From Diverse Sources to a Unified Framework: Constructing an Operational Ontology for Fire Management

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***Abstract*—Wildfires pose significant challenges that require interdisciplinary approaches and the integration of innovative technologies for effective mitigation. Designing a comprehensive ontology becomes essential to adequately capture and connect concepts from diverse disciplines involved in addressing this problem. However, the existing state of the art lacks a comprehensive ontology specifically tailored for wildfire management. This article outlines the process and efforts undertaken to develop such an ontology, aiming to fill this gap. The resulting ontology provides a unified representation of knowledge, facilitating information management and supporting effective fire prevention, detection, and environmental restoration efforts.**

Keywords—Wildfire, Operational Ontology, Taxonomy, Sensors, Tools & Resources, Biodiversity, Vulnerable objects, Climate

I. Introduction

In the field of complex domains such as wildfire management the design of a comprehensive ontology plays a vital role [1]. The SILVANUS project [2] offered an opportunity to develop such an ontology. The project's aim is the development of an integrated platform for effective wildfire management and emergency response. By leveraging interdisciplinary approaches and innovative technologies, it seeks to address the challenges posed by forest fires [3] and facilitate the prevention, detection, and restoration of fire-affected areas. For the development of an ontology capable of supporting wildfire management and emergency response, the state of the art was carefully analyzed to identify existing ontologies and taxonomies that could provide valuable insights and concepts. However, it became apparent that a single, exhaustive ontology did not exist. This highlighted the need to fill this gap and develop a new ontology that could serve as a foundation for managing information and interactions in the domain. Therefore, a systematic approach was taken to gather knowledge from multiple sources, including the data available to domain experts involved in the project and various relevant ontologies. This paper explores how concepts from said data and elements from the state of the art were studied and integrated to create an ontology which serves as a foundation for managing information and interactions related to wildfire management and for enabling effective prevention of fire, detection of fire incidents, and restoration of the environment.

An initial phase of domain analysis involved reviewing information from several sources and engaging with domain experts to extract requirements from internal knowledge. A set of macro-categories, including Sensors, Tools & Resources, Biodiversity, Vulnerable objects, Climate, Causes, and Fire were identified, contributing to the organization and structure of the ontology.

Subsequently, the state of the art was examined to identify existing ontologies and taxonomies relevant to the identified macro-categories. Several ontologies were discovered, each focusing on specific aspects such as crisis management, fire characteristics, fire causes, fire weather, environmental knowledge, forest inventory, weather phenomena, and emergency response. These ontologies provided a valuable foundation to build upon and ensure comprehensive coverage of relevant knowledge in the scope of wildfire management.

To create a unified ontology, concepts from the domain analysis and relevant ontologies were carefully analyzed and categorized into the identified macro-categories. Similar concepts within each macro-category were grouped together, and common classes were defined to represent them.

The resulting ontology, presented in various visual forms such as static HTML, graphical representations, and Protégé visualization, provides a comprehensive framework for managing fire-related information and interactions.

In the following sections, we will delve deeper into the domain analysis phase, the available ontologies and taxonomies, the analysis and choices made during the ontology's design, and the description of the ontology's structure and relationships. This paper highlights the importance of synthesizing knowledge from different sources to create a new and robust ontology that effectively supports the complex efforts of wildfire management.

II. Domain Analysis and Ontology Requirements

In the domain of wildfire management, effective management and coordination of various elements are crucial to mitigate the risks posed by forest fires. Several aspects need to be managed to enhance the prevention, detection, and restoration processes.

