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SBEO: Smart Building Evacuation Ontology

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Abstract. Semantically rich depiction of the concepts for context-aware indoor routing brings appealing benefits for the safety of occupants of smart spaces in emergency evacuation. In this paper, we propose Smart Building Evacuation Ontology (SBEO[3]), a reusable ontology for indoor spaces, based on three different data models: user, building, and context. We provide a common representation of indoor routing and navigation, describe users' characteristics and preferences, grouping of individuals and their role in a specific context, hazards, and emergency evacuation. Among other characteristics, we consider abilities of individuals, safety and accessibility of spaces related to each person, intensity, impact, and severity of an emergency event or activity. SBEO is flexible and compatible with other ontologies of its domain, including SEAS, SSN/SOSA, SEMA4A, and empathi. We evaluate SBEO based on several metrics demonstrating that it addresses the information needs for the context-aware route recommendation system for emergency evacuation in indoor spaces. In the end, a simulation-based application example exploits SBEO using Context-Aware Emergency Evacuation Software (CAREE)[4].

Keywords: ontology, linked data, smart building, hazard detection, emergency evacuation, indoor route recommendation, navigation.

1. Introduction

Ambient Intelligence (AmI) represents a responsive electronic environment that reacts to the actions of each person and the physical objects within itself. It has been growing fast as a multi-disciplinary field with a high impact on society for the last three decades [44].

It can be used to combine hazard detection and disaster management [5], crowd management [33], and route recommendation [9] in smart spaces [65] to obtain real-time information and aid decision making in dynamically changing emergency evacuation scenarios in large smart buildings with multitudes of occupants.

The objective of both outdoor and indoor navigation systems is to find a path for each user from their initial to target location that optimizes one or more of given performance indicators (e.g., distance, time and/or difficulty) [14]. Dynamic context-aware adaptation of the evacuation route and its communication to each evacuee are required for efficient

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[3] SBEO can be accessed at: https://w3id.org/sbeo
[4] https://github.com/qasimkhalid/CAREE

evacuation (see, e.g., [23]). While outdoor navigation systems use Global Positioning System (GPS) receivers, indoor navigation cannot rely on them due to the overlapping of the signal through the storeys of the building. Thus, other technologies must be employed for positioning (see, e.g., [46]). For example, Proximity-based Systems, WiFi-Based Systems, Ultra Wide-band Systems.

It becomes challenging and complex to handle indoor navigation in real time when various objectives are combined along with the localization of people. This is the case in the recommendation of routes to users based on their physical abilities and preferences during everyday or emergency scenarios. There are multiple reasons for its complexity. First, indoor location of persons is not entirely precise, always leaving a margin of error. Second, the (close to) real-time processing and fusion of data coming from heterogeneous sensors into a consistent, accurate, and useful information describing the evacuation context is a prerequisite for getting around the effects of possible emergency setbacks.

Here, we use ontologies to describe concepts and relationships between entities as a formal way of conceptualizing the domain knowledge. Ontologies are a key component of the semantic web [61] that is used to represent data, and provide a domain-specific knowledge for the representation of the metadata [48]). Previously, various ontologies and data models for indoor navigation, routing, and emergency and crisis management, were proposed for conventional buildings and spaces without ambient intelligence [4,27,58,15,28,40].

In [31], a semantically-enriched distributed architecture for context-aware and real-time evacuation guidance in indoor smart spaces was proposed. The architecture uses a multi-agent system for the coordination of the evacuation where each agent is responsible of the semantic reasoning concerning the safety of its assigned physical space and uses an ontology for indoor emergency evacuation. As a continuation of the previous work, in this paper, we propose an ontology for smart space context-aware route recommendation to evacuees with smart devices. We name the proposed ontology *Smart Building Evacuation Ontology* (SBEO). SBEO is composed of three modules: User Model, describing the characteristics (i.e., physical abilities) and preferences of an evacuee; Building Model that considers the routing, and geometry, devices and elements other than structural components of the building; and the Context Model, which illustrates the contextual information about the building and the evacuees.

The SBEO ontology is inline with terminologies used in the domain of indoor route recommendation and navigation. It is compatible with several other state-of-the-art ontologies and systems such as, SEAS [29], SOSA/SSN[24], SEMAA4a [40], Indoor Navigation Ontology (INO) and User Navigation Ontology (UNO)[26,58], and General User Model Ontology (GUMO)[21]. It was implemented using OWL 2[5] and the Protégé[6] development environment. SBEO is available at https://w3id.org/sbeo# and holds a GPL-3.0 license.

To the best of our knowledge, this is the first work that combines the concepts of smart spaces with context awareness, route recommendation and hazard detection considering users' relevant evacuation characteristics and preferences. The main contributions of SBEO are expressiveness, which provides a hierarchical description of the concepts in indoor emergency routing in smart buildings. In addition, as sharing and reusability

[5] https://www.w3.org/TR/owl2-overview/
[6] https://protege.stanford.edu/

are considered the fundamental concepts in the ontology engineering field [41], the proposed ontology is also reusable. Here, reusable refers to the adaptation of SBEO according to the need of the user and application. In other words, we can extend the models of SBEO individually. For example, people with impairments not covered thus far might also be described using the same ontology if needed. Consequently, concepts associated with such people might also be extended accordingly. Similarly, in terms of buildings, although SBEO covers the concepts for both conventional buildings and smart buildings, if any new type of buildings or related concepts is introduced, the ontology can easily be broadened. It also improves the automation, accountability, real-time context awareness, information sharing, and personalised routing in smart space evacuation.

The rest of the paper is organized as follows: In Section 2, we highlight related work in emergency management, user and crowd modeling, smart environments, and indoor routing. We describe the followed methodology in the development of SBEO together with the ontology audience and scope in Section 3. Section 4 states the competency questions and formal requirements to be met by the proposed ontology. SBEO is presented in Section 5. In Section 6, the proposed ontology is evaluated using various metrics found in the literature. In Section 7, a simulation-based application example of SBEO is described using Context-Aware Emergency Evacuation (CAREE) system. A task-based evaluation is performed using a hazard context. We conclude the paper with some proposed improvements and future work in Section 8.

2. Related Work

This section provides an overview of related state-of-the-art ontologies together with the positioning of SBEO.

2.1. Ontologies for emergency and crisis management

A general ontology for emergency response by Li et al. proposed in [30] includes the concepts of *response preparation, emergency response, emergency rescue and aftermath handling* and relevant properties and relations that connect these concepts.

The ontology for massive crisis management proposed in [50] covers the concepts related to the allocation of resources and the crisis impact related to the time and place of the crisis occurrence. An ontology-based proactive approach to enhance the response time during both natural (such as earthquake, tsunami, etc) and anthropic (such as terrorist attack, kidnapping, etc) events in [12] covers the concepts of the context, impact, and the services provided during an incident.

Sicilia and Santos [52] described Basic Formal Infrastructure Incident Assessment Ontology (BFiaO) to represent the adverse effects of incidents. BFiaO connects the concepts related to incidents, their causes and evolution, and their possible outcomes. Santos et al. [49] broadened BFiaO and made it more consistent with Coordination of Emergencies and Tracking of Actions and Resources (CESAR) data model to minimise the aftereffects of an incident. They modelled the concepts for the identification of events, mission, and resources and developed a set of rules to anticipate possible chain events connected with the existing/past events, such that the first response officers could prioritise their tasks to avoid jeopardy.

Recently, Gaur et al. [19] presented a rich ontology[7] for emergency management and planning during hazard crises including concepts related to emergency response, hazard type, impact, phase, events, involved individuals, and provided services.

In terms of notification services during emergency scenarios, Malizia et al. [35] proposed an ontology to express the concepts of emergency notification messages with respect to various kinds of users. They developed a class named EMEDIA (Emergency and MEDIA technologies) that provides the concepts and relations about emergency and communication devices and technologies. They integrated that class with other existing ontologies that describe accessibility guidelines, and users' profiles and action capabilities. Afterwards, Onorati et al. [40] extended their work by introducing some new concepts to express personalised routes based on the users' physical abilities, familiarity with the environment, preferences, location, available media for notification, and characteristics of the surrounding.

