchical structure model and the stronger its causal attribute. The smaller the factor's causality degree of a negative value, the higher its position in the hierarchical structure model and the stronger its result attribute. However, there was no significant correlation between the centrality of causative factors and their hierarchy; the centrality of a factor was obtained by adding the degrees of its attributes of influence and being influenced, which weakened its causal attribute and made its relationship with the hierarchical structure model expressing the path of causal relationship weak [29,30]. The above discussion shows that the causal attributes of factors obtained by the DEMATEL and the AISM methods support each other.

We validated our results by comparing the adversarial hierarchical topology model obtained by AISM analysis with the causative factor groups divided by the MICMAC method [27]. We found that the causative factors of the surface layer in AISM were all distributed in the second quadrant (dependent factors), shown in Figure 13. Most of the causative factors in the essential layer of AISM were distributed in the fourth quadrant (independent factors). The loop contributing factors in the transition layer completely corresponded to the first quadrant (linkage factors). The isolated factor UC14 was distributed in the third quadrant (autonomous factors). The analyses confirmed that the MICMAC results were consistent with the AISM confrontation hierarchical topology analysis results, indicating that the causal relationship between the causative factors was logical.

Causative factors with a large causality degree (positive value) and a large centrality degree at the essential layer were key root causative factors. By analyzing Figures 9 and 12, we concluded that the key root causative factors were SC05 and SC02. The key direct causative factors were those at the surface layer, with a low causality degree (negative value) and significant centrality degree. We further concluded that the key direct causative factors were UC04, UC01, and UA01. The key transition causative factors in the transition layer showed high centrality and causality degree (positive value). The key transition contributing factors were HUB06 and HUB07.

Electrical circuit failure (UC04) in unsafe conditions was the direct cause of the ignition of combustibles. According to China's Fire and Rescue Administration statistics, in 2021, electrical fires accounted for the highest proportion of residential fires [2]. Their main cause was the ignition of combustible materials due to electrical circuit faults [6,31]. In addition, this study also found that improper storage of large quantities of flammable materials (UC01) produced large amounts of toxic and harmful gases that helped the spread of fires. Improper fire extinguishing measures and escape methods (UA01) resulted in unsafe actions and caused the spread of fire and rescue failure. Fire safety evacuation was significant in preventing casualties and played a positive role in developing social health and stability [32–34]. The lack of attention to daily fire safety management (SC02) was the key root cause of inadequate fire hazard screening and rectification (HUB07). Poor promotion and fire safety education (SC05) was the key root cause of the inadequate knowledge of fire safety (HUB06) among rural residents [8]. Innovating and improving electrical appliances and strengthening fire safety education for high-risk groups could reduce the occurrence of residential fires [35]. Therefore, in the fire safety management of self-build housing in rural areas of China, key fire causes should be given special attention. Controlling the key direct causes is an important short-term fire safety measure. Effective long-term fire countermeasures will require continuous emphasis on the key root causative factors, and the control of the key transitional causative factors will be needed for a fast and effective countermeasure to block the transmission of causal pathways.

5. Conclusions

The fire safety problems of self-build housing in China's rural areas are serious and threaten the lives and property of rural residents. In order to explore the logical relationship between SBHFA causes, identify key causative factors, and improve fire safety management capability, this study analyzed 30 SBHFA survey reports using 24Model, encoding 44 causative factors and 97 causal relationships. Using the DEMATEL method, the causal attributes and importance of causative factors were obtained and ranked. Using AISM, an adversarial hierarchical topology model of SBHFA causative factors was constructed, and the logical relationships between causative factors and the characteristics of causal systems were analyzed. The driving forces and dependencies between causes were calculated using the MICMAC method and divided into four groups. By comparing and analyzing the results, the rationality of the model was verified, and the key causative factors were obtained.

This study found that the key direct causes of fires were improper fire extinguishing measures and escape methods (UA01), improper storage of large quantities of flammable materials (UC01), and electrical circuit failures (UC04). The key transition causative factors were weak fire safety awareness (HUB06) and inadequate rectification of the fire hazard inspection (HUB07). The key root causative factors were inadequate attention to daily fire safety management (SC02) and low fire safety public awareness and education (SC05). Through effective and reasonable control of these critical factors, the incidence of accidents can be reduced.

