An Ontological Model for Fire Evacuation Route Recommendation in Buildings

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Abstract. Guiding the occupants of a building to a safe place is an area of research that deserves the attention of researchers. Finding solutions for the problem of guiding the building occupants requires a perfect knowledge of the fire building evacuation domain. The use of ontologies to model the knowledge of a domain allows a common and shared understanding of that domain. This paper presents an ontology that has the purpose to deepen the understanding of that domain and help develop building evacuation solutions and systems capable of guiding the occupants during a building evacuation process. The proposed ontology considers the different variables and actors involved in the fire building evacuation process. The ontology development followed the *Methontology* methodology, and for implementation, the *Protégé* tool was used. The ontological model was successfully submitted to a thorough evaluation process and is publicly available on the Web.

Keywords: Fire Building Evacuation, Ontology, Knowledge Model, Fire Route Recommendation, Fire Emergency, Ontologies, Knowledge Representation

1 Introduction

Guiding the occupants of a building in a fire emergency on their way to exit the building or reach a safe place is a problem that deserves the research community's attention. The real-time recommendation of evacuation routes is an approach to be considered. However, developing those solutions requires a deep knowledge of the building evacuation domain, which we can achieve by developing an ontological model. The motivation for this research work falls within the scope of our ongoing PhD thesis, which aims to propose and evaluate a multi-agent recommender system for real-time guiding the occupants to a safe place [1]. The system supports its development on an ontological model that considers the interoperability between the different actors involved in an evacuation route recommendation process, allowing a thorough knowledge of the domain. To build the ontology, we chose to divide our research work into two steps: In the first step, we developed an ontology for the evacuation of buildings under fire emergency [2]. Then, in a second step, and based on the referred ontology, we develop the ontological model presented here using [2] as the basis for the work.

Section 2 presents some relevant research works that propose ontologies to model knowledge in the emergency domain. Section 3 briefly introduces the ontology concept and describes how to develop an ontology. In Section 4 we present all the steps the to build the ontology, and section 5 describes how the ontology was evaluated. Finally, in section 6, we write the conclusions and future work.

2 Ontologies for the building emergency domain: Related work

Researchers commonly use ontologies to model the knowledge of a domain, and the building emergency domain is not an exception. In our literature review, we found many research works and here, we will highlight the more relevant ones addressing the fire building emergency field. The ontology SEMA4A [3] aims to include information sharing and support for the interoperability between systems and between people in an emergency, addressing the domains of emergencies, accessibility guidelines and communication technologies. Using SEMA4A ontology, [4] developed an extended ontology focusing on the evacuee's notification of safe places and evacuation routes. [5] present an ontology that considers fire control concepts and their relationships from the community's perspective. The ontology defines how the community members contribute to controlling fire. The "Emergency Response Ontology" [6] addresses intelligent emergency response applications, focusing on interpreting and filtering relevant information from a large range of heterogeneous data. The EMERGEL (Emergency ELements) ontology, developed by [7] in the scope of the DISASTER project (Data Interoperability Solution in Emergency Reaction Stakeholders), contains knowledge and concepts related to emergencies. The *EmergencyFire* ontology [8] aims to share knowledge of the fire emergency response in buildings, contributing to the organisations' tactical and strategic plans. [2] present an ontology for the evacuation of buildings under fire emergency that contributes to a better understanding of the fire building evacuation domain and to help the development of building evacuation solutions and systems.

The literature review identifies different ontological approaches to deal with the problem of emergency fire in buildings. Some of the approaches focus on fire control knowledge; others are concerned with representing fire safety knowledge, as is the case with occupants evacuation. However, we did not identify research works focused on developing ontologies whose focus is the recommendation of evacuation routes in real-time, which is the domain and scope of this research work.

3 Building Ontologies

According to [9], in computing and information science, the term ontology is related to an artefact that models the knowledge about a domain. In the 1980s, Artificial Intelligence (AI) researchers used the term ontology to refer to a theory of a modelled world or a component of knowledge systems [9]. However, there are multiple and contradictory definitions for ontology in AI literature [10]. In a widely cited paper, Grubber [11] defines ontology in the context of AI as an "explicit specification of a conceptualisation", where objects, concepts or other entities, and their relationships, represent knowledge within a domain. The ontologies contribute to a better understanding of a domain and truly help the interoperability between people and heterogeneous systems and, consisting of a set of terms representing concepts (hierarchically organised) and some specification of its meaning [12].

