Critical Component Identification Study of Uncontrollable Heating Systems

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Abstract

As a complex thermal network ensuring civil and industrial energy supply, the failure of key components in heating systems can easily trigger cascading failures and large-scale heating outages. Aiming at the high computational complexity of traditional failure-simulation-based methods for key component identification, this study proposes a multi-dimensional index system and identification framework integrating graph-theoretic topology analysis and thermodynamic function evaluation. By constructing a modified betweenness index (topological importance), energy index and residual energy ratio (functional importance), and combining with system flow loss rate and user flow loss entropy (failure consequence indices), a complete quantitative evaluation system is formed. Verification using gridded heating system models with 4 to 25 nodes shows that the Spearman correlation coefficients between the modified betweenness and user flow loss entropy range from 0.82 to 0.93, and those between the energy index and system flow loss rate range from 0.65 to 0.96, with all coefficient of variation values less than 0.1, verifying the effectiveness and stability of the indices. The research results provide theoretical support for the efficient and accurate identification of key components in heating systems.

1 Introduction

As a crucial urban infrastructure, the heating system [1] ensures energy supply for over 800 million residents in northern China and covers a heating area exceeding 30 billion square meters, with its stability directly linked to social well-being and national energy efficiency strategies. Comprising complex networks of heat sources, pipelines, and exchange stations, component failures in such systems can trigger cascading risks [2]. In looped topologies, the hidden criticality of pipeline components further exacerbates safety challenges, necessitating precise identification methods.

Current research on heating system critical component identification lags behind mature lifeline domains such as power grids [3]. Existing approaches including topology-based analysis, fault tree analysis, and analytic hierarchy process (AHP) have made progress but remain limited: topology-based methods using node degree or betweenness [4] centrality overlook dynamic hydraulic parameters like flow and pressure; fault tree analysis relies heavily on historical data [5], struggling to adapt to variable operating conditions; and AHP-based evaluations suffer from subjectivity in weight determination [6]. These methods collectively fail to address the coupling of

structural topology and functional dynamics, such as flow-pressure interactions in heat transfer, thereby hindering identification accuracy for real-world engineering needs.

This study proposes a multi-dimensional identification framework to bridge these gaps. Section 2 deconstructs the structural and functional characteristics of heating systems. Section 3 develops a set of indices, including topological importance, functional contribution, and failure consequence metrics. Section 4 validates the framework across idealized gridded models, demonstrating its capacity to enable efficient critical components identification. The research results aim to provide essential theoretical support and technical approaches for enhancing the safety of heating systems.

2 Critical Heating Components Identification Framework

2.1 Topological and Functional Characteristics of Heating Systems

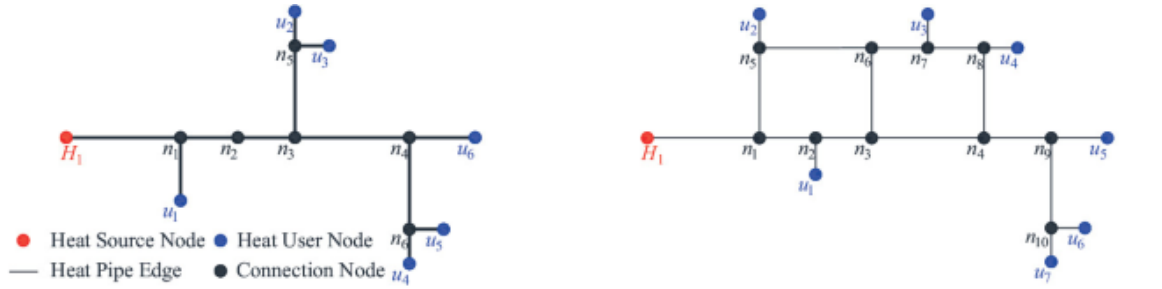
Topological Characteristics.

Topological parameters include connection forms between components, pipe diameters, pipeline lengths, etc. Based on graph theory, the heating system can be abstracted into a planar model G = (N, E), where nodes N represent heat sources, heat exchange stations, and thermal users, and edges E denote pipelines and accessories connecting nodes.