However, because of the limitations of Internet resources, the number of accident investigation reports in this study was insufficient. The information contained in the accident investigation reports was not comprehensive enough to account for the education level of those who died in fires, the time and season of the fires, and the impact of the external social and economic environments. In the future, more information can be obtained by visiting rural areas, and various factors can be comprehensively considered to improve the accuracy of research conclusions. With the gradual popularization of broadband networks in rural areas of China, we can also explore the use of the Internet of Things and image recognition technology to identify and control unsafe conditions in self-build housing in the future.

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Appendix A

The tables calculated by DEMATEL, AISM, and MICMAC methods.

Table A1. List of directed edges between SBHFA causative factors.

Source	Target	Weight	Source	Target	Weight	Source	Target	Weight
UC16	UA01	2	SMS04	HUB08	1	HUB07	UA10	8
UC12	UC13	1	SMS03	HUB02	1	HUB07	UC01	11
UC03	UC04	5	SMS03	HUB05	1	HUB06	UA01	1
UA11	HUB02	2	SMS03	HUB06	1	HUB06	UA02	1
UA10	UA06	1	SMS02	HUB05	1	HUB06	UA05	1
UA10	UC04	1	SMS01	HUB07	7	HUB06	UA07	1
UA10	UC07	1	SC05	HUB03	2	HUB06	UC03	1
UA10	UC10	1	SC05	HUB05	4	HUB06	UC08	1
UA10	UC11	1	SC05	HUB02	5	HUB06	UC12	1
UA10	UC15	1	SC05	HUB06	11	HUB06	HUB04	2
UA10	UC06	2	SC04	HUB07	1	HUB06	UA04	2
UA10	UC08	2	SC04	UA04	1	HUB06	UA06	2
UA09	UC04	3	SC03	SMS01	1	HUB06	UA08	2
UA07	SMS03	1	SC02	SMS03	1	HUB06	UA09	2
UA07	SMS04	1	SC02	SMS04	1	HUB06	UC01	2
UA07	UA01	1	SC02	SMS01	4	HUB06	UC05	2
UA07	UA10	1	SC02	HUB07	9	HUB06	HUB03	3
UA07	UC01	1	SC01	SMS01	2	HUB05	UC10	1
UA07	UC05	1	SC01	HUB07	4	HUB05	UA01	6
UA07	UC07	1	HUB08	UA01	1	HUB04	UC03	2
UA07	UC10	1	HUB08	UC03	1	HUB04	UC04	3
UA07	UA06	2	HUB08	UC16	1	HUB03	UA08	1
UA07	UA11	2	HUB07	UA04	1	HUB03	UC01	1

Table A1. *Cont.*

Source	Target	Weight	Source	Target	Weight	Source	Target	Weight
UA06	UC02	2	HUB07	UA06	1	HUB03	UA09	2
UA06	UC04	2	HUB07	UA07	1	HUB02	HUB06	1
UA05	UC01	1	HUB07	UC09	1	HUB02	UA03	1
UA05	UC07	2	HUB07	UC15	1	HUB02	UC10	1
UA04	UA07	1	HUB07	UA05	2	HUB02	UC12	1
UA04	UC02	1	HUB07	UC10	2	HUB02	UA01	5
UA04	UC15	1	HUB07	UC03	3	HUB01	UA02	1
UA04	UC01	2	HUB07	UC06	4	HUB01	UA08	1
SMS04	HUB06	1	HUB07	UC07	5			
SMS04	HUB07	1	HUB07	UC05	6			

Table A2. DEMATEL calculates the index value of causative factors.