In accordance with the ontology life cycle proposed in the Ontology Summit 2013 Communiqué [4], as well as in the Methontology [5] paper, the first step is the collection of ontology requirements. To gain a comprehensive understanding of the domain, an initial analysis focused on internal knowledge. The knowledge available within the project was analyzed, including several sources and insights from the domain experts involved [6]. This internal knowledge provided valuable insights into the specific requirements and operational scenarios within the SILVANUS project. By exploring the internal knowledge, it was possible to identify relevant concepts and gather the necessary information to inform the ontology design. The sources of such knowledge included:

- Other sources: Information from other sources related to the operational scenarios in the project was reviewed and extracted. These sources provided valuable insights and knowledge.
- Knowledge from domain experts: Knowledge from the domain experts involved in the project was collected, as well as feedback and suggestions on the ontology draft design.
- Knowledge from data available to domain experts: The colleagues working on a related task have been in touch with domain experts to gather requirements from the data they provided. This activity helped extract relevant concepts for the ontology. The concepts varied depending on the specific geographical regions in which the data originated. As an example, Table 1 represents a sample of concepts extracted from data shared by experts working in the Indonesian region.

Table 1 Sample of concepts extracted from data made available by domain experts.

Concepts from Indonesian region data
Available data on biodiversity model
Soil parameters in post fire
Post fire condition images
Highest levels of biodiversity
Estimation of each species in the observation area
Satellite multispectral image
Forest growth
To measure the soil parameters during rehabilitation and adaptation, we need to install some instruments with IoT Support.

During the domain analysis phase, relevant information and requirements were gathered from domain experts operating in different geographical regions. The aim was to extract concepts related to fire prevention, detection, and restoration. The concepts varied across the geographical regions and included factors such as fire fronts, smoke amount, propagation direction, access paths, weather conditions, infrastructure, causes of fire, vegetation conditions, and various data sources.

The knowledge collected in the domain analysis and ontology requirements phase served as the foundation for our ontology, which is essential for managing various types of information and interactions within the project.

III. State of the Art

In addition to internal knowledge, the state of the art related to the requirements derived from the domain analysis was investigated. Existing ontologies, taxonomies, and relevant research in the field of wildfire management were explored. This exploration aimed to identify available resources that could contribute to the design of the ontology. The aim of analyzing the state of the art was to leverage existing knowledge and ensure comprehensive coverage of the domain's concepts and relationships. This paragraph discusses the already available ontologies and taxonomies considered for building the ontology.

The first ontology mentioned is the beAWARE ontology [7] developed by Catalink. It addresses the shortcomings of existing ontologies by encompassing all aspects of crisis management related to climate-related natural disasters, analyzed data from multimodal sensors, and rescue team assignments. It imports the Simple Knowledge Organization System (SKOS) [8], which provides a set of metadata fields for enriching ontology documentation. Specifically, they use skos:definition for providing the definitions of the classes and properties, and skos:example for providing examples of usage. Competency questions are provided for each aspect to guide the ontology design. The beAWARE ontology represents natural disasters, climate parameters, impacts, incidents, analyzed data, media items, vulnerable objects, rescue unit assignments, and more. It utilizes a dual scheme of abstract and specific notions and contains classes and relationships to capture the relevant information. Figure 1 serves as an illustrative example, showcasing the incident category and its associated concepts within the beAWARE ontology.

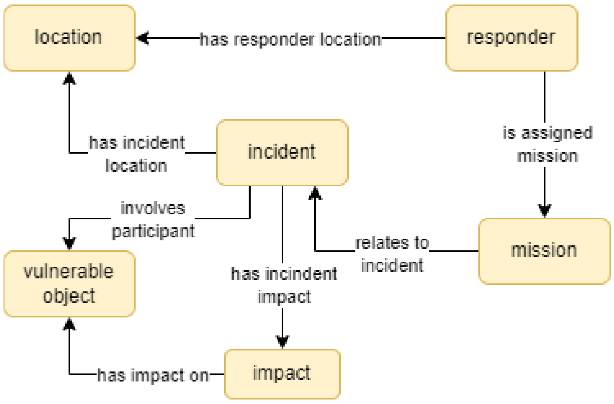

Figure 1 beAWARE's representation of an Incident with its related classes.