According to connection forms, heating system topologies are classified into branched and looped types (see Fig. 1). In branched structures, nodes connect to the heat source through unidirectional links, forming a tree-like network. This structure is simple and low-cost but has a critical flaw: single-point failures easily cause local heating outages. In contrast, looped structures feature closed-loop pipelines with redundant paths between nodes, endowing the system with fault self-healing capabilities to achieve "local failure without global operation impact". Additionally, actual heating systems typically have node degrees ≤3 (as four-way components significantly increase flow resistance and are rarely used except in small-diameter pipes) [7].

In branched structures, component criticality is easily distinguished: since hot water flows from the heat source downstream along pipelines, upstream component failures affect all downstream components, making upstream components inherently more critical. Looped structures, however, cannot be directly evaluated due to their fault redundancy.

Fig. 1.



(a) Planar model of branched heating system (b) Planar model of looped heating system

Heating systems planar models.

To quantitatively analyze the topology, incidence matrix **A** and loop matrix **B** [8] are constructed based on the planar model. For a heating system consisting of N_n nodes and N_e edges, the incidence matrix $\mathbf{A} = (a_{ij})_{(Nnod-1) \times Nedg}$ mathematically describes system connectivity, and the loop matrix $\mathbf{B} = (b_{kj})_{(Nedg-Nnod-1) \times Nedg}$ characterizes loop properties.

Functional Characteristics.

Functional indices (e.g., flow, temperature) are classified into design parameters and operation parameters. Design parameters represent the maximum functional values the system can achieve and guide system planning. Operation parameters, dynamically adjusted according to real-time outdoor conditions and actual user demands, reflect the system's actual operational performance. Notably, operation parameters are further divided into normal and fault parameters, with the latter significantly influenced by system controllability.

System controllability depends on the response speed and control accuracy of regulating devices. Most existing Chinese heating systems, due to long service years, have low controllability and are treated as completely uncontrollable in this study.

Assuming good thermal insulation, heat transmission is simplified as the product of flow and fixed temperature, with flow as the core functional parameter. Based on mass and energy conservation laws, a hydraulic calculation is constructed, seen in Eq. (1). Solved by the Newton-Raphson iteration method, it accurately simulates flow distributions under different conditions, supporting operation scheduling and fault analysis.

(1)

where **M** is the vector of the flow within each pipe, of size b × 1, t/h; **|M|** is the diagonal matrix of absolute pipe flows, of size $N_e \times N_e$, t/h; **Q** is the vector of the flow through each node injected from a source or discharged to a user, of size $(N_n - 1) \times 1$, t/h; **s** is the vector of the resistance coefficients of each pipe, of size $N_e \times N_e$, $Pa/(t/h)^2$.

2.2 Heating Failure Characteristics and Component Importance Identification

Heating System Failure Characteristics and Accident Impacts.

Composed of numerous components, heating systems face multiple risks during operation, with component failures directly threatening structural stability and functional integrity. Statistical analysis of typical heating accidents from 2010 to 2022 (Ref. [1]) reveals the following fault characteristics.

Dominance.of.pipe.faults. Pipe faults is the primary cause of heating incidents.

High.single.fault.rate. Over 90% of accidents are triggered by single-component failures, with the probability of dual-component failures being 1/1000 of single failures.

Heating Component Importance Identification Framework.