Factor	Influence Degree	Influenced Degree	Centrality	Causality
UA01	0	0.394	0.394	−0.394
UA02	0	0.05	0.05	−0.05
UA03	0	0.026	0.026	−0.026
UA04	0.115	0.111	0.226	0.003
UA05	0.065	0.094	0.159	−0.029
UA06	0.087	0.165	0.252	−0.078
UA07	0.276	0.085	0.361	0.19
UA08	0	0.103	0.103	−0.103
UA09	0.065	0.106	0.171	−0.041
UA10	0.219	0.285	0.504	−0.066
UA11	0.053	0.047	0.1	0.005
UC01	0	0.536	0.536	−0.536
UC02	0	0.075	0.075	−0.075
UC03	0.109	0.195	0.303	−0.086
UC04	0	0.349	0.349	−0.349
UC05	0	0.277	0.277	−0.277
UC06	0	0.187	0.187	−0.187
UC07	0	0.262	0.262	−0.262
UC08	0	0.084	0.084	−0.084
UC09	0	0.033	0.033	−0.033
UC10	0	0.167	0.167	−0.167
UC11	0	0.028	0.028	−0.028
UC12	0.022	0.054	0.076	−0.032
UC13	0	0.023	0.023	−0.023
UC14	0	0	0	0
UC15	0	0.085	0.085	−0.085
UC16	0.043	0.022	0.066	0.021
HUB01	0.043	0	0.043	0.043
HUB02	0.208	0.177	0.385	0.031
HUB03	0.09	0.129	0.219	−0.039
HUB04	0.113	0.057	0.17	0.056
HUB05	0.152	0.131	0.284	0.021
HUB06	0.554	0.31	0.865	0.244
HUB07	1.058	0.502	1.561	0.556
HUB08	0.069	0.023	0.091	0.046
SMS01	0.313	0.152	0.465	0.161
SMS02	0.025	0	0.025	0.025
SMS03	0.085	0.045	0.13	0.04
SMS04	0.102	0.045	0.147	0.056
SC01	0.236	0	0.236	0.236
SC02	0.564	0	0.564	0.564
SC03	0.029	0	0.029	0.029
SC04	0.069	0	0.069	0.069
SC05	0.651	0	0.651	0.651

Table A3. Reachable set and antecedent set of factors.

Factor	Reachable Set K	Antecedent Set X	Intersection Set G
UA01	1	1, 4, 7, 11, 27, 29, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44	1
UA02	2	2, 4, 7, 11, 28, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	2
UA03	3	3, 4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	3
UA04	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
UA05	5, 12, 18	4, 5, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	5
UA06	6, 13, 15	4, 6, 7, 10, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	6
UA07	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
UA08	8	4, 7, 8, 11, 28, 29, 30, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	8
UA09	9, 15	4, 7, 9, 11, 29, 30, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	9
UA10	6, 10, 13, 15, 17, 18, 19, 21, 22, 26	4, 7, 10, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	10
UA11	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
UC01	12	4, 5, 7, 11, 12, 29, 30, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	12
UC02	13	4, 6, 7, 10, 11, 13, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	13
UC03	14, 15	4, 7, 11, 14, 29, 31, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44	14
UC04	15	4, 6, 7, 9, 10, 11, 14, 15, 29, 30, 31, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44	15
UC05	16	4, 7, 11, 16, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	16
UC06	17	4, 7, 10, 11, 17, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	17
UC07	18	4, 5, 7, 10, 11, 18, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	18
UC08	19	4, 7, 10, 11, 19, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	19
UC09	20	4, 7, 11, 20, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	20
UC10	21	4, 7, 10, 11, 21, 29, 32, 33, 34, 36, 37, 38, 39, 40, 41, 42, 43, 44	21
UC11	22	4, 7, 10, 11, 22, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	22
UC12	23, 24	4, 7, 11, 23, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	23
UC13	24	4, 7, 11, 23, 24, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	24
UC14	25	25	25
UC15	26	4, 7, 10, 11, 26, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	26
UC16	1, 27	4, 7, 11, 27, 29, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44	27