The Bioportal Fire Ontology [9] serves as the basis for modeling the concept of fire in the wildfire management ontology. Bioportal [10] is an ontology repository dedicated to advancing biomedical science and clinical care by providing software, support services, and ontologies that enable semantically interoperable knowledge and data dissemination on the Internet. The Bioportal Fire Ontology is a comprehensive ontology specifically designed to represent concepts related to fires occurring in natural vegetation, including their characteristics, causes, and effects. The ontology consists of 53 classes, 9 individuals, and 19 properties. The maximum depth of the ontology is 3, and the average number of children per class is 4.

The European Forest Fire Information System [11] (EFFIS) utilizes a taxonomy approved by the European Union to categorize fire causes. The taxonomy comprises four main classes (deliberate, accident/negligence, natural, unknown) and a hierarchical structure with 29 classes, 8 groups, and 6 categories. It offers comprehensive definitions for each class, covering factors like lightning, negligence, deliberate arson, and more. The JRC has also created a report mapping 22 European countries' fire cause naming schemes to the EU classification.

The Canadian Fire Weather Index [12] (FWI) System consists of six components that assess fire behavior based on fuel moisture and weather conditions. The first three are fuel moisture codes, rating moisture content of the forest floor and dead organic matter. The remaining components are fire behavior indices, measuring fire spread rate, fuel availability, and frontal fire intensity. These components rely on temperature, humidity, wind speed, and precipitation. The Daily Severity Rating (DSR) reflects fire suppression difficulty. The Initial Spread Index (ISI) estimates fire spread, while the Buildup Index (BUI) indicates available fuel. The Fire Weather Index (FWI) rates fire intensity and danger in Canadian forests.

The Bioportal Environment Ontology [13] (ENVO) is a community ontology that represents knowledge about environments, ecosystems, habitats, and related entities. ENVO promotes standardization and interoperability by describing environmental types across different levels of granularity. It integrates with other ontologies, such as Open Biological and Biomedical Ontology and is used in diverse projects. ENVO covers environmental systems (e.g., biomes) and environmental materials (e.g., soil, water). It aims to facilitate understanding of environmental entities and promote interoperability in ecological applications.

In the Cross-Forest project [14], a set of eleven ontologies was developed to represent forest inventory and cartographic data. These ontologies, such as the Third Spanish Forest Inventory (IFN3), Spanish Land Cover Map (MFE50), and Portuguese Forest Inventory (IFN6), provide standardized and interoperable formats for publishing forest data. The ontologies are modular, consisting of high-level ontologies for concepts like measures and positions, forestry modules for specific country data, ontologies for soil erosion and Iberian forest fire statistics. This modular design allows for easy understanding and selective loading of relevant data. Furthermore, the ontologies establish links to external ontologies to enhance data connectivity while ensuring safe reuse through explicit alignment.

The BIMERR Weather Ontology [15] is part of the BIMERR project, which focuses on Building Information Modelling (BIM) for the renovation of existing buildings. The ontology network within BIMERR aims to establish semantic interoperability in the construction industry by linking and mapping diverse standards, formats, and data models. One module within the ontology network is dedicated to weather phenomena and exterior conditions. It includes classes and relations such as Atmospheric Phenomenon, Humidity, Illuminance, Precipitation, Pressure, Temperature, and Wind. The ontology provides a framework for representing and analyzing weather-related data in the context of building renovation processes.

The Bioportal Emergency Situation Ontology (ESO) is designed to facilitate efficient decision-making and coordination among individuals involved in rescue operations during emergency situations. The ontology contains classes, individuals, and properties that describe various aspects of emergency response. The ontology includes relevant areas such as climatological disasters, losses due to fires, emergency response, involved response authorities, service providers, environmental features, vehicles, resources, and facilities. These classes provide a framework for representing and understanding the different elements and entities related to emergency situations and response efforts.

IV. Analysis and Choices

The two main sources of concepts for our ontology are domain experts' data and the relevant ontologies and taxonomies found in the state of the art.

