Spatial-temporal Data Model for Indoor Fire Response Considering Multi-Factors

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Abstract

The complexity of high-rise building structures and functions significantly increases the challenges in emergency responses to indoor fire incidents. This complexity is due to multiple factors that must be evaluated for decision-making within the fire scenario, such as the entities within the building, the status of environment, and the actions of people. An effective and precise indoor fire emergency management model should fully take into consideration of multiple factors, aiming to ensure the safety and effectiveness of emergency response action.

This paper proposes a spatial-temporal data model to integrate the entity-status-action, for designing the most suitable action strategies in various environmental status by considering all related entities in the indoor fire scenario. Firstly, a list of factors is designed to represent the scenario features including spatial location, semantic description, attribute characteristics, geometric form, evolutionary process, and the relationships among objects. Then, employs an ontology-based descriptive method to integrate multi-dimensions and effectively represents the interrelations among entities, actions, and environmental status within the context of an indoor fire scenario. These environmental status considered in the model focus on the supporting path-planning during execution of direct response actions. Finally, a set of path-planning rules has been developed to infer a series of environmental status supporting to formulate the optimal evacuation strategy to minimize the risk of evacuation failure. The case study shows that the proposed model is effective in unified expression for multitude of factors associated with emergency response in indoor fire scenario and supporting the decision-making of the emergency response actions.

1. Introduction

With the acceleration of urbanization and rapid economic development, the complexity of indoor environments, such as high-rise buildings, underground parking lots, and shopping centers, has significantly increased. These environments have become the predominant settings for daily activities, elevating the importance of managing indoor emergencies. These emergencies pose substantial risks to life, property, and societal progress (Luo et al., 2021; Araujo Lima et al., 2021). Among them, indoor fire emergencies are the most common and severe, necessitating an innovative approach to emergency management for enhanced safety and effectiveness. In the first quarter of 2022, the Ministry of Emergency Management in China recorded 219,000 fires nationwide, underscoring a critical need for efficient emergency response mechanisms (Xiao, 2022). These incidents resulted in 625 fatalities, 397 injuries, and direct property losses amounting to 1.52 billion yuan. Indoor residential spaces accounted for 83,000 of these fires, leading to 503 deaths. While these residential fires constituted 38% of the total fire incidents, they accounted for 80.5% of the fatalities. Given that most fatalities are due to indoor residential fires, it is crucial to tackle the challenges faced by occupants and building managers during emergency response actions. The challenges arise from a series of inadequate decision-making, including insufficient safety management facilities and inspection systems, malfunctioning of critical firefighting facilities, or insufficient fire response manuals and interventions(Jung et al., 2020).

To effectively manage building fires, it is crucial to support and respond to fire risk accurately and effectively before or in the early stages(Kiyomoto et al., 2012). The first emergency responders include evacuees, building managers, firefighters, rescuers, and other trained members. The main emergency response actions include direct response and prevention actions. These Responders' fire response actions rely on the layouts indicated in the building's pre-established emergency plan (Cvetković et al., 2022). They should be aware of all aspects of the status to analyze all information about the fire scenario, including the internal structures, facilities, and site-specific risk factors, and make the best decisions under the given circumstances(Tashakkori et al., 2015). Despite the existing building fire management strategies emphasizing the importance of accurately and effectively responding to fire risks, rapidly and precisely acquiring and analyzing critical data in indoor fire scenarios to support appropriate emergency response strategies under different environmental conditions remains a significant challenge. The increasing complexity of building structures, the diversity of facilities and equipment, and the dynamic nature of fire risks have further complicated and challenged the fire emergency response. Therefore, it is crucial to provide a data model that aggregates data from entities within the indoor fire scenario to support appropriate emergency response action strategies across different environmental statuses.

Scholars have developed many data models for indoor fire scenarios, each based on varying application perspectives and prioritizing different types of information. Xiong et al. developed a quantitative geographical prediction model and a dynamic indoor environment representation model to assist in understanding fire evacuation. This model expands on IndoorGML by integrating three key objects: interior space, indoor emergency grid, and grid cell, ensuring a uniform representation and linkage between entities, evacuation actions, and environmental status. However, it omits detailed definitions of spatial risk factors (i.e., heating equipment and inflammable substances) and related expressions crucial for making informed decisions about prevention actions (Xiong et al., 2017). Gelido et al. employed a 3D geometric model of the building alongside a fire evacuation model to examine the impact of internal obstacles on evacuation efficiency, mainly