For ontology development, the most representative and commonly used methodologies [12] are TOVE [13], ENTERPRISE [14] and METHONTOLOGY [15]. The "Ontology Development 101" [10] is another widely followed methodology. As referred by [15] [12], independently of the used methodology, the development life cycle of an ontology typically follows a five stages process. The development process starts with the ***specification stage***, where we identify and define the scope and objective of the ontology. The following stage is the ***conceptualisation stage;*** the ontology is described through a conceptual model to meet the specification defined before, consisting of concepts in the domain and relationships between those concepts. The third stage is the ***formalisation*** **stage** and is where the conceptual model gives rise to a formal model. The next step is the implementation stage, under which the ontology is represented through a knowledge representation language. Finally, the last stage is the maintenance and includes updating and correcting the implemented ontology. During the whole development life cycle, the three following activities must be considered [16] [13]: Strengthen domain ***knowledge acquisition***, namely supported on the relevant bibliography or interviewing domain specialists; ontology ***avaluation;*** and ontology ***documentation.***

4 Building an Ontology for Fire Evacuation Route Recommendation in Buildings

We adopted the METHONTOLOGY methodology for ontology development, following the four main steps already described: i) specification, ii) conceptualisation, iii) formalisation, and iv) implementation. In addition, there was a systematic work of study throughout the development process to consolidate knowledge about the domain. Furthermore, the ontology development was also complemented with the respective documentation and evaluation in the different stages of the process.

As mentioned above, to build the herein presented ontology, we divide our research work into two phases. First, we start by developing an ontology for the evacuation of buildings under fire emergency [2], and then, we develop the ontological model presented in this paper, reusing that ontology. The ontology presented in [2] aims to develop a knowledge model about the thematic of buildings evacuation under fire, with the purpose that the ontology may contribute to a better understanding of the domain and help support the development of other ontologies related to the building evacuation domain, such as the one presented here.

4.1 Specification stage

We define the ontology's domain, scope, and purpose at the specification stage. According to [2], four main questions need to be answered: ***What is the ontology domain? Why build the ontology? What is the expected use of the ontology? What are the expected answers the ontology should give?***

As in [2], we will use a set of competency questions to help us to define the ontology's specifications and requirements.

Competency Questions	
Q1.	**How to transmit the alarm to the occupants?**
A1	The occupants are notified through audible alarms, previously recorded messages or visual alarms
Q2.	**How do the occupants behave in a fire emergency?**
A2	The occupant’s behaviour depends on personal characteristics and building knowledge. They also tend to follow the signage.
Q3.	**How do occupants know the location of building exits and safe zones?**
A3	Emergency signs identify the building's exits and safety zones and their routes.
Q4.	**How is the building evacuated? How are the evacuation routes identified?**
A4	The evacuation process must follow the building's organisation and management. The occupants follow the emergency signs and seek the support of building security staff, firefighters and police officers.
Q5.	**What type of emergency signage exists in the building? How could the emergency signage help occupants throughout the evacuation process?**
A5	Emergency signs are generally static and do not change during the evacuation process. However, dynamic emergency signage updated in real-time provides the occupants with better information about the safest evacuation routes.
Q6.	**What types of hazards are faced by the building occupants, and how do they influence the building evacuation process?**
A6	The hazards are toxic gases, smoke or route congestion. They influence the context in which the evacuation takes place, leading to blockage and congestion of the evacuation routes
Q7.	**How can context be captured and used to help occupants?**
A7	An occupant perceives the context that surrounds him. Context is captured by sensors installed in the building and used to help occupants get to a safe location.
Q8.	**How can context influence the evacuation process?**
A8	The context affects the evacuation routes and impacts how to evacuate the building.
Q9.	**How can the data produced by the sensors help the occupants in the building evacuation process?**
A9	The data produced by the sensors can be used to notify occupants and support an information system to help guide occupants through the building evacuation process.
Q10.	**How can the IoT (Internet Of Things) contribute to creating a solution capable of guiding occupants to a safe location in an emergency fire situation?**
A10	Sensors and digital signage can be IoT devices. The data collected by the IoT input devices (sensors, fire detection systems, smartphones) is sent to a central system for processing. That central system processes the data and presents (recommends) it to the occupants through IoT output devices (digital signage or smartphones).