A. *Concepts from Domain Experts Data*

The collection of raw concepts from the domain experts data was followed by the categorization of these concepts into macro-categories such as Sensors, Tools & Resources, Biodiversity, Vulnerable objects, Climate, Causes, and Fire. This allowed for the organization and structuring of the ontology. The next step was the definition of classes based on the collected knowledge, where similar concepts within each macro-category were grouped together and arranged in a way that facilitated the creation of common classes. For example, under the macro-category "Tools & Resources", concepts related to various types of Responders were grouped together. These included "patrol", "firefighting units", "volunteer fire brigades". These concepts were defined as the class "Responder", which represents the different responding units which can be assigned to a mission related to a fire event. Table 2 is a sample of the process carried out for all the collected concepts.

Table 2 Sample of the process of creation of common classes starting from raw concepts.

Area	Concepts	Class
Tools & Resources	Patrol	Responder
	firefighting units	
	Volunteer Fire Brigades	

Under the macro-category "Sensors", concepts related to various types of sensors and devices were grouped together. This included IoT sensors, drones, cameras, satellites, and more. These concepts were defined as classes such as "IoT Devices", which represents the different sensors and devices used for monitoring and data collection, "UAV" (unmanned aerial vehicle), "Camera" and more.

The macro-category "Tools & Resources" encompasses concepts related to firefighting units, vehicles, heliports, evacuation measures, and more. These concepts were grouped and defined into classes such as "Responder", "Vehicles", "Health resources", "Procedures" and more. These classes represent the tools, resources, and procedures used in firefighting and emergency response scenarios.

In the macro-category "Biodiversity," concepts related to vegetation types, soil, moisture, and post-fire conditions were grouped together. The Indonesian and Brazilian data were fruitful resources for this macro-category. These concepts were defined as classes such as “Biodiversity landscape”, “Vegetation type”, “Moisture”, and “Land use”. These classes capture relevant biodiversity aspects and environmental factors.

The macro-category “Vulnerable objects” included concepts related to urbanized areas, critical infrastructure, transportation, and more. These concepts were grouped and defined into classes such as “Urbanized areas”, “Critical infrastructure”, “Transportation”, and “Energy infrastructures”. These classes represent the various objects and areas that are vulnerable to fire incidents.

Under the macro-category “Climate”, concepts related to wind, temperature, precipitation, and atmospheric conditions were grouped together. These concepts were defined as classes such as "Wind," "Temperature," "Precipitation," and "Atmospheric pressure." These classes capture the climatic factors and meteorological data relevant to fire management.

In the macro-category “Fire”, concepts related to the characteristics of the fire were grouped together. These concepts were defined as classes such as “Fire speed”, “Active front numbers”, “Flame height”, “Fire type”. These classes capture the fire-related aspects used to represent the threat.

B. *Reuse of Existing Reference Ontologies and Taxonomies*

During the development of our ontology, existing ontologies and taxonomies were analyzed and incorporated to ensure comprehensive coverage of relevant knowledge. The aim was to merge these ontologies, highlight their strengths, and create a unified ontology that captured the key elements from each source.

To avoid cluttering our own ontology with irrelevant concepts, a decision was made to selectively replicate only the relevant entities from other ontologies. The "seeAlso" annotation was used to loosely link these replicated entities to their original ontologies, maintaining control over the ontology's content and allowing interoperability with other