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focusing on path congestion (Gelido et al., 2018). Nonetheless, their analysis overlooked the comprehensive environmental status prevalent during a fire. Huang et al. combined CityGML, IndoorGML, and SensorThings API data modeling standards to construct an ontology model for emergency evacuation, successfully merging information about entities in a fire scenario (Huang et al., 2022). However, designing evacuation paths presents challenges, as aligning entity information with environmental status to meet diverse planning requirements from multiple perspectives simultaneously proves difficult. Moreover, knowledge graph technology has been widely applied in fire emergency evacuation. Da et al. considered indoor fire emergency evacuation the main research object and proposed a four-tuple knowledge representation model based on spatio-temporal process analysis and domain ontology construction(Da et al., 2023). However, integrating objective indoor structures and pre-disaster environmental status to support evacuation still needs to be addressed. The current spatial data models are primarily for the geometric representation, attributes, and visualization required for building components. However, they need more integration and expression of multi-dimensional information to support the rational planning of evacuation paths. Current spatial data models concentrate on buildings' geometric aspects and visual characteristics, need more integration and expression of multi-dimensional information essential for rationally planning emergency response actions.

This paper introduces a spatial-temporal data model designed to identify optimal action strategies across various environmental statuses in indoor fire scenarios by aggregating entity data. It proposes a list of influence factors representing the multi-dimensional scenario features from knowledge representation, including spatial location, semantic description, attribute characteristics, geometric shape, evolutionary process, and object relationships (Lv et al., 2018). Utilizing an ontology-based approach, the model integrates these dimensional factors to illustrate the dynamics among entities, actions, and environmental status. It emphasizes environmental status, which supports path-planning for direct response actions. Based on the model, a series of path-planning rules facilitate the deduction of environmental status crucial for devising an optimal evacuation strategy, aiming to minimize evacuation failure risks. A case study validates the model's efficacy in providing a unified representation of multitude of factors in indoor fire scenarios and decision-making for emergency actions.

2. Method

2.1 Overall Methodology and Process

The modelling process comprises three steps:
(1) Designing a list of influence factors from knowledge representation to represent the multi-dimensional scenario features in the indoor fire scenario, aiming to ensure the safety and effectiveness of emergency response actions. The list should encompass spatial location, semantic description, attribute characteristics, geometric shape, evolutionary process, and object relationships.

(2) Based on the list of influence factors from knowledge representation designed to depict the multi-dimensional scenario features, constructing a Multi-Dimensional Scenario Features Model (MDSFM) involves abstract modeling of the indoor fire scenario. This approach incorporates six-dimensional features into a data model organized into three layers: domain (Entity), task (Action), and application (Status). It employs an ontology-based descriptive method to illustrate the interactions among entities, actions, and environmental status.

(3) Utilizing the Semantic Web Rule Language (SWRL) to develop path-planning rules for calculating the status of the environment to form suitable action strategies, supporting path-planning for the implementation of emergency response action.

2.2 Designing a List of Influence Factors for Knowledge Representation to Represent the Scenario Features

Based on the principles of spatial cognition, a knowledge representation is established for abstract mapping from the physical world to the information world in indoor fire scenarios. This approach forms a list of influence factors representing the multi-dimensional scenario features, encompassing spatial location, semantic description, attribute characteristics, geometric form, evolution process, and object relationships.

2.2.1 Spatial Location: The spatial location information of entities in an indoor fire scenario can be approached from two perspectives. Firstly, the location of entities can be identified by coordinates (x, y) or (x, y, z), where x, y, and z are fundamental values. Secondly, it encompasses detailed information that fulfills the requirements for indoor positioning to implement fire emergency response actions. For instance, positioning can use the room's door number and name, aligning with human spatial understanding, such as recognizing an area as a "conference room", equivalent to "room 112 on the 1st floor".

2.2.2 Semantic Description: Description of the function and purpose of entities related to actions and environmental status in the indoor fire scenario supporting fire emergency response efforts. In the context of fire evacuation, this involves identifying and marking critical information, including emergency exits, hazardous areas, and crowded spaces. The identification of hazardous and crowded areas is facilitated by the status of the environment, which provides information about various entities.

2.2.3 Attribute Characteristics: Description of the attributes of entities that drive actions and the status of the environment, interrelating in the indoor fire scenario. This includes, but is not limited to, the room's fire load, the room's holding capacity, the number of heating equipment units, and the pressure value of the fire sprinkler system. Environmental status can be inferred based on these entities' attributes.

2.2.4 Geometric Form: Description of the geometric structural characteristics of indoor objects in a fire scenario. A room, a fundamental type of indoor space, is defined by its clear boundaries and enclosed geometry. The center of this geometry serves as the room's node. Corridor nodes are determined by the intersection of a line connecting two room nodes—representing the room's door—and the corridor's centerline.

2.2.5 Evolution Process: Description of the status of the environment in an indoor fire scenario incorporates the dynamic information of various entities across time and space. Spaces are classified based on the model's explicit definitions. When information from a group of entities in a given area meets a path-planning rule, that area's environmental status is assigned a specific level. For instance, if sections X, Y, and Z of a corridor are identified and dangerous events have occurred in X and Y, space can be discretely categorized by environmental status levels, placing X and Y in the same status level category.