Bitencourt et al. [8] developed a formal domain ontology to describe the emergency response protocols of fire in buildings considering incident details, information about the victims, possible actions, planning, and operational phases. Related to gathering and medical emergency response, Haghighi et al. [20] presented *Domain Ontology for Mass Gathering* (DO4MG) considering the concepts related to gathering types, venue details, features of the crowd, environmental factors and general mass gathering plans.

One of the most comprehensive, general-purpose light-weight ontologies that can be used in Internet of Things and smart spaces is *Sensor, Observation, Sample, and Actuator* (SOSA) ontology [24]. SmartEnv ontology [3] covers various aspects of a smart environment such as sensing, networking, event, and topology, while *Smart Energy Aware Systems* (SEAS) ontology [29] couples the concepts related to energy and grid, and conceptualises city and building structures, time, weather, and user comfort.

2.2. Ontologies for spatial modeling, indoor navigation and routing

Rasmussen et al. [45] presented a core vocabulary named *Building Topology Ontology* (BOT) to describe the topology of buildings, along with its storeys and spaces. The BOT ontology is completely compatible with other ontologies in the domain such as SOSA and SSN[8].

For navigational and routing purposes, Brückner et al. [27] proposed an indoor-outdoor ontology-based data model for both robots and humans to develop a routing graph with the help of spatial information. Similarly, Yang and Worboys [64] also presented an ontological model for both outdoor and indoor navigation.

Indoor Navigation Ontology (INO) [58] covers concepts of navigation in indoor spaces and the geometry of buildings including multiple floors, elevators, points of interest[9], corridors, exits, etc. The ontology for indoor routing based on American Disability Act (ADA) standards [15] deals with the geometry of a building in such a way that its connections can be represented as horizontal and vertical paths for routing purposes.

[7] https://w3id.org/empathi/

[8] https://www.w3.org/TR/vocab-ssn/

[9] A point of interest is defined as any object or physical space that might be of importance or useful for the occupants of the building. For example, an (emergency) exit, location (or space) where a person is located subject to specific criteria, fire safety devices such as fire extinguisher, firehouse, fire door.

In the *Ontology Crowd Simulation* (ONTOCS) [10], the concepts of an indoor environment together with its geometry are modelled in the context of emergency evacuation in terms of the routes, travel time and distance.

2.3. Ontologies for user and crowd modeling

One of the pioneer works in the domain of user modeling has been carried out by Heckmann et al. [21]. They developed General User Model Ontology (GUMO) to describe the basic attributes of users such as demographics, abilities, proficiencies, states (emotional, physiological, mental), role, and so forth.

Later on, Kikiras et al. [26] developed User Navigation Ontology (UNO) on the basis of multiple wayfinding theories related to cognitive science, psychology, sensor abilities and physical characteristics of human beings. UNO covers the concepts related to users' navigation in indoor environments based on their demographics, cognitive characteristics, sensor- and motor- abilities, and navigational and interface preferences. Subsequently, Kritsotakis et al. [28] broadened the concepts of UNO and presented a User tracking Ontology (UTO) to describe the concepts for context awareness and tracking of users. On the other hand, Dudas et al. [15] also modeled the users in their ontology based-on American Disability Act (ADA) standards, in which they conceptualize users' preferences, familiarity with the building, and disabilities.

Similarly, Boje and Li [10] also modeled the information about the crowd in their simulated framework. They named it Crowd Simulation Information Model (CSIM) that covers the concepts related to persons, such as preferences, exit choices, and speed.

Whilst the above-mentioned works are interesting and provide the concepts about the geometrical information of the buildings, user characteristics, and routing and navigation in indoor environments, some of them are not available online, hence cannot be reused. In addition, the existing works do not provide sufficient information about the context awareness of the building and persons, especially in emergency management context. By comparison, SBEO aims to conceptualize context-aware indoor route recommendation and emergency evacuation. The proposed ontology not only describes the concepts related to building topology, routing and navigation, classification of users with respect to their abilities and preferences, but also conceptualizes context awareness, such as detection of any hazard, intensity, severity and impact of activities and events, evacuation action plan, social groups, movement of people, and people notification. Furthermore, SBEO has been published online and made available for public after being developed using state-of-the-art methodologies found in the literature.

3. Design Methodology

To date, several methodologies have been proposed for building ontologies, e.g., *Methontology* is a methodology to build ontologies from scratch [18], On-To-Knowledge[56], Digilent[42], Neon[54], and Ontology development 101[38]. In order to develop SBEO, we selected Methontology framework because it allows to develop the ontology from scratch, and also recommends to reuse the concepts from the existing meta-ontologies. In addition, as the ontology development is an on-going process due to the evolving prototype life cycle nature of this methodology, it permits the ontology authors to update the ontology from any of its phases.

Methontology proposes a process consisting of six steps: *specification*, where the purpose of the ontology, intended audience, scenarios of its use, scope and requirements are taken into account; *knowledge acquisition*, where several techniques can be used to get the specific and detailed knowledge about the topic of the ontology; *conceptualization*, where all the useful or potentially usable domain knowledge is brought together to create a conceptual model, and that model is compared with the existing ontologies to check its scope, completeness and reusability; *integration and implementation*, where to support the reuse of definitions, the concepts of the proposed conceptual model are scrutinized with the existing ontologies as per their scope, and then implemented the filtered concepts using one of the standard languages; *evaluation*, where the each activity of the ontology development process is verified and validated using various methods and metrics; and *documentation*, where each phase of the ontology development process is documented in natural language available on the Web or in the scientific literature.

Knowledge acquisition. Knowledge acquisition is a primitive stage for ontology development that is also considered as an on-going process. In the same way, we also reviewed the literature to acquire relevant knowledge and to get a broader view of the needs and requirements for the creation of an ontology (i.e., SBEO). In particular, the studies reported in: [58,15,28,40,10,32,7,2,37], represent the systems and/or models for indoor route recommendation during emergency evacuation; [1,55,11], depict crowd management and grouping during hazardous situations using simulated environments; [25], discuss indoor routing for people with special needs; [29], describes building geometry using an ontology; [65,63], define the smart spaces, together with its requirements, and [34,16], discuss some case studies related to the user behaviour during an emergency evacuation in a smart indoor environment.

Scope and Audience. SBEO offers a data model for building geometry, devices and elements not only regarding structure, route sets based on building topology, users' characteristics and preferences. It also considers the context awareness of both buildings (e.g., hazard detection, the status of spaces and evacuation routes in terms of availability and occupancy, severity and impact of activities and events, and safety of spaces) and an user/occupant (e.g., route tracking, coordination with their evacuation group, adaptation of an evacuation route in terms of fitness and accessibility to spaces). Hence, the proposed ontology has an ample scope to couple the information about a building with its occupants in order to use it for indoor localization, detection of a hazard or disaster, and preference-based routing during emergency evacuation. The target audience of SBEO is building occupants (e.g., visitor, resident, worker), building managers, civil engineering specialists, indoor designers, and architects involved in building design and development, but also researchers in building evacuation safety.

4. Ontology specification

From the requirements engineering point of view, we set two goal-level requirements that should be fulfilled by the proposed ontology. First, formal requirements, which are used to express the needs of the domains covered by the ontology, including preference-based route recommendation and context awareness in smart buildings; and Second, functional requirements, in the form of specific competency questions which must be answered by the ontology.