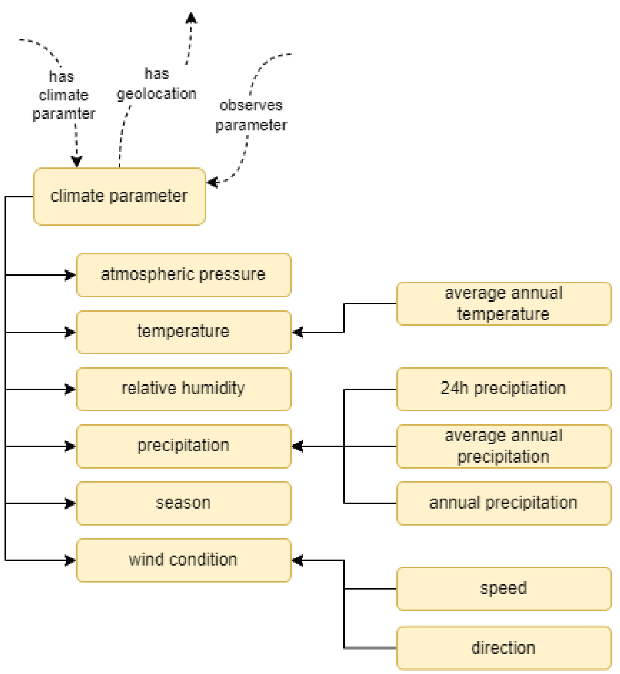

Figure 2 Zoomed-in view of part of the climate macro-category represented in Miró.

knowledge bases. Figure 2 illustrates some of the concepts imported for the climate macro-category.

The beAWARE ontology served as the starting base for our ontology. It included concepts related to infrastructure, structures, first responders, and rescue missions. Representing knowledge about these areas was considered valuable as wildfires can impact critical infrastructure and affect the work of first responders.

The Bioportal Fire ontology served as a foundation for modeling fire-related concepts in our ontology. It contributed classes for different types of fires, fire characteristics, fire risk, and spatio-temporal expansion.

The European Forest Fire Information System (EFFIS) played a significant role in harmonizing fire causes across European countries. To align with this shared taxonomy, all the causes reported in the EFFIS taxonomy were implemented in our ontology.

The Canadian Fire Weather Index System, crucial for wildfire prevention, contributed parameters such as temperature, relative humidity, wind speed, precipitation, and fuel moisture level. These parameters were included in the ontology to support fire weather calculations.

The Bioportal Environment Ontology (ENVO) contributed relevant classes, such as different types of roads, biomes, and land usage. These classes were aligned with their corresponding counterparts in our ontology.

The CrossForest collection of modular ontologies, like the Iberian Forestry Inventory Ontology (IFI), Iberian Land Usage Ontology (ILU), Spatial Position Ontology, and Simple Measures Ontology, enabled the representation of data related to forestry inventory, land use, spatial entities, and measures in different units.

The BIMERR Weather Ontology provided classes for weather-related concepts, including coordinates, sensors, atmospheric pressure, humidity, precipitation, temperature, wind conditions, and more. These classes were directly reused in our ontology.

The Bioportal Emergency Ontology contributed classes for various types of facilities, such as buildings, accommodations, communication facilities, education facilities, and medical facilities. These classes were incorporated into our ontology, enhancing its representation of emergency response infrastructure.

Overall, the merging of these ontologies and taxonomies allowed our ontology to capture the strengths of each source, create a unified representation of knowledge, and support interoperability with other systems in the domain of fire management and emergency response. Furthermore, this process of ontology development and integration has contributed to the guidelines related to fidelity and craftsmanship provided by the Ontology Summit 2013 Communiqué, ensuring the ontology's adherence to best practices and standards in ontology design.

V. Design and Description of Results

The work completed in the previous phases led to the completion and release of the first version of our ontology. The ontology has been made available in various visual forms to facilitate its understanding and consultation in accordance with the intelligibility guideline provided by the Ontology

Summit 2013 Communiqué. It is documented in static HTML format, which can be accessed on the SILVANUS website