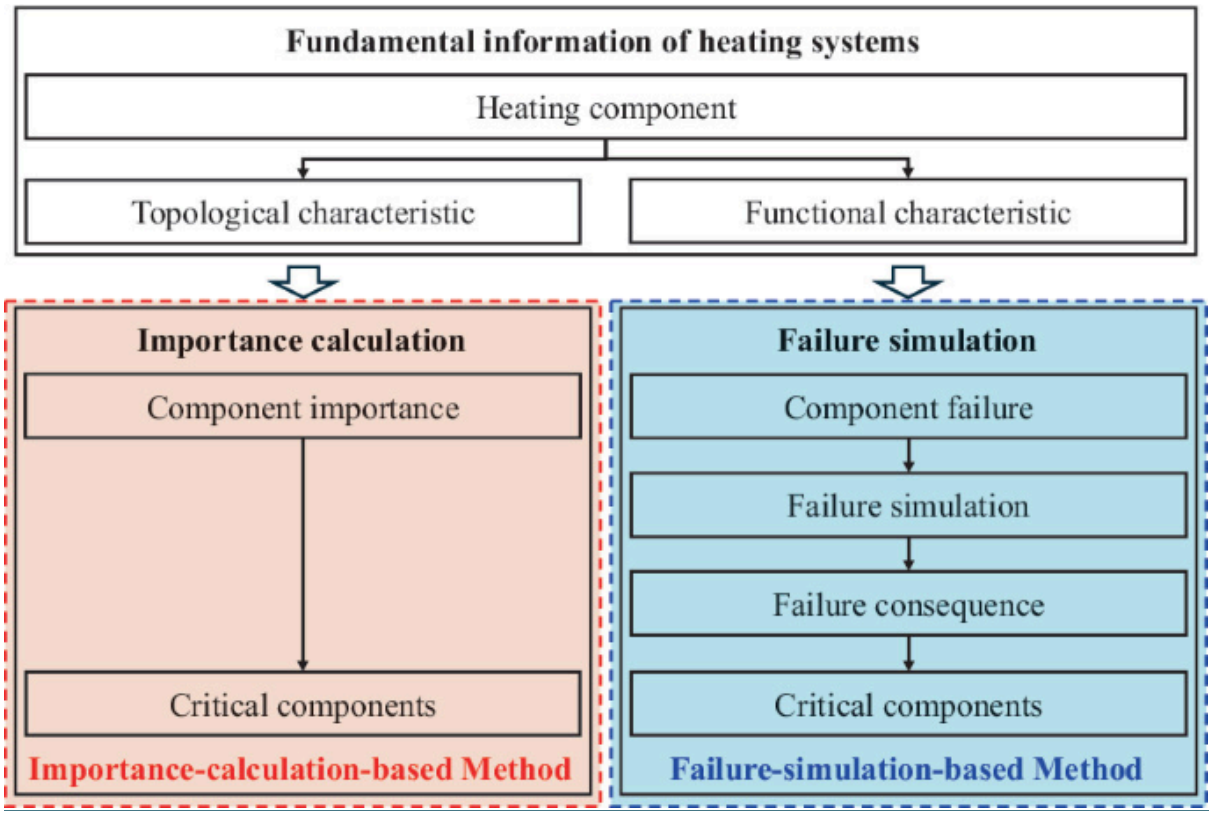
The methods currently used to identify key components can be divided into two categories:

Failure_simulate_based.method.(FSM). Simulate system responses to component failures to evaluate accident impacts directly, identifying components causing severe consequences as critical ones. FSM offers high accuracy but requires extensive single-failure simulation.

Importance_calculation_based.method.(ICM). Calculate component importance indices under normal operation, considering high-importance components as critical. For example, power systems use load magnitude as a key index.

To balance efficiency and accuracy, we take FSM results as the benchmark and compares ICM with FSM to explore suitable importance indices. The identification framework (see Fig. 2) integrates graph-theoretic topology analysis and thermodynamic function evaluation, comprising three modules:

Fig. 2.



Critical component identification framework for heating systems.

Component.importance.index.calculation¡ Based on normal-operation topology and thermal parameters, preliminarily identifies key components using indices like betweenness centrality, flow, and energy.

Failure.consequence.simulation.analysis¡ Simulates system topology and thermal parameter responses to each component failure, calculates consequence indices, and generates a “standard” critical component set.

Comparison.and.optimization¡ Compares ICM and FSM results to optimize indices, achieving rapid and accurate key component identification with balanced efficiency and accuracy.

3 Critical Heating Components Identification Indices

3.1 Components Importance Index

Topological Importance Index.