2.2.6 Objects Relationship: Description of the hierarchical connections between entities that make up the environmental status in the indoor fire scenario. Comprehending interactions among various entities, such as fire extinguishing facilities, evacuation facilities, and indoor spaces like rooms and corridors, is essential for creating effective emergency response mechanisms.

2.3 Constructing of the Multi-Dimensional Scenario Features Model

According to the list of influence factors depicting the multi-dimensional scenario features, entity-action-status is modeled consistently using ontology-based descriptive methods. The indoor fire scenario is abstractly modeled by integrating six-dimensional features and organizing them into three ontology layers: domain (Entity), task (Action), and application (Status).

Formally representing this model as Model = {*Entity*, *Action*, *Status*, *Rules*}, where *Entity* represents the domain ontology: entities; *Action* represents the task ontology: actions; *Status* represents the application ontology: status; and *Rules* represent the associative relationships between entities, actions, and status. The proposed ontological framework consists of the three components mentioned above, along with its associated categorization and definitions, as shown in the Figure 1 and further elaborated below.

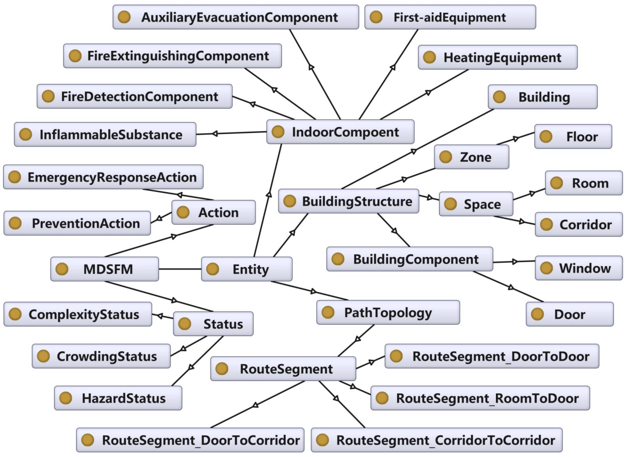


Figure 1. Multi-dimensional scenario features model.

2.3.1 Domain Ontology Layer - Entity: The domain ontology layer, informed by the function and structure of buildings, integrates a general understanding of indoor spaces with categorization objects pertinent to indoor fire emergency response actions. It includes three categories of entities: building structures, indoor components, and path topologies. These categories detail the attributes, states, operations, and relationships among objects within indoor spaces during fire scenarios. This structure aids in developing spatial reasoning mechanisms and establishes conditions for path-planning in dynamic indoor navigation. The definitions for each of the three entity categories are provided below.

Building Structures: Describing architectural space and its components in terms of spatial structure requires comprehending the organizational relationship of a building from the whole to its parts. The class hierarchy is delineated as "building - zone - space - component", with relationships between these classes characterized as "has-part" and "belongs-to." The "has-part" relationship encompasses several sub-attributes; for instance, "has-space" delineates the relationship between a zone and its spaces, whereas "has-door" outlines the connection between a room, its walls, and doors.

Indoor Components: Indoor components that create hazardous environments during a fire include entities identified as disaster-causing factors, such as heating equipment and flammable substances. Additionally, entities are designed to facilitate action tasks in an indoor fire scenario. Actions taken before, during, and after a fire incident encompass direct response actions and preventive measures aimed at disaster avoidance and damage mitigation. Direct response actions, focused on extinguishing fires, evacuating hazardous areas, providing emergency treatment, and utilizing various components and equipment. These include fire detection systems, fire extinguishing apparatus, auxiliary evacuation aids, and first-aid supplies. Prevention actions to reduce the fire risk, involve maintaining firefighting equipment and removing electrical hazards.

Path Topology: Path topology fundamentally describes access nodes like rooms, doors, stairway entrances, and the connecting paths. Rooms, the basic units of indoor space, serve various functions and purposes, such as offices, classrooms, or bedrooms, and often act as origin or destination points in path topology. Doors function as gateways linking different spaces and serve as critical transition points between nodes, with their open or closed status significantly impacting path availability. Stairway entrances provide essential vertical connectivity for evacuation and access across multiple building floors. Collectively, these entities constitute the navigation network within an indoor environment, forming the backbone of efficient and logical path-planning.

2.3.2 Task Ontology Layer - Action: Based on continuous changes in content and objects involved before, during, and after a fire incident and the dynamic nature of ontology, the task ontology layer is subdivided according to its involvement in significant business scenarios and facility usage states into two types: direct response actions and prevention actions. These actions define how emergency responders should ensure safety in the presence of fire risks and play a crucial role in indoor fire risk management and emergency response.