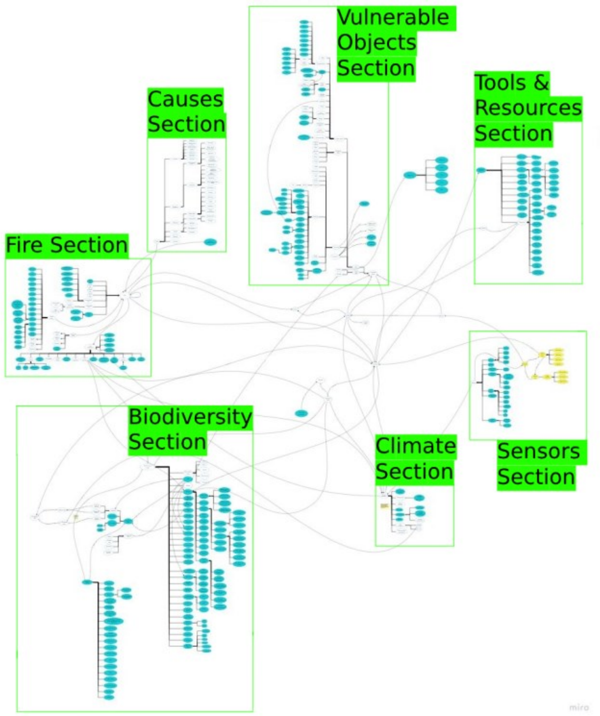

Figure 3 Bird's eye view of the ontology.

[16]. This documentation was produced using the Live OWL Documentation Environment (LODE) tool [17], which helps generate human-readable documentation from OWL ontologies. It is also visualized graphically (using Miró's virtual whiteboard [18]) to provide a high-level overview of the ontology's structure and relationships [19]. The graphical representation offers a bird's eye view that shows the macro-areas of the ontology, namely Fire, Cause, Biodiversity, Sensors, Tools & Resources, Vulnerable Objects, and Climate. Each macro-area can be explored in more detail, highlighting the classes and relationships within. Although impossible to read in detail at this scale, figure 3 highlights the macro-categories represented in the ontology from a bird's eye view to give an idea of its extension and modularity. Finally, a tabular visualization is available for more detailed exploration, primarily intended for developers using the ontology in their applications. Users familiar with the Protégé editing tool can access a Protégé visualization of our ontology.

The wildfire management ontology was developed through different approaches, namely terminology unification, creation of ontologies from scratch, and expansion of existing ontologies. The process involved gathering concepts from various sources, categorizing them, and determining common classes to represent similar concepts. The ontology was designed using the Protégé ontology editor [20], maintained by Stanford University, which provides a flexible and extensible environment for ontology development.

At the time of writing, the ontology is in the process of being populated through the first integrations with various data sources. These integrations are focused on incorporating data from IoT sensors, specifically sensors provided by project partners equipping Raspberry Pi devices with cameras, smoke sensing equipment and other relevant hardware, health-related sensors and data, and components from a social media analysis toolkit. These integrations aim to enhance and test the ontology by incorporating real data and information from different sources, enabling a more comprehensive and up-to-date representation of the domain. This ongoing process of data integration ensures that the ontology remains dynamic and adaptable to evolving scenarios. Moreover, this process aligns with the guidelines related to deployability provided by the Ontology Summit 2013 Communiqué, as it facilitates the practical implementation and utilization of the ontology in real-world applications and systems.

VI. Evaluation

In accordance with the guidelines provided by the Ontology Summit 2013 Communiqué, our ontology underwent a comprehensive evaluation process to ensure its quality, effectiveness, and suitability for its intended purpose.

The 2013 report is an effort in advancing the understanding and adoption of ontology evaluation practices. It discusses the challenges of evaluating ontologies, offers a model for the ontology life cycle and presents evaluation criteria in the context of the phases of said life cycle. The report recommends incorporating ontology evaluation strategies across all phases of the ontology life cycle and conducting evaluation against carefully identified requirements. The evaluation of our ontology encompassed multiple phases and criteria, as outlined below.

During the Requirements Development Phase, the rationale and expected benefits of the ontology were established. The ontology was deemed necessary to address the complex challenges posed by forest fires and to facilitate interdisciplinary collaboration and the integration of innovative technologies in fire management. Its intended usage encompasses fire prevention, detection, and restoration, serving as a knowledge framework and enabling interoperability among various stakeholders.