After simplifying the heating system into a planar model, graph-theoretic metrics (e.g., degree, betweenness, path length) characterize topological features. Degree and betweenness, as local indices, are commonly used to assess component importance. However, node degrees in heating systems are typically restricted to 1–3, making degree indices insufficient for distinguishing component criticality. In contrast, the betweenness index, calculated as the proportion of shortest paths passing through a

component, reflects its core role in network connectivity and is more suitable for key component identification.

The traditional betweenness definition, expressed as the ratio of shortest paths through a component to the total shortest paths, is given by Eq. (2):

(2)

where B_k is the betweenness of component k; is the number of shortest paths from node i to node j passing through component k; is the total number of shortest paths from node i to node j; **V** is the set of nodes;

This study modifies the betweenness:

Node.pair.restriction¡ Only node pairs consisting of heat sources and thermal users are considered to focus on core heat transfer paths.

Basic.path.definition¡ A “basic path” is defined as a source-to-user path that becomes disconnected if any edge is removed, excluding redundant paths.

The modified betweenness, suitable for evaluating topological importance in heating systems, is reconstructed based on all basic paths between source-user node pairs:

(3)

where T_k is the modified betweenness of component k; is the number of connected paths from the heat source h to the heat user u through the element k; is the total number of connected paths from the heat source h to the heat user u.

Functional Importance Index.

Assuming good thermal insulation and uniform network temperature, flow distribution intuitively reflects the system’s energy supply capacity. Components with higher flow rates, undertaking more heat transfer tasks, are evaluated using inflow as the basic functional index:

(4)

where F_k is the functional importance index of component k; $Q_{in,k}$ is the flow into component k, t/h;

Additionally, energy index combining pressure and flow comprehensively reflects component functionality, defined as the product of pressure and flow. For a heating pipe e, the energy at the inlet is P_1Q_e, and the outlet energy is P_2Q_e. The energy consumption within the pipe E_e is calculated by the product of pressure difference and flow:

(5)

Besides, when the pipe end connects to a heat user, a residual energy ratio index evaluates functional efficiency is been defined as shown in Eq. (6):

(6)

When the pipe end has no user connection, the residual energy ratio is:

(7)

The residual energy ratio index quantifies component effectiveness in heat distribution, supplementing functional importance evaluation.

3.2 Failure Consequence Simulation

Hydraulic Simulation Model.

Neglecting transient fluctuations caused by regulation, the hydraulic calculation model solves for flow distributions under fault conditions based on the system's structural matrix. The failure simulation process is**:** Update the adjacency matrix A_f and loop matrix B_f due to topological changes from component failure; For uncontrollable heating systems, maintain the resistance coefficient matrix s unchanged; Solve for the fault flow $M_{u,f}$ of heat users using the hydraulic model (Eq. (1)) for consequence evaluation:

Failure Consequence Indices.

The core function of heating systems is stable heating supply to end users, so consequence evaluation focuses on user flow loss. Two indices quantify accident impacts:

Network.flow.loss.rate.(KF)¡ From the standpoint of the service quantity provided by heating systems, the network flow loss rate ΔF is defined as the ratio of the decrease in flow after the failures to the output flow before the failures, as depicted in Eq. (8).

(8)

where Q_s is the total output flow of the heating systems before failures; $Q_{s,f}$ is the total output flow of the heating systems under the failure scenario f.

User.flow.loss.entropy.(KI)¡ Based on information entropy theory, the user flow loss entropy ΔI quantifies deviations of actual user flows from design values:

(9)

where ΔI is the user flow loss entropy; $\llcorner Q_{u,f}$ is the flow change value of the u-th user before and after the f-th failure scenario, t/h; $p_{u,f}$ is the flow reduction penalty coefficient of the u-th user under the f-th failure scenario as shown in Eq. (10); is the number of $\llcorner Q_{u,f}$ greater than zero under the f-th failure scenario.

(10)

where θ is the limited heating coefficient.

A larger ΔI indicates more severe disruption to user flow balance.