Table A3. *Cont.*

Factor	Reachable Set K	Antecedent Set X	Intersection Set G
HUB01	2, 8, 28	28	28
HUB02	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
HUB03	8, 9, 12, 15, 30	4, 7, 11, 29, 30, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	30
HUB04	14, 15, 31	4, 7, 11, 29, 31, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	31
HUB05	1, 21, 32	4, 7, 11, 29, 32, 33, 34, 36, 37, 38, 39, 40, 41, 42, 43, 44	32
HUB06	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
HUB07	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
HUB08	1, 14, 15, 27, 35	4, 7, 11, 29, 33, 34, 35, 36, 38, 39, 40, 41, 42, 43, 44	35
SMS01	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 36, 38, 39	36, 40, 41, 42	36
SMS02	1, 21, 32, 37	37	37
SMS03	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
SMS04	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39	4, 7, 11, 29, 33, 34, 36, 38, 39, 40, 41, 42, 43, 44	33, 34, 4, 38, 7, 39, 11, 29
SC01	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 36, 38, 39, 40	40	40
SC02	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 36, 38, 39, 41	41	41
SC03	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 36, 38, 39, 42	42	42
SC04	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39, 43	43	43
SC05	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 26, 27, 29, 30, 31, 32, 33, 34, 35, 38, 39, 44	44	44

Table A4. The driving force and dependence of SBHFA causative factors.

No.	Factor	Driving Force	Dependency Degree	No.	Factor	Driving Force	Dependency Degree
1	UA01	1	19	23	UC12	2	15
2	UA02	1	16	24	UC13	1	16
3	UA03	1	15	25	UC14	1	1
4	UA04	35	14	26	UC15	1	16
5	UA05	3	15	27	UC16	2	16
6	UA06	3	16	28	HUB01	3	1
7	UA07	35	14	29	HUB02	35	14
8	UA08	1	17	30	HUB03	5	15
9	UA09	2	16	31	HUB04	3	15

Table A4. *Cont.*

No.	Factor	Driving Force	Dependency Degree	No.	Factor	Driving Force	Dependency Degree
10	UA10	10	15	32	HUB05	3	16
11	UA11	35	14	33	HUB06	35	14
12	UC01	1	17	34	HUB07	35	14
13	UC02	1	17	35	HUB08	5	15
14	UC03	2	17	36	SMS01	36	4
15	UC04	1	22	37	SMS02	4	1
16	UC05	1	15	38	SMS03	35	14
17	UC06	1	16	39	SMS04	35	14
18	UC07	1	17	40	SC01	37	1
19	UC08	1	16	41	SC02	37	1
20	UC09	1	15	42	SC03	37	1
21	UC10	1	18	43	SC04	36	1
22	UC11	1	16	44	SC05	36	1

Appendix B

The matrices calculated by DEMATEL and AISM methods.