Direct Response Actions: Direct response actions encompass fire extinguishing, employing a range of firefighting equipment and techniques to control or extinguish a blaze; evacuation, vital for the safe and orderly relocation of individuals from hazardous areas, which includes planning and marking clear escape paths; and first aid, offering prompt medical care to those injured in a fire, covering treatment for burns, smoke inhalation, and injuries incurred during evacuation.

Prevention Actions: Within the framework of managing and preventing indoor fire risks, prevention actions constitute a systematic approach to minimize the probability of fire outbreaks and their ensuing damages. These measures include the upkeep of firefighting equipment, entailing the swift deployment of repair teams to address any malfunctions or alarm activations in firefighting apparatus, thus mitigating safety risks. The elimination of electrical hazards involves actions by responsible personnel to inspect and rectify issues upon the detection of fault arcs by arc detectors prompted by alarm signals. Furthermore, minimizing the diversity and amount of combustible and flammable materials in a given area reduce the fire load.

2.3.3 Application Ontology Layer - Status: These environmental status considered in the model focus on the supporting path-planning during execution of direct response actions.

Complexity Status of the Path: Evacuees may have constraints when navigating through a given indoor location due to barriers, path curvature, and other complicated properties of the environment. The complexity of a path is determined by a combination of factors, including the proportion of obstacles, path characteristics such as the presence of inclines, steps, and the number of steps, all of which affect the efficiency of movement through space. The levels of complexity are primarily categorized into not complex (A_Notcomplex), low complexity (B_LowComplexity), below moderate complexity (C_BelowModerateComplexity), moderate complexity (D_ModerateComplexity), above moderate complexity (E_AboveModerateComplexity), high complexity (F_HighComplexity), and severe complexity (G_SevereComplexity). When the complexity of a path within a discrete space reaches above moderate complexity, it can trigger actions to remove obstacles, thereby reducing the space's complexity.

Crowding Status of the Path: Beyond the structural complexity of the indoor environment, the degree of crowding in the area is a critical factor that must be considered. This factor is often assessed directly or indirectly based on the space's carrying capacity or functional use. Crowding levels, determined by the ratio of population density to the area of indoor spaces, are classified into five categories: not crowded (A_NotCrowded), lightly crowded (B_LightlyCrowded), moderately crowded (C_ModeratelyCrowded), highly crowded (D_HighlyCrowded), and severely crowded (E_SeverelyCrowded). Measures to mitigate pedestrian congestion are considered when the crowding level in a specific path segment reaches a highly crowded status.

Hazard Status of the Path: This status denotes the potential for fire hazards in indoor environments, characterized by the indoor use of heating equipment and the storage of combustible or flammable materials, contributing to a high building fire load density. Additionally, malfunctioning fire sprinkler systems increase the risk of turning spaces into potential fire hazards. The hazard level is categorized into seven tiers: minimal hazard (A_MinimalHazard), low hazard (B_LowHazard), below moderate hazard (C_BelowModerateHazard), moderate hazard (D_ModerateHazard), above moderate hazard (E_AboveModerateHazard), high hazard (F_HighHazard), and severe hazard (G_SevereHazard). To reduce fire risks, any hazard level above minimal triggers preventive actions, with varying fire hazard degrees influencing the planning of evacuation paths.

2.4 Path-Planning Rules Development and Reasoning

The rules provide complex logic for calculating environmental status. The path-planning rules emphasize creating new properties by a set of processing. On the one hand, if the new property only involves one entity, a SWRL rule could be used to figure out the generation process. For example, the rule "Room(?room)^hasArea(?room,?area)^hasRoomCapacity(?room,?capacity)^swrlb:divide(?occupancyDensity,?capacity,?area)^swrlb:Equal(?occupancyDensity,0)->hasCrowdingStatus(?room,NotCrowded)" The rule serves as a logical expression to determine if a room is in a "Not Crowded" status. By calculating the "occupancy density" (i.e., the room capacity divided by the room area) and checking if this density equals 0, the rule can conclude that if the occupancy density is 0, indicating no occupants at that period, then the room is categorized as “NotCrowded”. On the other hand, if the creation of the new property involves multiple entities, external functions are required. For instance, as shown in Figure 2, the generation of the hazard status attribute of a room contains three steps. Firstly, a SPARQL query is used to collect the whole fire load of all combustible materials for the room. Then, each set of selected results is added to the ontology. Finally, a SWRL rule is utilized to calculate the fire load density and, by reasoning with other attributes, obtain the room's hazard status. Some examples of the path-planning rules are listed in Table 1. Moreover, the reasoner provided by Protégé combined with SWRL rules can be used to verify the consistency of the MDSFM ontology model.