3.3 Correlation Analysis of Indices

The Spearman rank correlation coefficient measures the consistency between ICM and FSM identification results. For variables X_i and Y_i, their ranks $R(X_i)$ and $R(Y_i)$ are first determined, followed by calculating rank differences $d_i = R(X_i) - R(Y_i)$. Then, using Eq. (11) to compute the Spearman correlation coefficient:

(11)

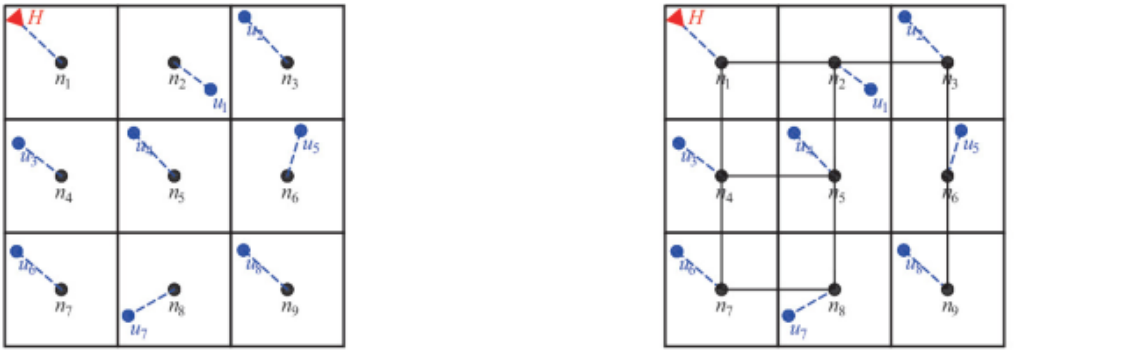
where d_i denotes the rank difference between the two variables in each observation and n represents the number of samples.

4 Verification of Heating Component Importance Indices

4.1 Construction of Idealized Heating System Models

To systematically verify the effectiveness of heating component importance indices under different topological structures, this study constructs gridded heating system models. As shown in Fig. 3(a), the model divides the heating area into grids, with each grid representing an independent heating unit; red dots denote heat stations (heating load points), and red triangles represent heat sources located at the upper-left corner of the heating grid area. Trunk nodes (black dots) are set at grid centers, connected to users via fixed branch lines (blue dashed lines). Based on municipal heating pipeline laying requirements, the following connection constraints for trunk nodes are established:

Fig. 3.



(a) 9-node gridded heating area model (b) 9-node gridded heating system model

Gridded heating system models.

Connection.range.constraint¡ Only adjacent nodes can be connected, and cross-node connection is prohibited. For example, node n_1 can only connect to nod n_2, not directly to node n_3.

Diagonal.connection.rule¡ Diagonal connections (e.g., between node n_1 and n_5) are allowed, but diagonal intersections must be avoided. If n_1 connects to n_5, n_2 cannot connect to n_4.

Node.degree.limitation¡ Considering the scarcity of four-way valves in actual heating systems, node degrees are restricted to ≤4 (degree-4 nodes are treated as simplifications of two adjacent tees).

Connectivity.check¡ After setting node connections, the pipeline network's connectivity is verified, and adjustments are made if requirements are unmet.