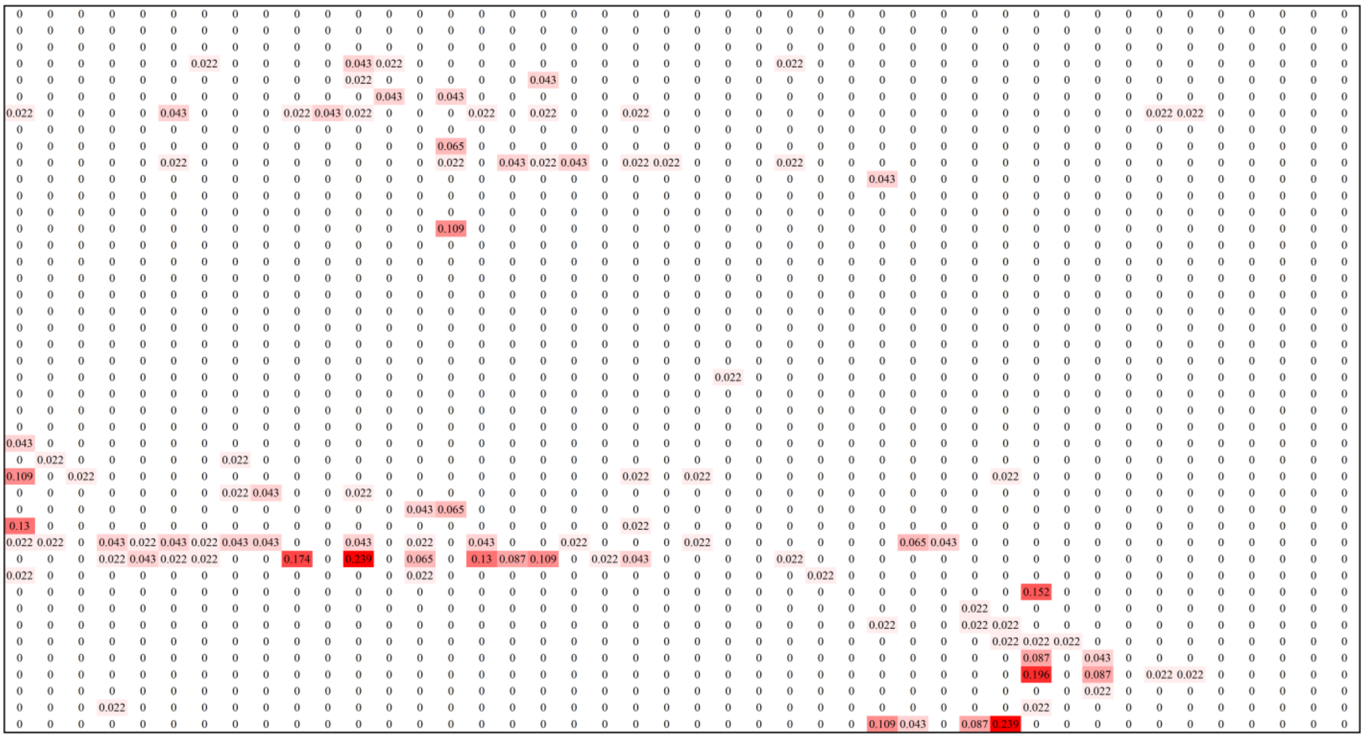

Figure A1. Normalized direct relation matrix *N*. (The darker the color in the matrix, the larger the numerical value).