4.1. Formal Requirements

In terms of formal requirements, SBEO must be able to represent the concepts related to the users (i.e., occupants), the buildings, and the context related to both users and the building. These are as follows:

Users:

- Demographics of a person (e.g., age, name, individual and group identity numbers, and family members).
- Physical abilities (e.g., mental, spatial, sensor, mobility).
- Navigational and routing preferences (e.g., avoidance of stairs or crowded areas, fastest route, simplest route with least turns).
- Level of involvement (i.e., role) while performing a specific activity (e.g., either a person is dependent or responsible for others during immediate egress from an area).
- Type of an impairment of the person (if it exists).

Buildings:

- Structural elements (e.g., stairs, elevators, corridors, rooms).
- Devices installed in the building, which are not a part of the building structure (e.g., sensors, equipment for safety and access control).
- Representation of a building as a traversable graph (i.e., for routing purposes).
- Classification of routes (e.g., shortest path and simplest path [14]);

Context related to the users and buildings:

- Individuals' fitness status (e.g., fit, injured).
- Motion status (e.g., running, walking, standing).
- Deviation status (e.g., classification of persons based on the
- Frequency of deviations from their provided route).
- Safety level of spaces concerning each person.
- Availability and accessibility of spaces (where the availability of space states that either space is usable or not, the accessibility of space, on the other hand, refers to a specific person or type of persons, either it is accessible for him/her/them or not).
- Intrinsic concepts related to activities and events (e.g., type, starting and ending time), along with their effects. For example, Intensity which refers to the magnitude, severity which relates to the specific persons and varies accordingly, and Impact, that refers to their effects on users.
- Comprehensive concepts, such as time taken by an individual and role of an individual while performing an activity (e.g., responsible, visitor, group leader).

4.2. Functional Requirements: Competency Questions

For functional requirements, we use competency questions. A competency question (CQ) is a question in a natural language that is supposed to be answered by an ontology. Usually, it has a specific pattern [60]. Ren et al. [47] defined some patterns using a feature-based modelling method to describe competency questions.

Table 1. Some sample competency questions to be asked by SBEO.

Module Type	Competency Questions
	User Model
Characteristics	1. Who is not capable of running? 2. How many families are located in the building? 3. Who has a bad quality of hearing ability (in the building)? 4. What are the types of people concerning their physical characteristics?
Preferences	5. What are the route preferences (for emergency evacuation, e.g., simplest path, shortest path) of each person? 6. What are the notification preferences (in terms of description, e.g., audio, textual) of each person?
	Building Model
Spatial Information	7. What is the relative occupancy ratio of all corridors? 8. How many points of interest are located on each floor of the building? 9. Which other spaces are adjacent to a specific space (e.g., kitchen) in the building? 10. Which space (e.g., a specific building block) is a sub-part of which space (e.g., building)? 11. What is the area of all corridors (it can be of any shape, such as, rectangular, circular, trapezoidal or triangular)? 12. Which spaces are excluded (due to any reason such as limited access on account of mobility impairment or privacy policy of spaces, e.g., hotels) for which person?
Route Graph	13. How many nodes and edges are there in the graph-based representation of the building? 14. What is the type of each route in terms of its graph-based representation (e.g., Shortest Path or Simplest Path)? 15. What is the travel time of all exit routes for each person (the starting and ending points of each exit route are considered as origin and destination, respectively)?
Devices	16. Who is using a hand-held device, and of what type? 17. Which sensors are installed in each space of a specific type (e.g., office)? 18. How many fire protection devices are installed on the same floor where a specific person is located?
	Context Model
Building	19. Which activities (e.g, visit, evacuation, shopping) are being done in the building? 20. What is the availability status (i.e., Available or Unavailable) of each space?
User	21. Where is each person located in the building? 22. What is the role of each member within any group? 23. How many times a person has deviated from the provided path? 24. What is the fitness status (i.e, Exhausted, Fit, or Injured) of each person? 25. Which route is assigned to whom of which group (refers to a number of people that are classified together, e.g., a family)? 26. What is the motion state of each person (refers to the movement of a person, e.g., walking, standing, running, rolling, or scooting)? 27. What is the navigational state of each person (refers to the state while following a path to check whether a person is following the provided path or deviating from it)?
Event (e.g., Emergency Evacuation)	28. Is there an incident in the building? 29. At what time an incident occurred? 30. What is the availability status of the spaces that are a part of emergency evacuation routes? 31. How many groups are still in the process of evacuating the building? 32. What is the impact of activities on persons having the mild quality of seeing ability? 33. What is the severity of the incidents for mobility-impaired persons (of all types)? 34. What are the intensities (refers to the magnitude or strength) of the events occurred? 35. Who has evacuated the building successfully (refers to the activity status of a person who completes his/her provided exit route)?

In this study, we adopted the same patterns to determine the scope of the proposed ontology. Table 1 includes some competency questions the proposed ontology should answer. The motivation for choosing these competency questions is based on our previous work (see, e.g., [31], [33], and [32]), where not only the concepts related to both buildings and users were limited, but it also lacked the contextual information of these entities. In this regard, most of these questions are explicitly shaped to answer the specific attributes of buildings, users, and the relevant context. Nevertheless, the potential ontology user may develop their own set of customized competency questions concerning the application type within the scope of the ontology. On the other hand, these competency questions might also be used as a metric to evaluate each ontology module such that their answers could be used in the typical application scenarios the ontology is aimed at, like the task-based evaluation mentioned in Section 6 and the application described in Section 7.

The table is divided into three information models: user, building and context. The first column expresses a module type for each information model, and the second column states the list of competency questions which cover the aforementioned information model and module type.

In the information model, firstly, *User model* represents the occupants (of any category such as visitor, resident, worker) of the building, along with its two modules to indicate their demographics and preferences. Secondly, *Building model* portrays the indoor spaces (and only those outdoors ones which are used to connect indoor ones), together with its module types and relevant competency questions. Lastly, *Context model* denotes context awareness of the aforesaid information models, hence its module types—user and building. The event module type is also added in this model as per the scope of the ontology.

5. Ontology Description

This section describes SBEO based on the knowledge acquired from the literature and the specification mentioned in the previous sections. SBEO reuses various concepts from the existing ontologies such as FOAF[10], Semantic Sensor Network Ontology[11], The Ordered List Ontology[12], and SEAS Building Ontology[13]. On the contrary, some ontologies e.g., Indoor Navigation Ontology (INO)[58], User Navigation Ontology (UNO)[58], User Tracking Ontology (UTO)[28], are not available online. Therefore, the relevant concepts are borrowed by `sbeo` namespace.

Fig. 1 shows the Smart Building Evacuation Ontology (SBEO) in a nutshell. SBEO encompasses three main parts, (i) User model, for specifying characteristics and relations of buildings' occupants; (ii) Building model, for describing buildings topology and infrastructures installed in them; and (iii) Context model, for representing the dynamic changing state of buildings and occupants.

Fig. 2 shows the core concepts of Smart Building Evacuation Ontology (SBEO). In the following, we describe each of the models in more detail.

[10] http://xmlns.com/foaf/spec/
[11] https://www.w3.org/TR/vocab-ssn/
[12] http://purl.org/ontology/olo/20100723/orderedlistontology.html
[13] https://w3id.org/seas/BuildingOntology-1.0

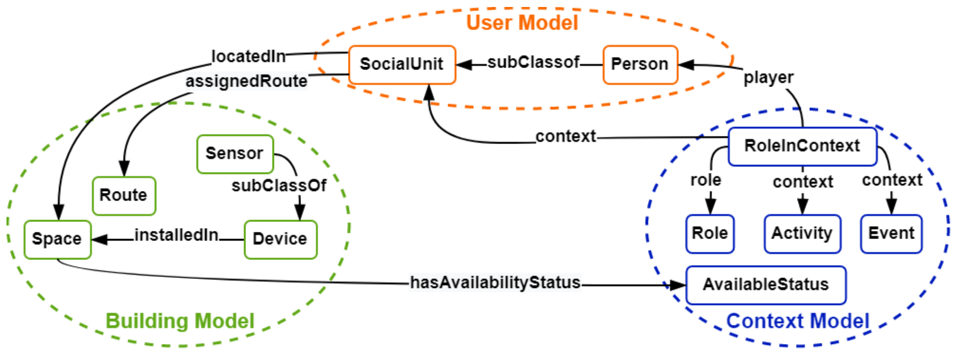

Fig. 1. Smart Building Evacuation Ontology (SBEO) in a nutshell

5.1. User Model

The User Model is used to represent the demographics, physical abilities, and people preferences (e.g. type of route or notification means). The demographics part includes the basic information about a person using object (`acquaintanceOf` and `responsibleTo`) and/ data properties (e.g. `foaf:firstName`, `foaf:lastName`, `foaf:gender`, `foaf:age`, and `id`).