① A SPARQL query to collect the whole fire load for a room.

```
SELECT ?room (SUM (?heatingValue) AS ?fireLoad)
WHERE {
        ?room ex: hasInflammableSubstance ?substance .
        ?substance ex: hasHeatingValue ?heatingValue .
}
GROUP BY ?room
```

② for each pair of (?room ?fireLoad),
add (?room, ex: hasFireLoad, ?fireLoad) to the ontology.

③ A SWRL rule to calculate the Hazard Status with the fireLoad for the room.

```
Room (?room) ^ hasArea (?room, ?area) ^ hasFireLoad (?room, ?
fireLoad) ^ swrlb: divide (?fireLoadDensity, ?fireLoad, ?area) ^
swrlb: lessThan (?fireLoadDensity, 420) ^
hasNumberofHeatingEquipment (?room, ?number) ^ swrlb:
greaterThan (?number, 0) ^ hasHeatingEquipment (?room, ?
heatingEquipment) ^ HeatingEquipment (?heatingEquipment) ^
hasWorkingCondition (?heatingEquipment, false) ^
hasFireExtinguishingComponent (?room, ?fireSprinkler) ^
FireSprinkler (?fireSprinkler) ^ hasPressureValue (?fireSprinkler, ?
pressure) ^ swrlb: lessThan (?pressure, 0.050) ->
hasHazardStatus (?room, C_BelowModerateHazard)
```

Figure 2. Algorithm to obtain the Hazard Status for a room.

3. Case Study Implementation

3.1 Populating the Instances

This case study involves a four-story teaching building to demonstrate the proposed framework. As shown in Figure 3, the teaching building contains three exits that allow people to exit the building. The area of the four-story teaching building is approximately 4744 square meters. It includes two indoor staircases between floors and two staircases connected to the outdoors. The first floor alone has 39 doors, serving as primary transition points within the structure. Interior segmentation divides rooms and staircases into 34 compartments, each with fire detectors and sprinklers. The indoor routing network, essential for path-planning, is developed from the building's CAD drawings, comprising passage nodes and connected segments.

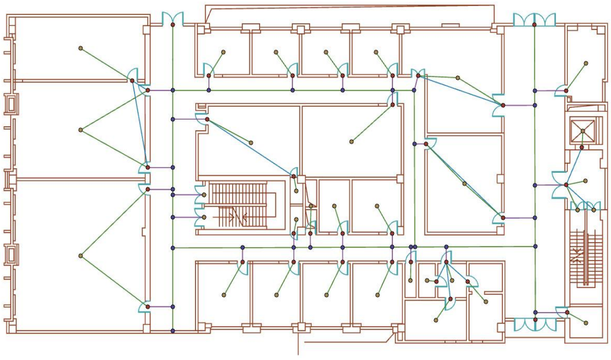


Figure 3. Floor plan and topology model of teaching building first floor.

The MDSFM model instance comprises passage nodes, including rooms, doors, and corridors, alongside connected segment nodes represented by the connecting pathways between these passage nodes. For example, within the structure depicted by the MDSFM model, room nodes "F1_R11" and "F1_R12" are linked to their respective door nodes "F1_R11_111" and "F1_R12_112". A perpendicular node, "F1_c2_111_112", is established by drawing lines perpendicular to the corridor from both door nodes. The segments that connect room-to-door and door-to-corridor passage nodes, such as "Edge_R11-111" and "Edge_R12-112" for room-door connections, and "Edge_111-C2_111_112" and "Edge_112-C2_111_112" for door-corridor connections, are illustrated in Figure 4. Moreover, the environmental status of the corridor node "F1_c2_111_112" depends on both the environmental status of room nodes "F1_R11" and "F1_R12".

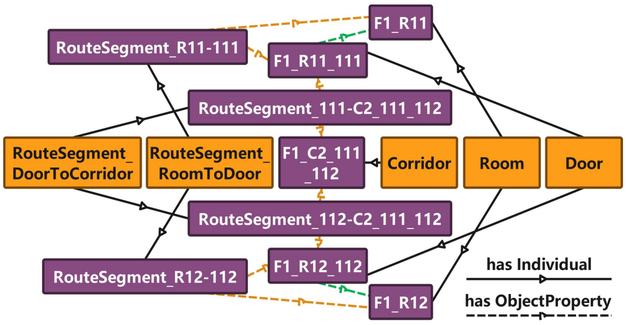


Figure 4. Part of the knowledge graph presents correlations between passage nodes and connected segment nodes.