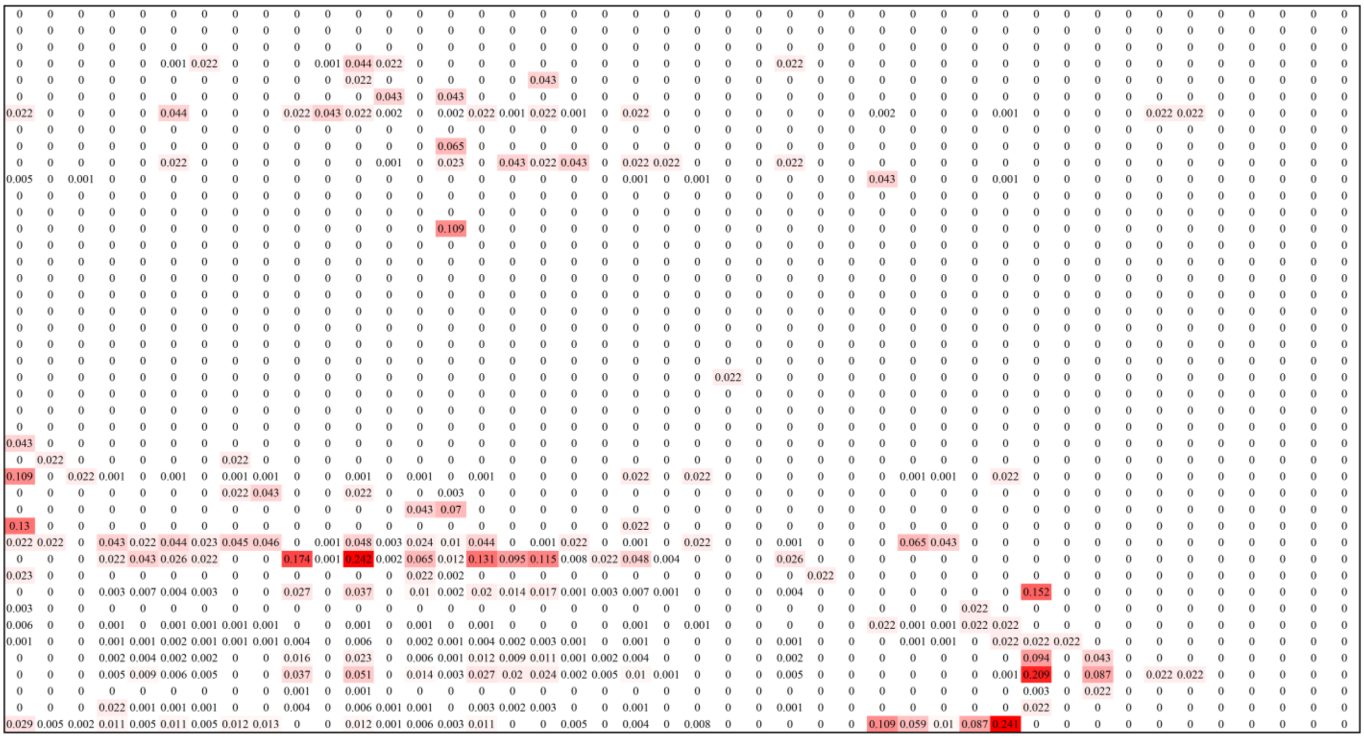

Figure A2. Comprehensive influence matrix *T*. (The darker the color in the matrix, the larger the numerical value).

Figure A3. Adjacency matrix *A*.

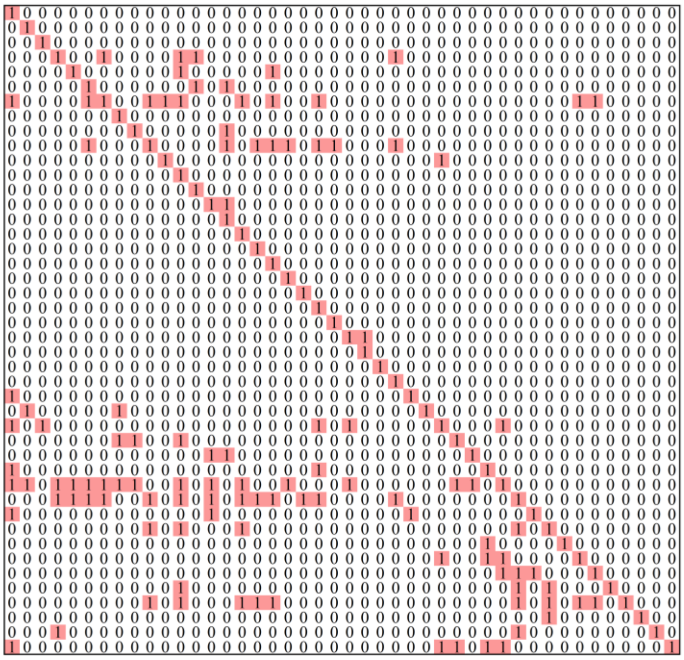

Figure A4. Multiplicative matrix O.

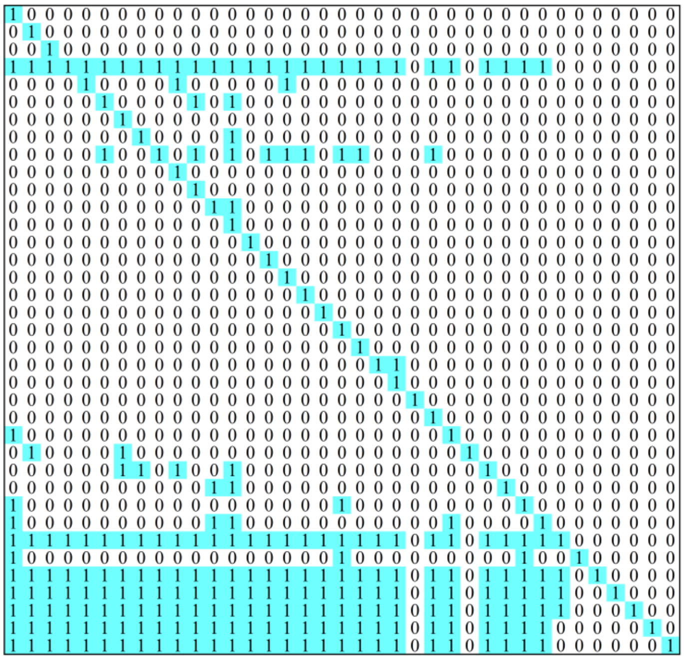

Figure A5. Reduced reachable matrix R'.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure A6. Skeleton matrix *S*.

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