A route or even a route element (e.g., space in the route) may not be appropriate for a specific person (or group of persons). Thus, it is crucial to model the physical abilities of individuals for personalized route selection. Ontologies like User Navigation Ontology (UNO)[26] and General User Model Ontology (GUMO)[21], provide a core knowledge base for users and their characteristics by modeling the abilities such as mental abilities, mobility capabilities, along with their quality. In the same way, the physical abilities of users are conceptualized in SBEO based on UNO and GUMO. Furthermore, we know that we can only describe a binary relation (i.e., either between two individuals or an individual and a value) in Semantic Web languages (e.g., RDF or OWL). As a solution, we may use n-ary design pattern to link an individual to more than one individual or even a value. A potential reader may consult [39] for further information. Thus, we also exploit n-ary relations to make use of the aforementioned concepts to associate them with a user. A new concept, `PersonAbility`, is also introduced to express the ability (using `hasAbility` property) of each person, together with its quality (using `hasQuality` property. Note that the `Ability` class is similar to UNO and GUMO. Under this parent class, other sub-classes are introduced to mention different types of abilities such as `MentalAbility`, `SpatialAbility`, `SensorAbility` and `MobilityAbility`.

In terms of navigational preferences, three relations–`hasNavigationalType`, `route Preference`, and `meansOfNotification`–are used. For example, `hasNavigati onalType` relation is used to express what type of navigation is provided to (or performed by) a person. The possible types of navigation can be `AssistedNavigation`, `AutonomousNavigation`, `Collborative Navigation` or `MultiObjective Navigation`. In `AssistedNavigation`, a person is assisted by another person or a machine to perform a specific activity. In `AutonomousNavigation`, a person plans and executes their path without any hu-

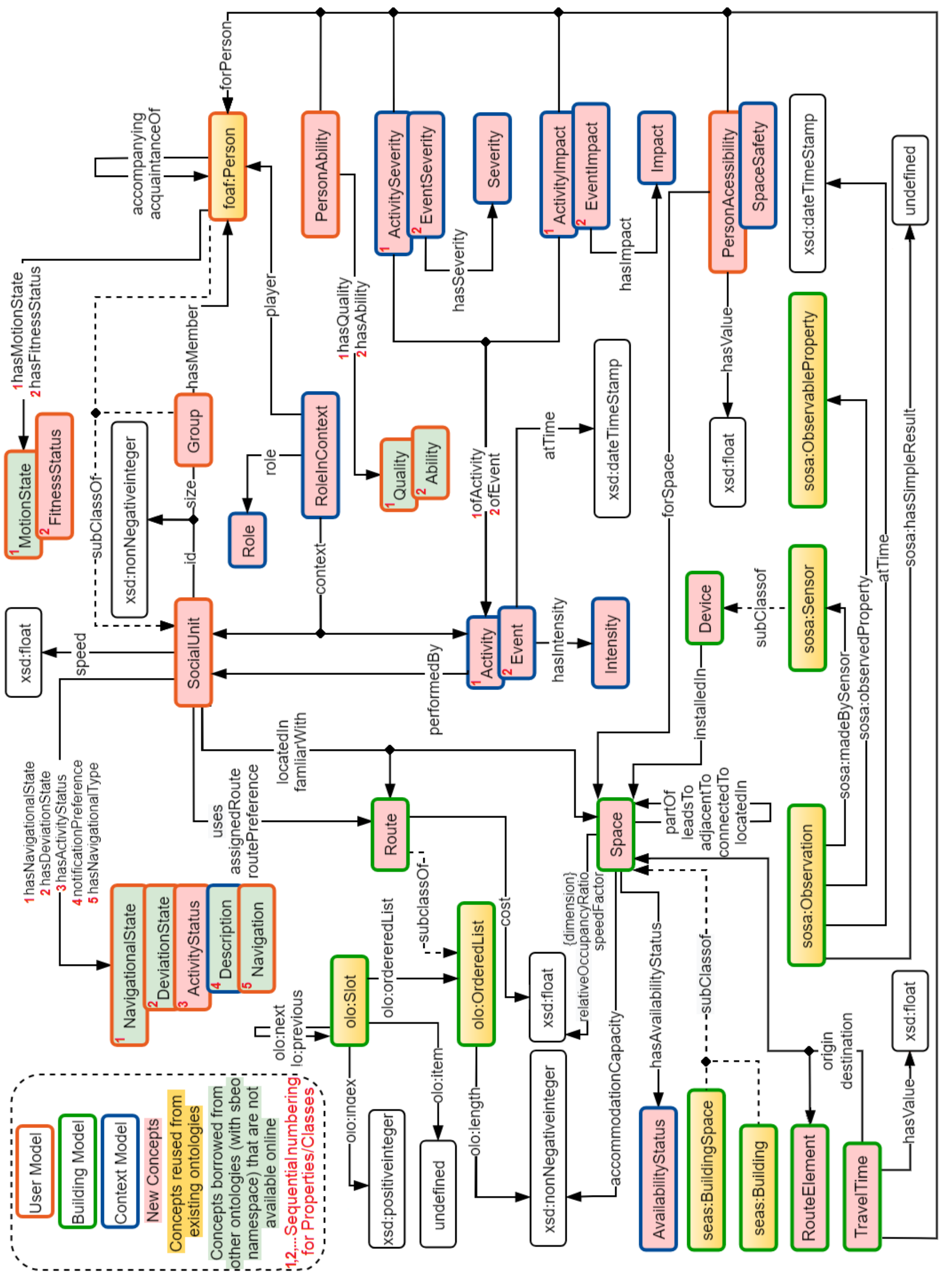

Fig. 2. Core concepts and relationships of Smart Building Evacuation Ontology (SBEO).

man or machine intervention. In `CollaborativeNavigation`, two or more persons are involved that may or may not have same objectives. Lastly, in `MultiObjective Navigation`, there can be various tasks to be done in it, such as visiting numerous points of interest, picking up multiple dependent persons.

Similarly, an individual may use `routePreference` relation to specify their route preference, such as shortest path and simplest path[14]. `meansOfNotification` property is used to choose the method for notifying a person about any piece of information related to space, route, activity, event, or any route element (e.g., door, stairs, waiting zone, assembly point, entrance, exit). An instance of user model is given in Fig. 3.

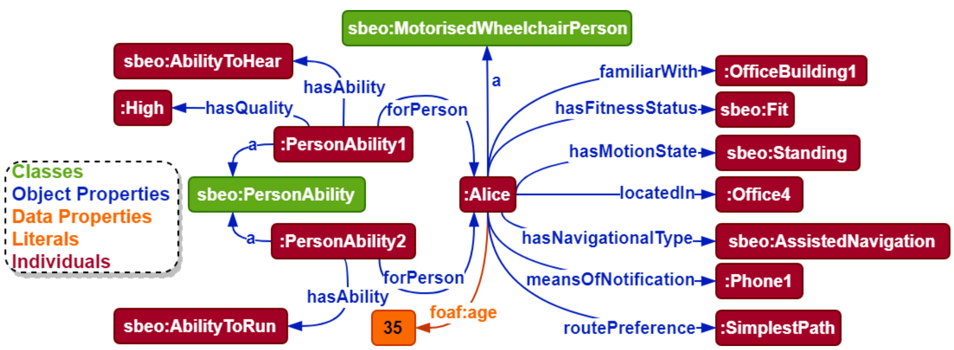

Fig. 3. User modelling

5.2. Building Model

In this model, concepts related to the geometry (or structure) of the building are described. Other spatial information about the building is also taken into account, such as sensors, fire safety equipment.