Table 1. Competency questions and answers

The set of competency questions was formulated based on Portuguese legislation and regulations[1] and in a report [16] about the self-protective fire safety measures in buildings, published by the Portuguese National Emergency and Civil Protection Authority, and with the contribution of experts in the field. **Table 1** presents those competency questions and summarises relevant aspects of the answers to those questions.

Since the present ontology is based on the ontology presented in [2], to a certain extent, it also inherits the competency questions then considered. That is why we consider in this paper those most relevant to the scope of the ontology we present here, complementing them with new competency questions

From the above, the ontology domain fits the real-time recommendation of evacuation routes to the occupants of a building under fire emergency. As for the second question: Why build the ontology? This research work aims to build a representation model that addresses the real-time recommendation of evacuation routes to occupants in buildings supported on IoT. Concerning the expected use of ontology, the ontological model proposed here inherits from [2] the ability to strengthen and consolidate knowledge about building evacuation under fire emergencies. In addition, however, it adds the knowledge needed to support the development of evacuation solutions capable of guiding the occupants of a building in a fire emergency, such as the one we are developing and studying in the context of our PhD research work [1].

Regarding the fourth question, about the ontology's answers, we consider the set of competency questions [13] presented in **Table 1**. Besides helping to define the questions that the ontology must be able to answer, the set of competency questions will also be used to test the ontology at the evaluation stage. In **Table 2**, we define the ontology specification and requirements.

Ontology specification and requirements	
Ontology domain:	The domain is the real-time recommendation of safe evacuation routes to the occupants of a building under a fire emergency.
Ontology goal:	To develop a representation model that addresses the real-time recommendation of evacuation routes to occupants in buildings supported on IoT.
Ontology contribution:	Provides the ability to strengthen and consolidate knowledge about building evacuation under fire emergencies Provides a knowledge model to support the development of evacuation solutions to real-time guiding the occupants of a building in a fire emergency
Answers that the ontology should give:	• How does context influence occupant behaviour? • How can contextual information be used to guide occupants? • How does the type of emergency signage influence the evacuation process? • How is it possible to provide real-time information to occupants? • How are occupants guided to reach a safe place? • How is the building represented on the Recommender System? • How are evacuation route recommendations generated?

[1] Decreto-Lei n.º 220/2008 de 12/11 - Regime Jurídico da Segurança Contra Incêndios em Edifícios (SCIE)

Table 2. . Ontology specification and requirements

4.2 Conceptualisation stage

With the knowledge acquired during the specification phase, we need to describe the ontology through a conceptual model; that conceptual model consists of concepts or terms and the relationships between them, which we represent through a conceptual map built using the *mindomo*[2] framework.

The herein presented conceptual map was built on top of the "*Conceptual map of the Fire Building Evacuation Ontology*" [17], which was the basis of the ontology presented on [2]. Furthermore, based on the ontology´s specification and requirements summarized in **Table 2** and the answers to the competency questions summarized in **Table 1**, we immediately identify the following terms: *Route Recommender System*, *Internet of Things (IoT)*, *IoT Device*, *IoT Input Device*, *IoT Output Device*, and we build the conceptual map presented on **Fig. 1**, and available on [18]. As shown in **Fig. 1**, the conceptual map uses the "*Conceptual map of the Fire Building Evacuation Ontology*" [17], highlighting the terms to which the new conceptual map relates.