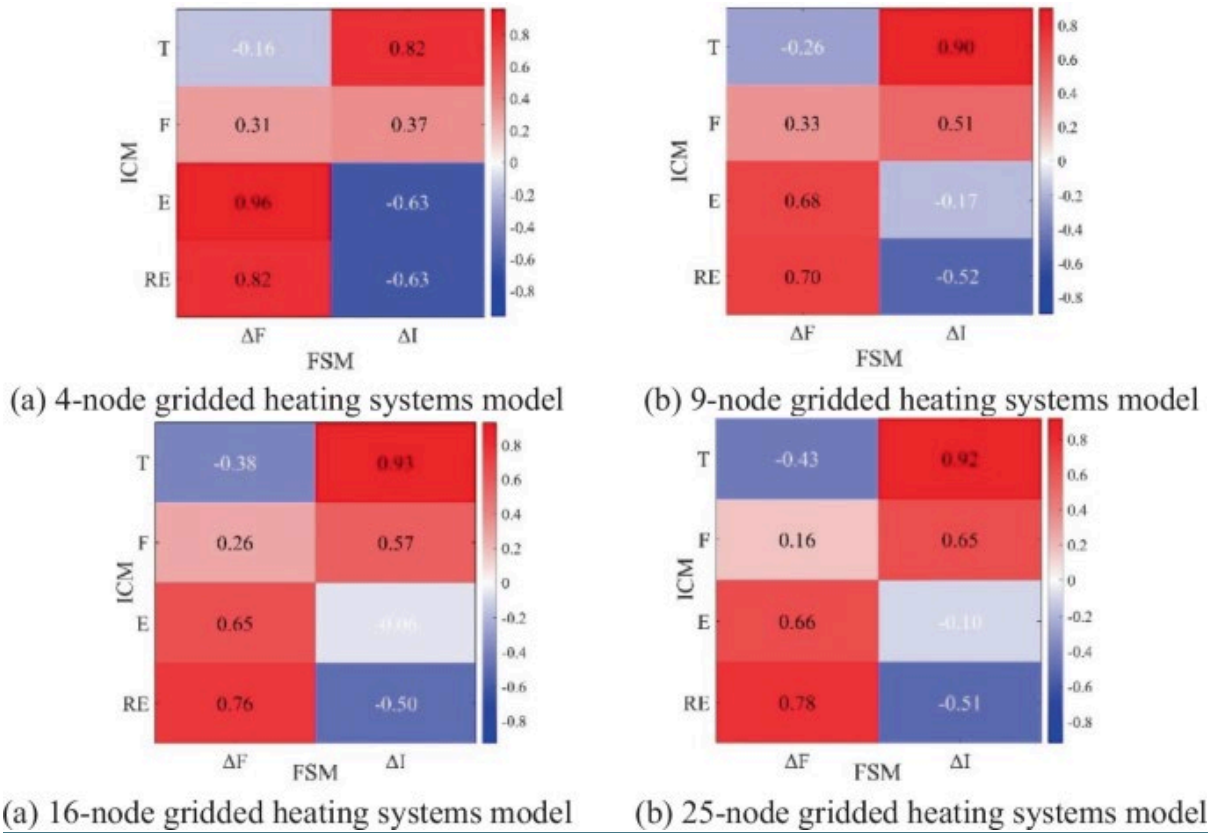
To verify the applicability of heating component importance indices in different-scale systems, this study constructs heating system models with 4, 9, 16, and 25 nodes. And, according to the above connectivity rules, a 9-node heating system model is shown in Fig. 3(b). Based on the above assumptions, a total of 25 4-node, 354 9-node, 1253 16-node, and 4915 25-node heating system models are constructed, forming a verification dataset covering various topological structures.

4.2 Verification Results

Each gridded model is subjected to key component identification using both ICM and FSM, and the Spearman rank correlation coefficient of the identification results is calculated. Since heating system models of the same scale have multiple topological connection forms, this study further calculates the mean of Spearman correlation coefficients for each scale. The average values of correlation coefficients between FSM and ICM for different-scale heating systems are shown in Fig. 4.

As indicated in the figure, the Spearman coefficient between the topological importance index T in ICM and the user flow loss entropy ΔI in FSM ranges from 0.82 to 0.93, demonstrating a high degree of correlation. Besides, among the three functional importance indices, the energy index and residual energy ratio index show higher correlation with the network flow loss rate in FSM: 1) The Spearman correlation coefficient between the energy index and network flow loss rate ranges from 0.65 to 0.96. 2) The Spearman correlation coefficient between the residual energy ratio index and network flow loss rate is more stable, ranging from 0.70 to 0.82. Unexpectedly, the flow index of heating components exhibits a small correlation coefficient with failure consequence indices, suggesting that using the flow data of components under normal operating conditions to distinguish their importance is not very accurate.