Geometrical elements. Geometrical elements are mentioned with the help of `Space` concept that represents any physical space. The type of a building and the specific site of any building can be described using `seas:Building` and `seas: SiteOf Building` respectively. All other atomic parts of a building (e.g., room, hall, door, stairs) are mentioned as the sub-classes of `seas:BuildingSpace`. These atomic elements use `locat edIn` property to mention where these are located in a specific building, whereas `partOf` property is use to mention which building or an atomic part of the building belongs to which other building. If any space is connected or adjacent to any other space, `connecte dTo` and `adjacentTo` properties are respectively used to express that relation between them. Similarly, as each space, e.g., `seas:Corridor`, `seas:Hall`, `seas:Escalat or`, has a specific shape, data properties such as `length`, `width`, `height`, `base`, `radius`, and `area`, are defined. Additionally, `accommodation Capacity` property is used to express the accommodation capacity of a space in terms of persons where as, another data property named `relativeOccupancyRatio` is introduced that states the ratio of occupied to total usable (`accommodationCapacity`) space. `Congestion` can also be expressed using a boolean property named as `hasCongestion`. An instance of building geometry model is given in Fig. 4 that represents a Kids Area, along with the properties as mentioned in this paragraph.

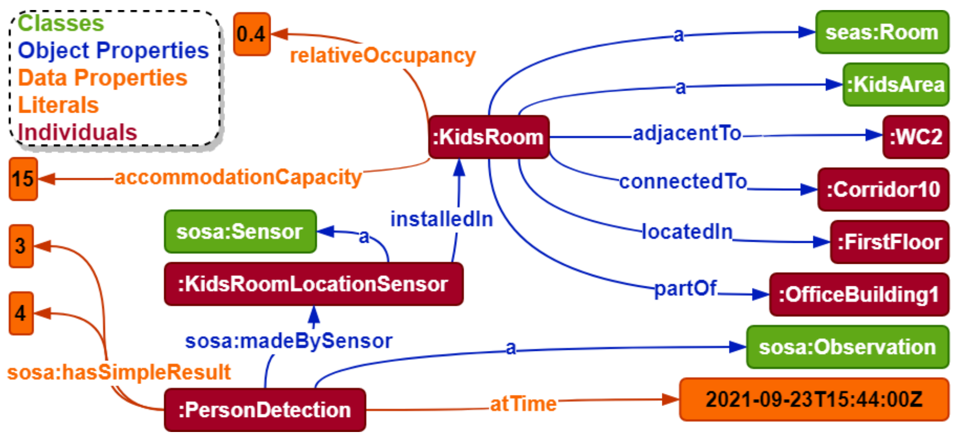

Fig. 4. Building space and sensor modelling

Routes. A route is sequence of connected spaces which is used to go from a starting point to a destination. We can also represent the geometry of a building as a graph, consisting of nodes and edges, such that it can be used for routing purposes. The existing approach in RDF vocabulary for specifying sequences (e.g., a route in this case), i.e. `rdf:list`, is not efficient because finding or accessing any specific element in the sequence is tiresome. To be precise, it doesn't allow to access an element with an index. As a solution, Ordered List Ontology (OLO) provides a simple data structure to express the ordered lists, that can also be used to represent the routes. Moreover, the elements of the routes can also be accessed easily.

In this regard, `Route` is conceptualized as a sub-class of `olo:OrderedList`, and `RouteElement` is introduced to represent the nodes and edges of a graph based on the information about the building structure. The edges and the nodes of a graph are represented with the help of `Passage` (e.g., corridor, door, elevator, stairs) and `RoutePoint` (e.g., entrance, exit, waiting zone, assembly point) concepts respectively. It is a choice of an ontology user how he/she wants to express the routes. For example, e.g., either using nodes or edges. In terms of usage,`Route` is allocated to any `SocialUnit` using `assignedRoute` relation.

In terms of travel time, `TravelTime` class is defined with the help of n-ary relation. In this class, the time (using `hasValue`) from one point to another point (using `origin` and `destination` properties respectively, e.g., `Room`, `Door`, `AssemblyPoint`, `Exit`) can be mentioned for a specific person (i.e., `forPerson`).

Elements other than the building structure. `Device` concept is used to express the elements that are not a part of building structure. It includes `IncidentProtectionDevice`, `Displayscreen`, `Telephone`, etc. In addition, some concepts and properties are reused from SOSA ontology [24], to express the `sosa:Sensor` and its values. In terms of relations, `installedIn` property is used to mention the location of the space where a device is located (either permanently or movable), where as `uses` property is used to state who is using a specific device. An instance of a sensor is shown in Fig 4.

5.3. Context Model

The context model describes the concepts related to the situation of building and its occupants.

Activity and Event. By definition, activities are different from events. Because an activity is the happening that is being done by someone, for example visiting a museum, whereas an event is the happening of something, for example a fire in a museum. Due to this reason, `Event` and `Activity` concepts are stated separately. To cover the temporal dimension of them, `hasTimeDuration`, `endedAtTime`, and `startedAtTime` are used, respectively, to express the total time duration, ending time, and starting time, of any activity or event.

Some particular events are also defined in SBEO. For example, an `Incident` that expresses an unexpected event or occurrence that may result in property damage or may cause a serious injury or illness to people. Furthermore, it has also been classified in some evacuation-related concepts, such as `Congestion` and `Panic` (including `Stempeding`). In addition, activities may also be divided into different categories, such as `Navigation`, `EmergencyActivity`, `Visit`, whereas a social unit who is involved in a specific activity is linked with it using `performedBy` relation.

SBEO also conceptualizes intensity, severity, and the impact of an event or activity. As we know that the impact and the severity of an event or activity may differ for each person, we created n-ary relation to express these concepts in the ontology. On the other hand, the intensity of any event or activity remains the same for everyone. Thus, it is expressed using a class `Intensity`, along with a `hasIntensity` relation. Fig. 5 shows a fire event (i.e., :Fire1) and and evacuation activity (i.e., :Activity1), along with their intensity, severity, and impact.

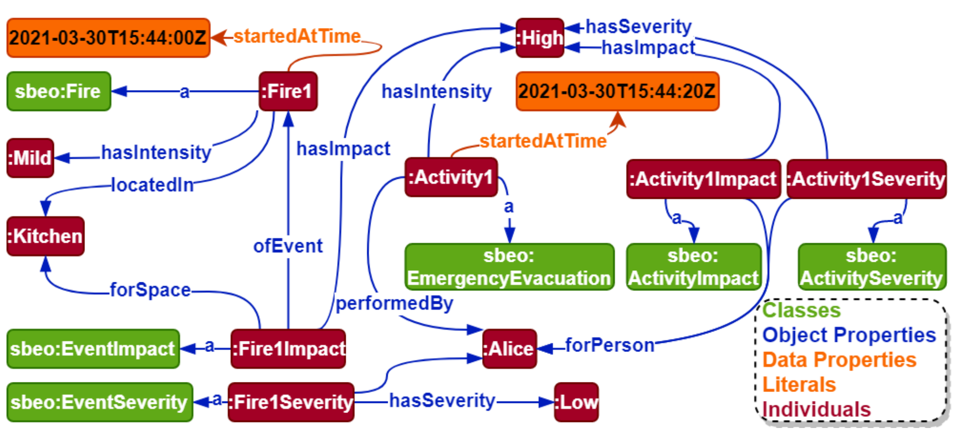

Fig. 5. Activity and event modelling

State and status of individuals. Various states and statuses of individuals related to their motion, navigation, fitness, and deviation, are also described in SBEO. For example, the state of their motion is expressed with the help of `motionState` property whose range can be either of the instances of `MotionState` class. These instances are explicitly enumerated as `Standing`, `Walking`, `Scooting`, `Running`, and `Rolling` (e.g., persons who use a manual wheelchair). The state of the navigation of the individuals using `hasNavigationState` whose range can be either of instances of `Navigational State` class (i.e., `DeviatingFromPath` or `FollowingPath`). The deviation is further divided into multiple types using `hasDeviationState` relation, whose range can be one of the individuals of `DeviationState` class, i.e., `NoDeviate`, `RareDeviate`, `OftenDeviate` , or `TooOftenDeviate`.