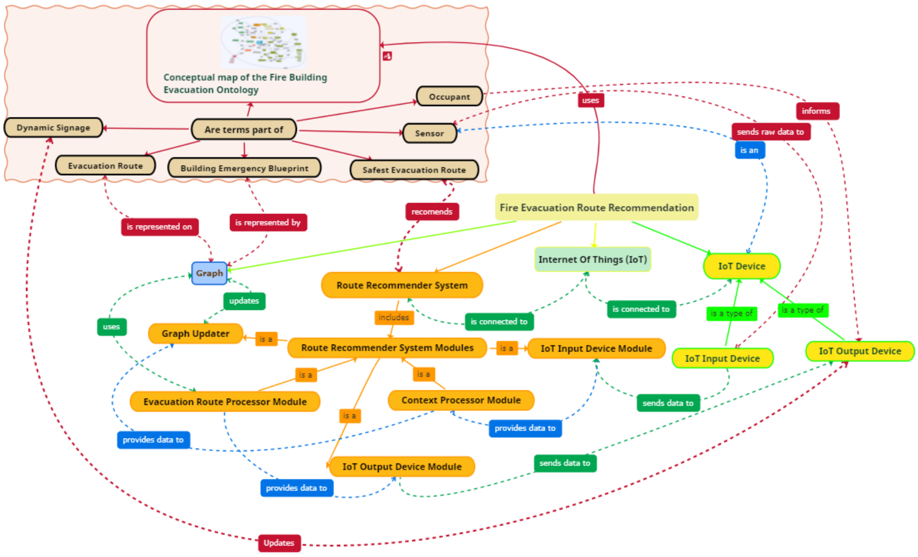

Fig. 1. Conceptual Map

[2] www.mindomo.com

4.3 Formalisation and implementation stages

The next step involves transforming the conceptual model into a formal one and implementing the formalised ontology in a knowledge representation language with *Protégé* [19], an open-source platform to construct and describe ontologies.

Based on the conceptual model presented in the previous section, we create and describe the 14 new classes, highlighted in **Fig. 2**, and 20 object properties that characterise the relationships identified in the conceptualisation stage.

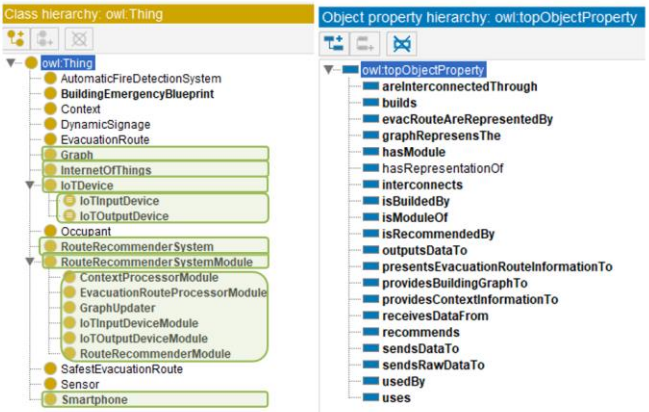

Fig. 2. List of classes and sub-classes

In **Fig. 3**, we exemplify the classes characterisation with the >*RouteRecommender-System*, with a *Protégé* screen capture.

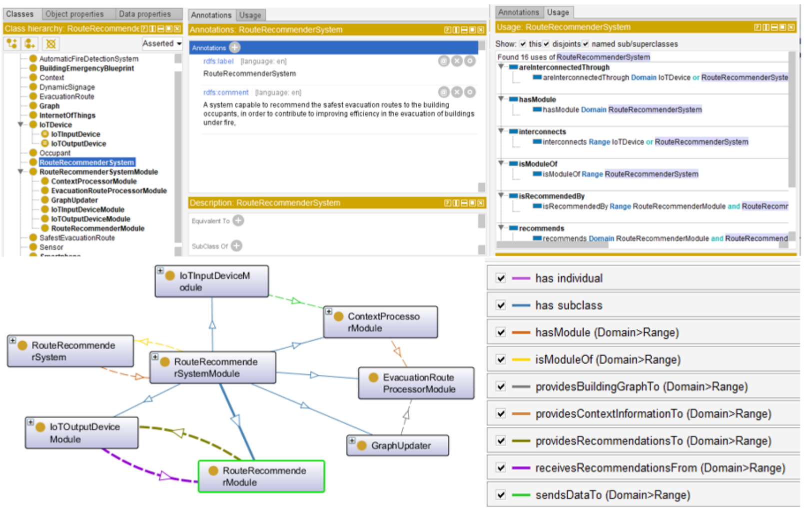

Fig. 3. Class representation on *Protégé*

Object properties set the relationship between instances of two classes [20]. For example, in **Fig. 4**, we present the example of the property *hasModule*, that defines a relationship between an individual of the class *RouteRecomenderSystem* (domain) and an individual of the class *RouteRecommenderSystemModule* (range), establishing that a Route Recommender System has modules, represented by instances of subclasses of RouteRecommederSystemModule class.

