Towards an Ontology for User Activities on Smart Environments

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Abstract. *Most applications in smart environments must obtain data about their users and represent them (their context). One of the problems to be addressed in this domain is the user context representation. One of the main categories of context information in smart environments is user activity. This paper presents a mapping of the recent literature corresponding to human activity modeling using ontologies. Based on the results of this analysis, this work presents an ontology for representing human activities in smart spaces called ActivEOn. This ontology contains a high-level modeling of activities and related concepts that can be extended for specific domains. Two case studies using Protégé software demonstrated the developed ontology's potential.*

1. Introduction

Nowadays, the advent of technologies such as mobile computing and the Internet of Things allows the spread of smart environments. Examples of such environments include smart cities, smart homes, smart buildings, and smart classrooms. These environments usually apply the ubiquitous computing concept, where computing must be present in environments to assist the user in performing their daily tasks efficiently. These environments advance otherwise passive surroundings to become active partners for their users. Equipped with technology that enables them to perceive and respond intelligently, smart environments integrate various technologies, including artificial intelligence, sensor networks, and ubiquitous computing. They offer possibilities for improving our lives by providing assistance, convenience, and efficiency. Examples of applications include Ambient Assistive Living, which assists the elderly and people with disabilities in their daily activities, and Urban Environments. Smart environments also enable effective data-driven decision-making, trust communities, resource optimization, and interconnected environments.

Applications in smart environments must deal with dynamic conditions since the situation of resources and their users change frequently. Therefore, many of these applications and services can provide better results when using *context* information. Context is "any useful information to characterize the situation of an entity (a person, object or place) that may affect the interaction between users and systems" [Abowd et al. 1999]. Therefore, context-aware systems use this information to provide services that are most relevant to their users.

An important aspect of context information is how to characterize them. There are several context dimensions identified by different researchers [Perera et al. 2014]. When dealing with smart environments, a relevant context category is related to the actions or tasks performed by users, also known as *activities*. Examples of activities that context-aware systems can detect include walking, running, sitting, and the use of vehicles such as cars and buses [Nascimento et al. 2021].

When it comes to context-aware systems, a crucial challenge turns around the information exchange between these systems. The question arises: How can contextual information be shared among systems using a common representation pattern that all relevant agents can understand? This issue is fundamental for seamless communication and collaboration in context-aware environments.

In this context, the concept of *ontology* stands out. An ontology defines a common vocabulary within a specific domain. It includes a set of semantic definitions that are interpretable by computer programs, where the concepts of a domain and the relationships among them are defined [Noy et al. 2001].

This paper aims to present an investigation through a systematic literature mapping of recent solutions in representing human activities using ontologies. Based on the mapping results, we developed an ontology called *ActivEOn* (Activity in smart Environments Ontology) that allows semantically representing activities performed by users in smart environments.

The remainder of this article is organized as follows. Section 2 presents the analysis of the recent literature from the systematic literature mapping. In Section 3, the proposed ontology is presented. A case study is presented in section 4 to evaluate the ontology and demonstrate its potentialities. Finally, Section 6 concludes the article.

2. The Systematic Literature Mapping

The systematic mapping study presented in this paper followed the steps proposed in [Petersen et al. 2015] and answered answered the four Research Questions (RQ) presented below.

- RQ1: Which are the existing approaches for human activities modeling using ontologies?
- RQ2: What application domains were used?
- RQ3: How were the activities modeled?
- RQ4: Is there any specific approach for smart environments?

Aiming to perform the search to answer our RQs, we defined the following search string: *("human activity" OR "activities of daily living" OR ADL) AND (ontology OR ontological OR "knowledge-based model"OR OWL OR RDF)*. We performed searches for primary studies using the following databases and search tools: *ACM Digital Library*, *IEEE Xplore*, *Science Direct*, and *Springer Link*. We also applied additional filters in the search tools to select just studies in English, from 2018 to 2023, studies in the computer science area, and papers published in journals or conference proceedings.

To filter studies, we applied some inclusion and exclusion criteria, enabling us to answer our RQs. We employed the following inclusion (I) and exclusion (E) criteria.

- I1: Studies published in English.
- I2: Scientific papers of conferences or journals related to Computer Science.
- I3: Studies from 2018 to 2023.
- E1: Papers that do not present a primary study.
- E2: Studies with less than 4 pages.
- E3: Papers that are duplicates of other studies.
- E4: Studies that do not discuss human activity modeling through ontologies.
- E5: Opening of proceedings.

We conducted the SMS from October 2023 to May 2024. The initial search returned 1334 papers. The authors carried out two revision rounds on the returned papers. The first round comprehended the first filtering based on the metadata analysis like title, keywords, and abstract. As a result, we obtained 86 papers. In the second round, we went deeper, analyzing the introduction, conclusion, and other sections where the authors explained their proposals. Finally, we got a total of 32 papers showed in Table 1.

RQ1: Which are the existing approaches for human activities modeling using ontologies? The search results (Table 1) show that there are several recent approaches for human activities modeling through ontologies. The first analysis on these works was a counting of keywords present in the selected papers.

The *recognition* word appeared in about a third of the papers which indicates that most proposed ontologies were used in activity recognition solutions, as a component of a larger architecture. The presence of the word *smart* shows that several works present ontologies related to smart environments, such as smart homes, smart cities, and smart buildings.