In terms of status, `hasActivityStatus` relation is used to express the instantaneous information about an activity being performed by an individual whose range can be one of the instances of `ActivityStatus` class, for example `Evacuating`, `Evacuated`, `Visiting`, `PickingUpDependents`. Furthermore, `hasFitnessStatus` property states the fitness status of a person that can be either `Fit`, `Exhausted` or `Injured`.

Group and role in a context. Two or more persons can be expressed as a `Group` if they are involved in any common activity (e.g, `Evacuation`, `Visiting`, `PickingUpDep endents`), having family- or friend- ties or an acquaintance, or sharing a common space (e.g., located in the same building, room or building floor). In addition, `hasMember` and `size` properties state the members and the size of a group respectively. If a person becomes responsible or a leader of a social unit (e.g, person or even a group), he/she can also be expressed with the help of `responsibleTo` property.

In terms of role, `RoleInContext` concept is introduced based on n-ary design pattern. It consists of three properties named `role`, `player`, and `context`, to express the information about a role of a person, the person identity, and a context (e.g., `Activity`, `Event` or `SocialUnit`) in which a person is playing that role, respectively.

Space safety and accessibility. The safety of a particular space tells us how safe the space is, for a specific person (or types of persons). On the contrary, the accessibility of a space tells us how accessible the space is, for a specific person (or types of persons). Due to this reason, as the safety and the accessibility of a particular space may differ from one person (or types of persons) to another, two different parameters are introduced; `SpaceSafety` and `PersonAccessibility`. Both of these concepts are linked with the specific space using `ofSpace` property whose safety/accessibility is required to mention, while `hasValue` and `forPerson` properties are used to express the safety/accessibility value of that particular space and the relevant persons associated with that value respectively. These concepts can be seen in Fig. 6, along with their usage. Note that the range of `hasValue` property of each parameter is taken as a fraction because it is a choice of the ontology user that how he or she wants to exploit it in a specific application.

In the context model, some other information related to building spaces is also described using various properties. It is as follows:

1. `relativeOccupancyRatio` - expresses the ratio of occupied to total usable (i.e., capacity) space.

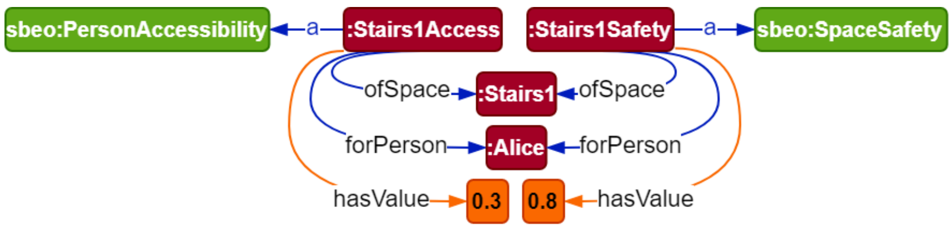

Fig. 6. Space safety and accessibility modelling

2. `accompanying` - a relation to mention who is accompanying whom in a particular space.
3. `speedFactor` - a value bound to any space (if applicable) that may affect the speed of individuals while passing through it. By default, it is equal to unity, but can be changed depending on various factors, such as `Congestion`, `relativeOccupancyRatio`.
4. `hasAvailabilitystatus` - states the availability status of any device, space or route as one of the instances of `AvailabilityStatus` class (i.e., `Available` or `UnAvailable`).
5. `excludedFor` - mentions any specific space that is not preferred (or incapable of accessing) by a person.

Potential Inferences. Inference in Semantic Web is a method of discovering new relationships between resources based on the existing data from the vocabulary. In this regard, some relationships are also inferred in SBEO based on the existing relationships among the individuals (instantiation) of the concepts. These are as follows:

- **Functional:** `hasAbility, hasAvailabilityStatus, hasDeviationState, hasFitnessStatus, hasImpact, hasIntensity, hasSeverity, hasValue, hasQuality, hasMotionState, hasNavigationalState, foaf:age, foaf:gender, accommodationCapacity, relativeOccupancyRatio, hasCongestion, startedAtTime, endedAtTime, hasXTimesDeviated, area, base, height, length, radius, size, speed, width, olo:ordered_list, olo:next, destination, origin, upper, lower`
- **Inverse Functional:** `olo:previous, upper, lower`
- **Transitive:** `accompanying, installedIn, leadsTo, partOf`
- **Symmetric:** `leadsTo, accompanying, acquaintanceOf, adjacentTo, connectedTo`
- **Asymmetric:** `responsibleTo, locatedIn`
- **Reflexive:** `acquaintanceOf`
- **Disjointness:** `adjacentTo and connectedTo, endedAtTime and startedAtTime`
- **Inverse:** `lower and upper, olo:next and olo:previous, olo:ordered_list and olo:slot`

6. Evaluation

Turchet et al. [59] mentioned that ontology designing is somehow a matter of subjectivity similar to the implementation of an algorithm, which is an interpretation of the computer programmer. Hlomani and Stacey [22] discussed several approaches, methods and metrics to evaluate an ontology. They found out that there are two major perspectives which are needed to evaluate any ontology; quality and correctness. Accordingly, SBEO is evaluated using various formal methods and approaches, and metrics, to find out its quality and correctness.

Ontology Metrics. Fernandez et al. [17] proposed twelve different measures to evaluate the ontology in terms of its generality and performance. In this study, we have shortlisted some of these metrics that fit the scope of SBEO. These metrics give an insight to the potential user of the ontology in terms of concepts and their relationships, popularity (i.e., current usage), and reliability (or availability).

Table 2. A comparison of SBEO with other ontologies in the field using 'Knowledge coverage and popularity measures' proposed by Fernandez et al. [17]

Ontology	No. of classes	No. of properties		No. of individuals	Direct popularity	Indirect popularity		
		Data	Object			Ontology Imports (Direct, Indirect)	Classes	Properties
SBEO	191	31	52	33	low	0, 0	21%	18%
SEAS (Building)	102	3	32	5	low	1, 8	34%	85%
SOSA	16	2	21	1	high	0, 0	0%	0%
SSN	23	2	36	2	very high	1, 1	21%	58%
empathi	237	98	171	10	low	9, 0	31%	98%
BOT	10	1	16	5	medium	0, 0	30%	0%

Table 2 shows a comparison of these ontology metrics of SBEO with other ontologies in the field and which are cited in the related works section. In the table, the number of properties is further divided into two sub-columns; object properties and data properties. As for the proposed ontology, there are 191 classes and 83 properties (both object and data) described in it in which 40 classes are reused from other ontologies, and the remaining 151 classes are created from scratch. The term direct popularity means how many existing ontologies are importing the given ontology, whereas inverse popularity [59] means how many concepts and properties are imported from existing ontologies to develop the given ontology. In this regard, as SBEO has been developed recently, its direct popularity is low. On the other hand, in terms of indirect popularity, concepts and properties from various four existing ontologies (i.e., seas, olo, sosa, foaf) are used in sbeo.