Type	Level	Examples of path-planning rules
Complexity status	Not complex (Room)	Room(?room)^hasArea(?room,?area)^hasBarrierArea(?room,?barrierArea)^swrlb:divide(?barrierRatio,?barrierArea,?area)^swrlb:greaterThanOrEqual(?barrierRatio,0)^swrlb:lessThan(?barrierRatio,0.25)->hasComplexityStatus(?room,A_NotComplex)
	Not complex (Route segment)	RouteSegment(?routeSegment)^hasArea(?routeSegment,?area)^hasBarrierArea(?routeSegment,?barrierArea)^swrlb:divide(?barrierRatio,?barrierArea,?area)^swrlb:equal(?barrierRatio,0)^hasIncline(?routeSegment,false)^hasSteps(?routeSegment,?steps)^swrlb:equal(?steps,0)->hasComplexityStatus(?routeSegment,A_NotComplex)
Crowding status	Not crowded	Room(?room)^hasArea(?room,?area)^hasRoomCapacity(?room,?capacity)^swrlb:divide(?occupancyDensity,?capacity,?area)^swrlb:equal(?occupancyDensity,0)->hasCrowdingStatus(?room,A_NotCrowded)
	Severely crowded	Room(?room)^hasArea(?room,?area)^hasRoomCapacity(?room,?capacity)^swrlb:divide(?occupancyDensity,?capacity,?area)^swrlb:greaterThanOrEqual(?occupancyDensity,0.75)^swrlb:lessThan(?occupancyDensity,1)->hasCrowdingState(?room,E_SeverelyCrowded)
Hazard status	Below moderate hazard	Room(?room)^hasArea(?room,?area)^hasFireLoad(?room,?fireLoad)^swrlb:divide(?fireLoadDensity,?fireLoad,?area)^swrlb:lessThan(?fireLoadDensity,420)^hasNumberofHeatingEquipment(?room,?number)^swrlb:greaterThan(?number,0)^hasHeatingEquipment(?room,?heatingEquipment)^HeatingEquipment(?heatingEquipment)^hasWorkingCondition(?heatingEquipment,false)^hasFireExtinguishingComponent(?room,?fireSprinkler)^FireSprinkler(?fireSprinkler)^hasPressureValue(?fireSprinkler,?pressure)^swrlb:lessThan(?pressure,0.050)->hasHazardStatus(?room,C_BelowModerateHazard)
	Severe hazard	Room(?room)^hasArea(?room,?area)^hasFireLoad(?room,?fireLoad)^swrlb:divide(?fireLoadDensity,?fireLoad,?area)^swrlb:greaterThan(?fireLoadDensity,420)^hasNumberofHeatingEquipment(?room,?number)^swrlb:greaterThan(?number,0)^hasHeatingEquipment(?room,?heatingEquipment)^HeatingEquipment(?heatingEquipment)^hasWorkingCondition(?heatingEquipment,true)^hasFireExtinguishingComponent(?room,?fireSprinkler)^FireSprinkler(?fireSprinkler)^hasPressureValue(?fireSprinkler,?pressure)^swrlb:equal(?pressure,0)->hasHazardState(?room,G_SevereHazard)

Table 1. Examples of path-planning rules for reasoning environmental status.

3.2 Implementation Results and Discussion

During the preparation of the calculation mapping rules, these rules could be converted into a knowledge graph to resent corresponding logic and make the reasoning process understandable to the users. For instance, the rules for determining a room's fire load density (as stated in Table 1) may be represented as a knowledge graph, as shown in Figure 5. The notations of the knowledge graph are derived from those in the Conceptual Graph proposed by W. Solihin and C. Eastman (Solihin and Eastman, 2015). A rectangle with a yellow background represents an entity in the knowledge graph. The red frame one represents the core object of the status reasoning goal, a circle with a blue background represents a data property connected to its corresponding entity by a solid line, a yellow rectangle with a dotted line and rounded corners represents a status reasoned by calculation mapping rules, a blue circle with a dotted line and rounded corners represents an action reasoned by SWRL rules that trigger actions. The dotted line corresponding entities, status, and actions represent object properties based on their properties and relations with others. The path-planning rules are represented by the line starting with a solid dot and ending with an arrow. The arrow points to the mapping direction, and the mapping logics are specified with a green dotted box indicating a SWRL rule while a purple double solid line box indicating an operation based on SPARQL queries. The notation, namely the numeric line, is derived from the method proposed to represent procedural dealing (Jiang et al., 2022). The lines marked with the same number describe the reasoning process of the same reasoning rule.

Meanwhile, the user could add extra information for the designed MDSFM model. This information focuses on information aimed at executing the action task, including direct response action and prevention action in the indoor fire scenario, such as the room function, the location of the room, and many others. All these knowledge supplementations are collected as a DatatypeProperty focusing on passage nodes and connected segment nodes in the designed model ontology; based on their properties and relations with others, specific status and actions are inferred as new object properties for entities. For instance, taking Room "F1_R12" as a passage node, according to the Chinese load code (GB50009-2012), supposing the heating value of inflammable substance in the room, as shown in Figure 5. Circles one, two and seven represent wooden furniture, circle three represents plastic furniture, Circle four and five represent the fiber fabric, and Circle eight represents the paper product. Based on SPARQL queries, the data property fireLoad which refers to the room's whole fire load by adding heating value of an inflammable substance, is 4809. Circle six represents the heating equipment, which has a "false" working condition and is off. Circle ten represents the fire sprinkler with a pressure value of 0.03.