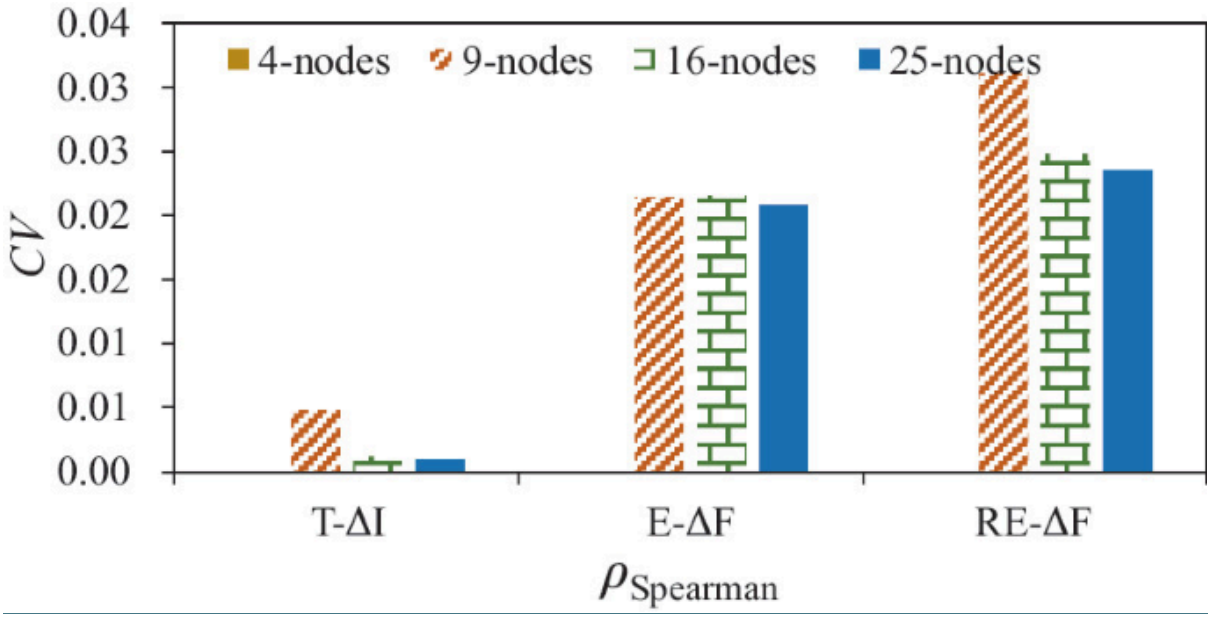
Fig. 4.



Average Spearman correlation coefficients between ICM indices and FSM indices in different-scale gridded heating system models.

The CV values between T-ΔI, E-ΔF and RE-ΔF are shown in Fig. 5.

Fig. 5.



CV values of the correlation coefficients between T-ΔI, E-ΔF and RE-ΔF.

From the figure above, in heating system models of any scale, the CV values of the three Spearman correlation coefficients are all lower than 0.1. This further proves the stability and rationality of using the T index to replace ΔI and using the E or RE indices to replace the ΔF index for identifying critical components in heating systems.

5 Conclusion

Identifying key components of heating systems is of great significance for ensuring heating safety. However, the failure-simulation-based method for identifying critical components is overly complex. Considering this, this study establishes critical component identification indices and proposes a Heating Component Importance Identification Framework based on the structural and functional characteristics of heating systems and component failure characteristics. The rationality of the critical component identification indices is verified by comparing the Failure-Simulate-Based Method (FSM) and Importance-Calculation-Based Method (ICM), improving the rapidity and accuracy of identifying critical heating components. The detailed conclusions of this paper are as follows:

Based on the structural characteristics of heating systems, a modified betweenness index is proposed to measure the importance of heating components from a structural perspective. Based on the functional characteristics of heating systems, energy and residual energy ratio indices are proposed to measure the importance of heating components from a functional perspective.

The applicability of the proposed indices is verified through gridded models of heating systems. The results show that the modified betweenness index has a high correlation with the User Flow Loss Entropy, and the energy and residual energy ratio indices have a high correlation with the Network Flow Loss Rate index. Therefore, the modified betweenness can be used to measure the importance of components in maintaining the uniformity of heat supply to thermal users, and the energy and residual energy ratio indices can be used to measure the importance of components in maintaining the total heat supply to thermal users.

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