Oops! Pitfall Scanner. We have evaluated SBEO using a tool named Oops! Pitfall Scanner [43] that assesses an ontology qualitatively by checking its quality across three various dimensions, namely: structural, functional and usability-profiling. In addition, it also examines the consistency, completeness and conciseness of an ontology.

Among 41 pitfalls (i.e., checking points), 3 minor (i.e., P08, P13,and P22) and 2 important (i.e., P11 and P30) pitfalls have been identified due to: (1) missing annotations; (2) the absence of inverse relationships; (3) naming convention other than CamelCase; (4) missing domain/range; (5) some concepts seem equivalent. As regards, first, third and fourth points, depends on the concepts we have reused from the existing ontologies (i.e., SEAS, SOSA/SSN, OLO, FOAF) in SBEO. For the second point, most of the properties are either n-ary relations or do not support an adequate converse term, therefore these are exempted from this rule [62]. The justification of fifth point is, all of these concepts have different meanings in the proposed ontology, hence they will be kept in their current form.

The results from this tool imply that the quality of the proposed ontology meets the best practices. Consequently, critical problems related to modelling and reasoning might be avoided, such as logical inconsistencies or undesired inferences.

Reasoners to find any inconsistency. Three different reasoners—FaCT++ (version 1.6.5) [57], Pellet (version 2.2.0) [53], HermiT (version 1.4.3.456) [51]—have been used to check the logical consistency of SBEO, and no inconsistencies have been found in it. It implies that the SBEO classes may have instances (OWL individuals), and useful knowledge can be inferred from it.

Answering Competency Questions (CQs). The competency questions (CQs) are an important part to evaluate an ontology. In this regard, SPARQL-based queries are used to answer the competency questions stated in section 4. Due to the space issue, the answer to each CQ can be found here[14].

MIRO: Minimum Information for the Reporting of an Ontology Matentzoglu et al. in [36], defined some guidelines named Minimum Information for Reporting an Ontology (MIRO). According to them, MIRO guidelines provide a better level of completeness and consistency to an ontology documentation. Hence, SBEO is described using MIRO guidelines. The report[15] can be found on Github repository.

Task-based Evaluation - A Use-case Task-based evaluation is one of the methods to evaluate an ontology by measuring the quality of the results a specific application delivers [48]. In this regard, a simple scenario is described where SBEO is used to define the semantics for a smart building evacuation system. Due to the lack of the space the use-case of the scenario[16] can be found on Github repository.

7. Application example: CAREE

In this section, we describe a Context-Aware Emergency Evacuation (CAREE)[17] system, which uses SBEO ontology for knowledge representation. CAREE uses complex event processing and semantic stream reasoning technologies for analysing streams of data coming from sensors installed in a smart building, identifying emergency conditions (e.g. hazardous situations that can be dangerous for the safety of the occupants of the building) and proposing safe and efficient individual evacuation routes to the occupants

[14] https://github.com/qasimkhalid/SBEO/blob/master/Competency%20Questions.md
[15] https://github.com/qasimkhalid/SBEO/blob/master/MIRO%20Evaluation.md
[16] https://github.com/qasimkhalid/SBEO/blob/master/Examples/SmallOfficeSpace/Documentation/SBEO_TaskBasedEvaluation_SmallOfficeScenario.docx
[17] https://github.com/qasimkhalid/CAREE

of the building according to the context (status of the building and people's characteristics).

Fig. 7 shows a block diagram of CAREE architecture. The raw data from sensors (raw events) are annotated using SBEO and organised in several data streams according to their type (e.g., locations of people, temperature, humidity, and smoke).

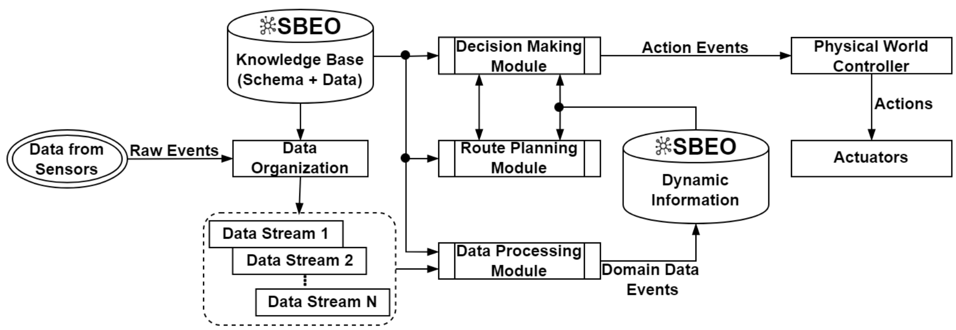

Fig. 7. The architecture of Context-Aware Emergency Evacuation (CAREE) software

The *Data Processing Module* aims to generate contextual information by processing data streams and static knowledge (i.e., building topology, user information). We use C-SPARQL[6]), an engine for processing continuous streams of RDF data. C-SPARQL[18] queries are attached to specific data streams to identify patterns in the data and generate pieces of contextual information (e.g. movement of people, fire detection, etc.). The contextual information is generated using SBEO ontology and is stored in an RDF repository on a real-time basis. For example, if *Sensor1* detects *PersonA*, and *Sensor1* is installed in *Office1* then the triple (*PersonA sbeo:locatedIn Office1*) is added to the context repository.

The *Decision Making Module* processes the information from Domain Data Events and the knowledge base running SPARQL queries. If a building evacuation is needed, it communicates with the *Route Planning Module* to get the optimal routes for each person. The *Route Planning Module* calculates available, safe and accessible routes to the persons depending on their physical characteristics and preferences, as well as the instantaneous situation of the building. Lastly, the *Decision Making Module* generates relevant Action Events according to the predefined criteria.

The actions events are then fed to the *Physical World Controller* such that specific actions could be performed as remedies to these events, such as assigning routes to persons, making hazardous spaces unavailable, and informing persons about the Points of Interest. The Physical World Controller works as a bridge between the system and the physical world (Actuators, i.e. IoT devices).

We have developed an agent-based simulated environment to test CAREE, where each person is considered a separate agent in a common and shared environment. We used Java and SPARQL languages for its development. Also, we have exploited Apache Jena and

[18] C-SPARQL language is a variation of the SPARQL query language for RDF, including stream processing characteristics such as windows and continuous processing

C-SPARQL frameworks to extract and update the SBEO-based data model. The simulator replicates the free-flow movements of people between two nodes that share a common arc and generates the values of Temperature, Smoke, and Humidity sensors, in a custom format. These simulated values are then fed into CAREE in the form of data streams after a customized time interval (e.g., one second). This simulated environment is deterministic in nature, and a scheduler is used to carry out the movement of each person in the building that gets updated after every timestep (e.g., one second). As soon as, any hazard is detected and the evacuation process is set off, the evacuation route (i.e., a path from a person's location to the nearest and feasible exit) is calculated in terms of timesteps and updated in the scheduler. Later on, the scheduler simulates the movement of the persons on each timestep until they reach their destination (i.e., exit). Once, a person reaches his/her destination, he/she is eliminated from the scheduler. Listing 1 shows a snapshot of the output of the simulator. This is updated after every timestep.

```
//Edge
(node#, node#) | cost | safety value | capacity
(node1, node2)    10        0.5          2
(node1, node3)    15        0.3          3
(node2, node3)    20        0.1          1

//Node
node# | safety value | capacity |  No. of persons positioned at a node
node1       0.0           14                     2
node2       1.0           10                     1
node3       0.4           10                     0
node4       0.6           16                     3

//Person
person# | location of a person
person1         node1
person2         node2
person3         node1

//Inaccessible edges list
person# | list of edges that are not apt for evacuation
person1             {} //empty set
person2             {(node1, node3)}
person3             {(node2, node3)}
```

Listing 1. Simulator output after every timestep.