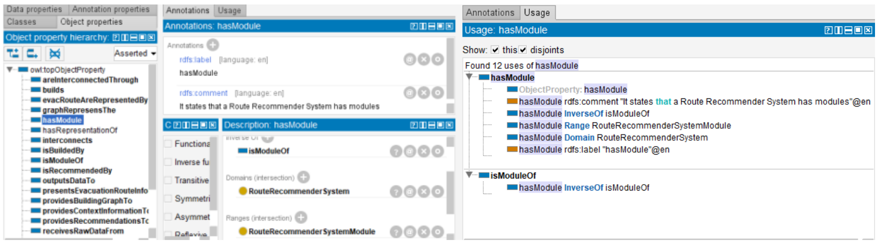

Fig. 4. The object property hasModule

Datatype properties refers to the relation of an individual of a class to a primitive value [20]. For example, in **Fig. 5**, we show the property *isAnIoTDevice*, which relates an individual of the inferred class (*DynamicSignage* ***or*** *Smartphone* ***or*** *AutomaticFire-DetectionSystem* ***or*** *Sensor*) to a primitive of type Boolean. The property states that an IoT Device is any individual of that class, if the property *isAnIoTDevice* equals *true*.

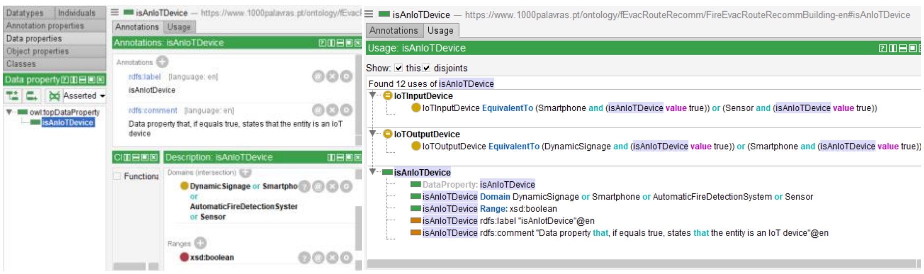

Fig. 5. Datatype properties in *Protégé.* The example of *isAnIoTDevice* data property

5 Evaluation

The ontology evaluation is an iterative process throughout the ontology's development cycle. It is a technical judgment of its content against a referential[21] that, in this case, is embodied by the ontology requirements and specifications described in **Table 2** and by the set of competency questions and answers summarized in **Table 1**.

As from [2], the technical evaluation of an ontology considers the aspects of ontology structure and architecture, namely syntactic class and properties validation. In addition, it also deals with aspects related to ontology documentation to ensure an adequate understanding of the ontology knowledge model. Our evaluation process used the Web tool, *Ontology Improvement Tool (V2)*[3], which provides tools and services for

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[3] http://perfectsemanticweb.appspot.com/?p=ontologyValidation

ontology validation and improvement, such as syntactic validation check, with the RDF *Triple-Checker*[4], ontology consistency, with the *OOps! (OntOlogy Pitfall Scanner)*[5] [22] or to verify if the semantic Web follows best practices[6,7,8], a service provided by *Vapour*[9]. The tests carried were completed and are available on the ontology URL[10]. To document the ontology, we used *WIDOCO*[11] [23]. This wizard identifies missing metadata and allows integrating other tools for ontology validation (with *OOPS*!), ontology terms documentation (with *LODE*[12]) and ontology visualisation (with *WebVowl*[13]). In addition, the WIDOCO tool produces a Web page ready for publishing.