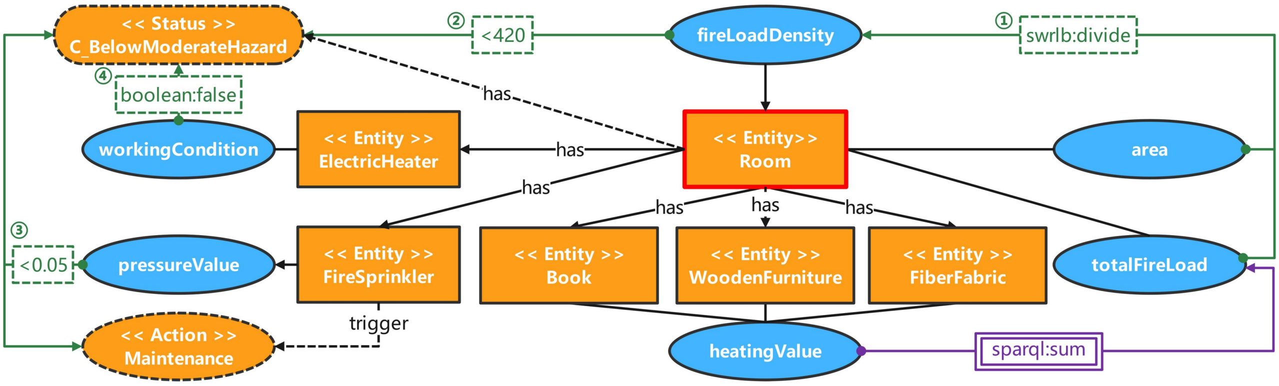
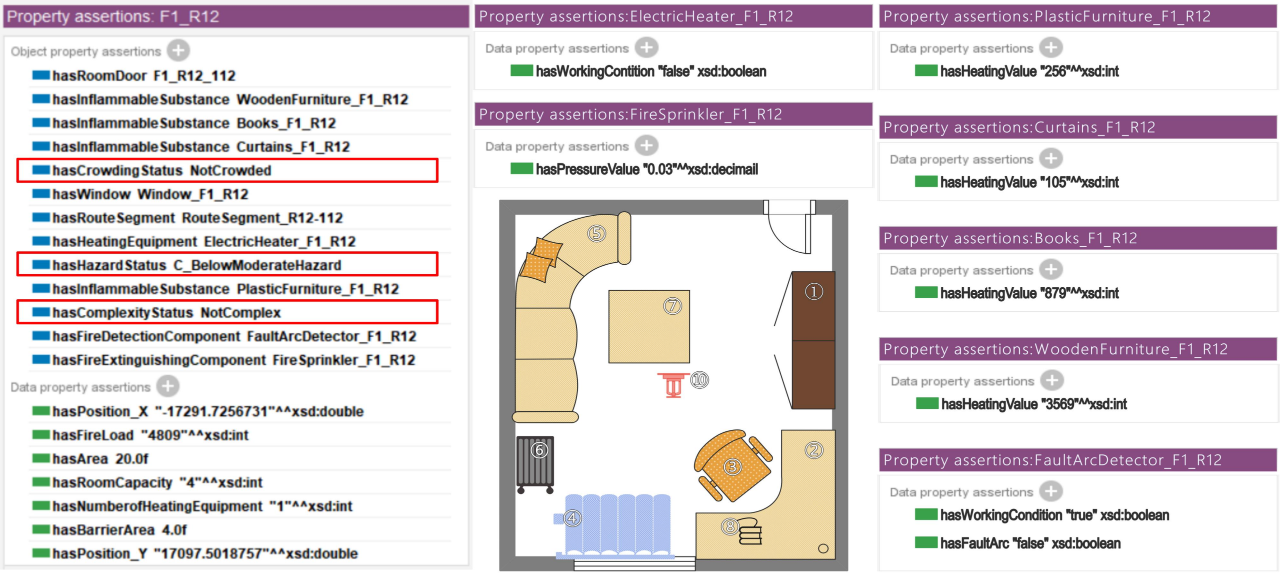


Figure 5. An example knowledge graph presenting the path-planning rules.