According to the scope of the paper, we ran a simple scenario of a building floor in our simulated environment, as shown in Fig. 8. Each entity, such as space, floor exit, and fire extinguisher, is represented using Smart Building Evacuation Ontology (SBEO). Also, specific attributes of spaces, such as accommodation capacity, connections with other spaces, and the distance between the connected spaces (e.g., cost of each Origin-Destination (O-D) pair), are expressed.

In addition, the building floor is further represented as a graph **G** = (**N**, **A**), as seen in Fig. 9, with 17 nodes, where each node in **N** represents an entity shown in Fig. 8, e.g., closed space, junction[19], point of interest, or entrance or emergency exit. On the other hand, **A** represents the arcs between the connected nodes. We also assume that each node, as seen in Fig. 8 with a diamond symbol, is equipped with four types–Temperature, Smoke, Humidity, and Human Detection–of sensors and modelled using SBEO. In the end, we also modelled ten persons (including their demographics and physical characteristics) using SBEO, in which two of them are mobility impaired.

[19] A junction is an imaginary route element that connects multiple corridors or other route elements (i.e., nodes).

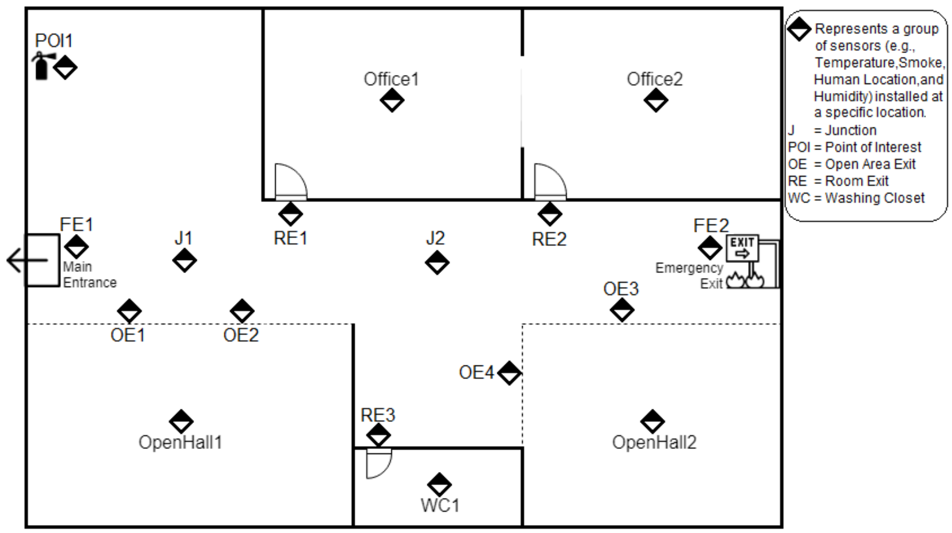

Fig. 8. A building floor plan with an entrance (which may also be an exit), an emergency exit and some closed spaces

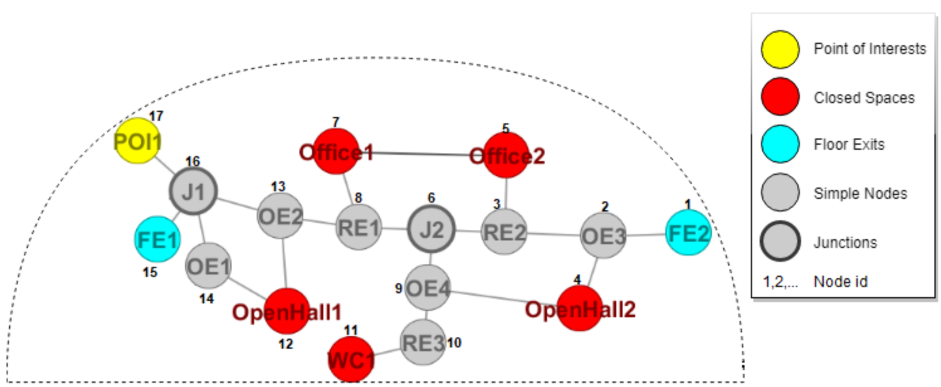

Fig. 9. Network modelling from a smart building floor plan. Nodes are labelled as names and Ids, and Arcs between two connected nodes are expressed as lines.

The access to a specific space is determined with the help of a `sbeo:hasSafetyValue` in SBEO. For this particular application scenario, it ranges between 0 and 1, which express the minimum and maximum safety, respectively. During the usual conditions, the safety of all spaces is 1, as the temperature and humidity are equal to 25 degrees Centigrade and 40%, respectively. On the other hand, we assume that the critical safety for both arcs and nodes is 0.5. Thus, the space whose safety is less than 0.5 is not apt for evacuation for mobility-impaired persons, whereas if it is equal to 0 is not apt for evacuation for anyone.

For the sake of simulation purposes, a fire event is triggered if the following conditions are met for a particular space altogether:

1. The temperature rises to 60 degrees Centigrade.
2. Humidity is less than 20%.
3. Smoke exists.

Here, we describe the results of the simulation-based experimental setup mentioned above. Initially, as we described earlier, at timestep t_0, the temperature ($temp$) of each space was 25 degrees Centigrade, the humidity (h) was 40%, and the smoke (s) was not detected. After each time interval (i.e., one second in this experiment), the temperature value of each sensor was randomly updated within the range of $temp_{t_{x-1}} + 5$ and $temp_{t_{x-1}} - 2$, where x is an integer that increases after each timestep, t. Based on the temperature value of a sensor, the humidity and safety values of the same sensor are also updated. For example, at timestep t_4, *Office1* (i.e., Node 7) had a safety value of 0.87, and one person was in it. Similarly, the corridor (i.e., arc) between *Office1* and *Office2* (i.e., (Node 7, Node 5)) had a safety value of 0.88. It implies that every person can access *Office1* and the corridor between *Office1* and *Office2*. Furthermore, *Person6* is located in *Office1* (i.e., Node 7).

Suddenly, at timestep t_{18}, fire event is detected on the arcs between *POI1* and *J1* (i.e., (Node 17, Node 16)) and *OpenHall2* and *OE4* (i.e., (Node 4, Node 9)). Subsequently, their safety values are also reduced to 0.44 and 0.47. As a result, the Decision Making Module updates the safety of these arcs not to be apt for evacuation to mobility-impaired people and sets off the evacuation process.

Once the evacuation process starts, the details of accessible space nodes depending on the allowed safety values concerning the type of each evacuee, along with the location of each person, are sent to the Route Planning Module. This module calculates feasible, and shortest paths using Dijkstra's Algorithm [13] for each person to evacuate the building by reaching either of the exits (i.e., *FE1* and *FE2*) from their current locations. We assume that one unit cost equals one timestep. For example, if a cost of an arc between two nodes is five units, it takes five timesteps to traverse that arc. Thus, the total cost of a path is equal to the cumulative cost of all the arcs involved. In this regard, each person evacuated the building (i.e., reached one of the safe exits) corresponding to the time equal to the cost of the complete route found and assigned to them by the algorithm.

8. Conclusion and Future Work

In this paper, a light-weight, but comprehensive, ontology was proposed for route recommendation in smart buildings during both normal and emergency conditions. The proposed data model provides the concepts and relationships for an efficient route planning in smart buildings. It includes the information about users, buildings and the context awareness.

The creation of the ontology is motivated by the need for facilitating the interoperability of smart gadgets and IoT-enabled buildings. The ontology is developed using a well-known methodology (i.e., METHONTOLOGY), and design patterns recommended by W3C. Furthermore, the ontology was evaluated using various metrics and methodologies, found consistent, and considered applicable in its domain. The proposed ontology is compatible and integrated with some popular ontologies such as SOSA, FOAF, SEAS, etc.

As a future work, we plan to integrate SBEO with the digital twin of a smart building in order to test its applicability and reliability. Afterwards, we will discuss the acquired results with the emergency response officers such that we might compare these results with the real data captured by them. That will allow us to evolve and evaluate the ontology based on the potentially expected real-world use-cases.

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