We also evaluate the ontology against a referential, embodied by the specification requirements and the competency questions, which the ontology must answer. This kind of evaluation pretends to assess whether classes, properties, and axioms can answer the questions and requirements at the origin of the creation and development of the ontology. That can be done by querying the ontology using the *SPARQL* language. **Table 3** shows an example with axioms obtained with a *SPARQL* query, as well as a graphical visualisation provided by *Protégé's OntoGraf* plug-in.

Question	Axioms
How are occupants guided to reach a safe place?	1. *IoTInputDevice=>sendsRawDataTo=>IoTInputDeviceModule* 2. *IoTInputDeviceModule=>sendsDataTo=>ContextProcessorModule* 3. *ContextProcessorModule=>providesContextInformationTo=> EvacuationRouteProcessorModule* 4. *EvacuationRouteProcessorModule =>sendsSafestRoutesTo=>RouteRecommenderModule* 5. *RouteRecommenderModule=>providesRecommendationsTo=>IoTOutputDeviceModule* 6. *IoTOutputDeviceModule=>outputsDataTo=>IoTOutputDevice6* 7. *IoTOutputDevice=>presentsEvacuationRouteInformationTo=>Occupant*

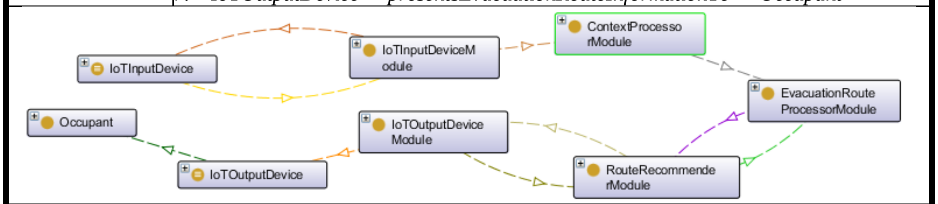

Table 3. Axioms obtained with SPARQL and related graphical representation

4 http://graphite.ecs.soton.ac.uk/checker/
5 OOPS! - OntOlogy Pitfall Scanner! (linkeddata.es)
6 Linked Data - Design Issues (w3.org)
7 Best Practice Recipes for Publishing RDF Vocabularies (w3.org)
8 Cool URIs for the Semantic Web (w3.org)
9 http://linkeddata.uriburner.com:8000/vapour
10 https://www.1000palavras.pt/ontology/fbevac/FireBuildingEvacuation-en.html
11 http://dgarijo.github.io/Widoco/
12 https://essepuntato.it/lode/
13 http://vowl.visualdataweb.org/webvowl.html

6 Conclusion and future work

The ontologic model proposed in this paper aims to make contributions to understanding the domain of real-time recommendation of safe evacuation routes to the occupants of a building under a fire emergency. The main purpose of this ontology is to develop a knowledge model capable of supporting the future development of more suitable building evacuation solutions and systems. The ontology was implemented with the *Protégé* tool and was successfully evaluated using tools available on the Web and against the requirements and competency questions formulated in the specification phase. The ontology is publicly available at the URI: https://www.1000palavras.pt/ontology/fEvacRouteRecomm/FireEvacRouteRecommBuilding-en. As future work, we plan to deepen the ontology by creating use cases to consolidate the knowledge model and support the development of the multi-agent recommender system proposed by [1].