Property assertions: F1_R12

Object property assertions

hasRoomDoor F1_R12_112
hasInflammableSubstance WoodenFurniture_F1_R12
hasInflammableSubstance Books_F1_R12
hasInflammableSubstance Curtains_F1_R12
hasCrowdingStatus NotCrowded
hasWindow Window_F1_R12
hasRouteSegment RouteSegment_R12-112
hasHeatingEquipment ElectricHeater_F1_R12
hasHazardStatus C_BelowModerateHazard
hasInflammableSubstance PlasticFurniture_F1_R12
hasComplexityStatus NotComplex
hasFireDetectionComponent FaultArcDetector_F1_R12
hasFireExtinguishingComponent FireSprinkler_F1_R12

Data property assertions

hasPosition_X "-17291.7256731"^^xsd:double
hasFireLoad "4809"^^xsd:int
hasArea 20.0f
hasRoomCapacity "4"^^xsd:int
hasNumberofHeatingEquipment "1"^^xsd:int
hasBarrierArea 4.0f
hasPosition_Y "17097.5018757"^^xsd:double

Property assertions:ElectricHeater_F1_R12

Data property assertions

hasWorkingContition "false" xsd:boolean

Property assertions:FireSprinkler_F1_R12

Data property assertions

hasPressureValue "0.03"^^xsd:decimail

Property assertions:PlasticFurniture_F1_R12

Data property assertions

hasHeatingValue "256"^^xsd:int

Property assertions:Curtains_F1_R12

Data property assertions

hasHeatingValue "105"^^xsd:int

Property assertions:Books_F1_R12

Data property assertions

hasHeatingValue "879"^^xsd:int

Property assertions:WoodenFurniture_F1_R12

Data property assertions

hasHeatingValue "3569"^^xsd:int

Property assertions:FaultArcDetector_F1_R12

Data property assertions

hasWorkingCondition "true" xsd:boolean
hasFaultArc "false" xsd:boolean

Figure 6. An example information fusion based on the multi-dimensional scenario features of indoor fire scenario.

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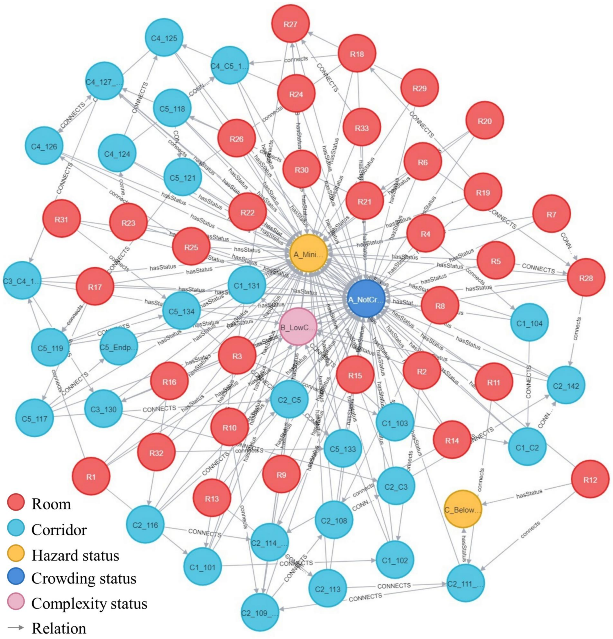

Figure 7. The knowledge graph of the indoor environmental status.

Based on the path-planning rules, each of the above passage nodes and connected segment nodes obtain corresponding environmental status of the route at the application ontology layer based on their respective object properties and data properties, including NotCrowed crowding status, C_BelowModerateHazardas hazard status, and NotComplex complexity status. as shown in Figure 6 marked in red frames, thereby driving actions at the task ontology layer, such as the maintenance action in Figure 5. Figure 7 shows a complete knowledge graph of the environmental status at a particular moment within the study area, obtained through knowledge reasoning. It includes all the rooms and corridor nodes related to the preset evacuation path-planning.

4. Conclusion and Future Work

For effective management of building fires, the accuracy and comprehensiveness of information in indoor fire scenarios are essential. Emergency responders require precise and comprehensive information about building interiors to make informed decisions. Therefore, this study aims to develop a spatial-temporal data model addressing the complexity of indoor fire emergency management by synchronizing entity and environmental status information to fulfill varied planning needs concurrently.

This research simulated a specific structural-functional building use case to illustrate the necessity and benefits of integrating diverse factors via the proposed model and method. Simulation results show that the model effectively integrates multidimensional information, enabling dynamic updates in response to triggered actions. Developed using ontology semantic web technology, the model and its path-planning rules enhance indoor fire emergency management by enabling responders to pinpoint potential countermeasures and risks. Additionally, facility managers can capitalize on digitizing fire response information, ensuring continuous updates throughout the building's lifecycle.

However, rules development currently depends on manual effort. Future improvements could leverage natural language processing and deep learning to automate the conversion of clauses into knowledge graphs and path-planning rules, enhancing efficiency and reducing time and costs. Furthermore, identifying specific environmental status and response actions could guide the allocation of edge weights to nodes using a path-planning algorithm for optimization. This method seeks to compute paths optimized for executing specific tasks, enhancing task-specific responses.

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