To determine the scope of the ontology and identify relevant concepts, a set of competency questions were formulated. These questions guided the development process and ensured that the ontology covered key aspects of fire management, such as sensors and devices, fire causes and characteristics, climatic parameters, resources and tools, critical infrastructure, biodiversity, and best practices. The competency questions were representative of the intended usages and provided a foundation for capturing the domain-specific knowledge.

The Ontological Analysis Phase aimed to verify the adequacy of the ontology in capturing relevant terms and entities within the defined scope. The documentation and unambiguous nature of the ontology were examined, along with the agreement of domain experts with the ontological analysis. The ontology successfully met these evaluation criteria, with feedback from experts helping refine the representation.

The Ontology Design Phase focused on the chosen ontology language, the expressiveness of the query language, and the adherence to design principles. The ontology was designed using the RDF language, which is widely adopted for ontology development. SPARQL, a query language, was chosen to formalize the competency questions. The design also emphasized the reuse of existing ontologies by selectively incorporating relevant parts and establishing loose links using the "seeAlso" property.

The System Design Phase examined the integration of the ontology within the overall system architecture. The operations to be performed using the ontology, the interfaces, data sources, and tools required for ontology development, evaluation, configuration management, and maintenance were considered. The system design phase ensured that the ontology would be compatible with the adjacent components and facilitated knowledge base population.

During the Ontology Development Phase, the informal and formal modeling results were evaluated. The ontology's fidelity, including the documentation of terms and the capture of entities within its scope, was verified.

The System Development and Integration Phase involved building the system as specified in the design phase and ensuring successful integration of the ontology with other components. A collaboration with project partners enabled the integration and operational adaptation of the ontology.

In the Deployment Phase, the ontology's compliance with requirements and its provision of new capabilities were evaluated. Although at the time of writing the project just only reached its halfway point, no outstanding problems were identified that would disrupt the deployment of the ontology.

Through rigorous evaluation following the guidelines provided by the Ontology Summit 2013 Communiqué, the ontology demonstrated its fitness for purpose, capturing relevant knowledge, meeting requirements, and supporting interoperability in the domain of fire management and emergency response. Notably, out of the 53 evaluation questions suggested in the Ontology Summit 2013 Communiqué, 44 questions were answered positively, corresponding to an 83% of compliance with the Ontology Summit 2013 Communiqué guidelines. This level of compliance reinforces the ontology's robustness and adherence to best practices in ontology development, further validating its suitability for practical application in the challenging domain of wildfire management. Ongoing maintenance and collaboration efforts with project partners aim to further refine and adapt the ontology for operational use.

CONCLUSIONS

In the context of the European project SILVANUS, which addresses the management of forest fire phases through a multidisciplinary approach and the utilization of diverse technologies, the development and implementation of an ontology became crucial. This ontology was designed to facilitate semantic interoperability among the numerous project modules and to establish standardized terminology. While the paper does not delve into the intricate details of the methodology employed, it provides a comprehensive operational ontology that emerged from the various stages of the project. The primary objective of this paper is to provide professionals involved in forest fire management with a well-founded ontology, adhering to the guidelines set forth in the Ontology Summit 2013, thereby providing them with a valuable starting point. Notably, this ontology was absent when the SILVANUS project was initiated, and it now serves as a fundamental resource for future endeavors in this domain. As our work demonstrates the successful synthesis of diverse knowledge sources and existing ontologies into a cohesive framework, future efforts will delve deeper into two key areas. One forthcoming paper will detail the methodology employed in constructing the wildfire management ontology, providing insights into the intricacies of its design and implementation. Another forthcoming publication will shed light on the dynamic evolution and operational deployment of the ontology, showcasing its adaptability in real-world scenarios and its pivotal role in enhancing fire prevention, detection, and environmental restoration efforts. These forthcoming works underscore our commitment to advancing the field and contributing to the ever-evolving landscape of comprehensive knowledge representation for effective crisis management.

ACKNOWLEDGMENT

This work has been supported by the Silvanus Project (Grant agreement ID: 101037247, Project Acronym: SILVANUS).

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