7 References

1. J. Neto, A. J. Morais, R. Gonçalves, and A. Leça Coelho, "A Multi-agent System for Recommending Fire Evacuation Routes in Buildings, Based on Context and IoT," in *Communications in Computer and Information Science*, 2019, pp. 343–347.
2. J. Neto, A. Jorge Morais, R. Gonçalves, and A. L. Coelho, "An Ontology for Fire Building Evacuation," Springer, Singapore, 2022, pp. 975–985.
3. A. Malizia, T. Onorati, P. Diaz, I. Aedo, and F. Astorga-Paliza, "SEMA4A: An ontology for emergency notification systems accessibility," *Expert Syst. Appl.*, vol. 37, no. 4, pp. 3380–3391, Apr. 2010.
4. T. Onorati, A. Malizia, P. Diaz, and I. Aedo, "Modeling an ontology on accessible evacuation routes for emergencies," *Expert Syst. Appl.*, vol. 41, no. 16, pp. 7124–7134, Nov. 2014.
5. G. Liu, B. Xu, Q. Tu, Y. Sha, and Z. Xu, "Towards building ontology for community-based fire management," in *Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering, TMEE 2011*, 2011, pp. 1366–1369.
6. A. Hristoskova, F. Ongenae, and F. De Turck, "Semantic reasoning for intelligent emergency response applications," in *IEEE International Conference on Industrial Informatics (INDIN)*, 2013, pp. 547–554.
7. R. Casado, E. Rubiera, M. Sacristan, F. Schütte, and R. Peters, "Data interoperability software solution for emergency reaction in the Europe Union," *Nat. Hazards Earth Syst. Sci.*, vol. 15, no. 7, pp. 1563–1576, Jul. 2015.
8. K. Bitencourt, F. Durão, and M. Mendonça, "EmergencyFire: An Ontology for Fire Emergency Situations," in *Proceedings of the 21st Brazilian Symposium on Multimedia and the Web - WebMedia '15*, 2015, pp. 73–76.
9. T. Gruber, "Ontology," in *Encyclopedia of Database Systems*, L. LIU and M. T. ÖZSU, Eds. Boston, MA: Springer US, 2009, pp. 1963–1965.
10. N. Noy and D. McGuinness, "Ontology development 101: A guide to creating your first ontology," *Protege*, vol. 32, pp. 1–25, 2001.
11. T. Gruber, "Toward principles for the design of ontologies used for knowledge sharing," *Int. J. Hum. - Comput. Stud.*, vol. 43, no. 5–6, pp. 907–928, Nov. 1995.
12. H. S. Pinto and J. P. Martins, "Ontologies: How can They be Built?," *Knowl. Inf. Syst.*, vol. 6, no. 4, pp. 441–464, Jul. 2004.

13. M. Grüninger and M. S. Fox, “Methodology for the Design and Evaluation of Ontologies,” 1995.
14. M. Uschold and M. King, “Towards a Methodology for Building Ontologies,” 1995.
15. M. Fernández-López, A. Gomez-Perez, and N. Juristo, “METHONTOLOGY: from ontological art towards ontological engineering,” *Eng. Work. Ontol. Eng.*, 1997.
16. J. Pinheiro, “MEDIDAS DE AUTOPROTEÇÃO DE SEGURANÇA CONTRA INCÊNDIO EM EDIFÍCIOS.” Autoridade Nacional de Protecção Civil, 2012.
17. J. Neto, “Conceptual map of the Fire Building Evacuation Ontology,” 2020. [Online]. Available: https://www.mindomo.com/pt/mindmap/38f6214ddb874641b486f3fdc2a06f4a. [Accessed: 18-Jan-2021].
18. J. Neto, “Fire Evacuation Route Recommeendation,” 2021. [Online]. Available: https://www.mindomo.com/pt/mindmap/fire-evacuation-route-recommendation-2198e2da36074dd2939793a4a35f7cb4. [Accessed: 22-Nov-2021].
19. M. A. Musen, “The protégé project: A look back and a look forward,” *AI Matters*, vol. 1, no. 4, pp. 4–12, Jun. 2015.
20. W3C, “OWL Web Ontology Language Overview,” 2004. [Online]. Available: https://www.w3.org/TR/2004/REC-owl-features-20040210/#property. [Accessed: 08-Dec-2020].
21. [21] A. Gómez-Pérez, M. Fernández-López, and O. Corcho, *Ontological engineering : with examples from the areas of knowledge management, e-commerce and the Semantic Web*. Springer, 2004.
22. [22] M. Poveda-Villalón, A. Gómez-Pérez, and M. C. Suárez-Figueroa, “OOPS! (OntOlogy Pitfall Scanner!): An on-line tool for ontology evaluation,” *Int. J. Semant. Web Inf. Syst.*, vol. 10, no. 2, pp. 7–34, Apr. 2014.
23. [23] D. Garijo, “WIDOCO: A wizard for documenting ontologies,” in *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 2017, vol. 10588 LNCS, pp. 94–102.