The keywords *context*, *context-aware*, and *context-awareness* highlight the close relationship between the activity and context concepts. The activity modeling is included in ontologies that aim to model context (S1, S24). As described in other works in literature, activities are commonly used as part of the user's context. On the other hand, activities also have context. Several selected ontologies contain concepts describing activities context (S3, S11, S12, S28, S29).

RQ2: What application domains were used? Almost half of the works applied modeled human activities in the smart home domain (S2, S3, S4, S5, S6, S8, S9, S16, S19, S23, S25, S26, S27, S29, S30). The ontologies in these works describe *Activities of Daily Living* (ADLs) that mainly include activities of personal care (such as eating, drinking, sitting, walking, taking medicine, and using the toilet) and also activities related to housework (such as cleaning and food preparation). Most of the ontologies are used as part of a solution related to health care or elderly care contexts.

Other domains related to smart environments present in the selected works are *smart cities* and *smart buildings*. In these domains, activities are part of users' context (S24, S32), provide indicators that can provide relevant information about activities (S18), or related activities that can be done in certain Points of Interest (S15, S17).

Seven works present ontologies that are not related to a specific domain (S1, S10, S11, S12, S22, S28, S31). In general, these works present an upper-level ontological des-

Tabela 1. List of selected papers.

Id.	Title	Year
S1	3LConOnt: a three-level ontology for context modeling in context-aware computing	2019
S2	A collaborative semantic framework based on activities for the development of applications in Smart Home living labs	2023
S3	A Context-aware Hybrid Framework for Human Behavior Analysis	2020
S4	A Framework for Constructing and Augmenting Knowledge Graphs using Virtual Space: Towards Analysis of Daily Activities	2021
S5	A Knowledge-Based Approach for Multiagent Collaboration in Smart Home: From Activity Recognition to Guidance Service	2020
S6	A novel ontology consistent with acknowledged standards in smart homes	2019
S7	A Personalized Recommendation System to Support Diabetes Self-Management for American Indians	2018
S8	Activities of Daily Living Ontology for Ubiquitous Systems	2018
S9	Activity recognition using wearable sensors for tracking the elderly	2020
S10	An approach to the acquisition of tacit knowledge based on an ontological model	2020
S11	CAVIAR: Context-driven Active and Incremental Activity Recognition	2020
S12	Context-aware Adaptive Recommendation System for Personal Well-being Services	2020
S13	Cyber Identity: Salient Trait Ontology and Computational Framework to Aid in Solving Cybercrime	2018
S14	Decision Support Systems to Promote Health and Well-Being of People During Their Working Age: The Case of the WorkingAge EU Project	2020
S15	Deriving human activity from geo-located data by ontological and statistical reasoning	2018
S16	Domain Ontology Construction with Activity Logs and Sensors Data – Case Study of Smart Home Activities	2022
S17	Exploiting a multi-device knowledge meshing to agent-based activity tracking	2020
S18	Exploiting Smart City Ontology and Citizens' Profiles for Urban Data Exploration	2018
S19	Fuzzy-Based Fine-Grained Human Activity Recognition within Smart Environments	2019
S20	HeLiS: An Ontology for Supporting Healthy Lifestyles	2018
S21	Heterogeneous self-tracked health and fitness data integration and sharing according to a linked open data approach	2022
S22	Hybrid approach for anticipating human activities in Ambient Intelligence environments	2022
S23	Hybrid Approach for Human Activity Recognition by Ubiquitous Robots	2018
S24	Intelligent context-awareness system for energy efficiency in smart building based on ontology	2019
S25	Knowledge-Based Architecture for Recognising Activities of Older People	2019
S26	Modeling a User-Oriented Ontology on Accessible Homes for Supporting Activities of Daily Living (ADL) in Healthy Aging	2019
S27	Multi-modal activity recognition from egocentric vision, semantic enrichment and lifelogging applications for the care of dementia	2018
S28	Probabilistic knowledge infusion through symbolic features for context-aware activity recognition	2023
S29	Probabilistic Ontology Reasoning in Ambient Assistance: Predicting Human Actions	2018
S30	Stream Reasoning approach for Anticipating Human Activities in Ambient Intelligence environments	2022
S31	TAO: Context Detection from Daily Activity Patterns Using Temporal Analysis and Ontology	2023
S32	Towards an Extensible Context Model for Mobile User in Smart Cities	2018

cription of activities without specifying numerous activity subclasses. These high-level concepts can be specialized in domain ontologies. Other domains include the *physical activities modeling* (S7, S20, S21), *cybersecurity* (S13), and *working activities modeling* (S14).

RQ3: How were the activities modeled? Most works model activities from a main concept called *Activity*. There are several properties related to this concept. Each work used a different list of properties, most applicable to the problem modeled by each one.

Two works defined properties related to the identification and description of activities. The other two works defined properties of goals and motivation of activities. The selected activities are executed by people, and it is crucial to model information about actors who are directly involved in the activity execution and about other individuals who participate. Several works presented properties related to the activities' context. Most context properties specify the locations where activities take place. Location is important information to understand the context of activities. For example, if a person is *driving*, it can be important to know in which street the person is located on. Other context information modeled as properties in the analyzed papers include information such as social context, physiological context, and information about speed and number of steps.

A time when an activity occurred is another essential information. Most works define at least one property related to time. This information is modeled in different forms: some papers are concerned just with an instant of time of activity occurrence, while others are concerned with the time interval when an activity took place and the time duration of the activity development.

In smart spaces, activities usually involve the use of one or more resources. These resources can include things such as sensors, objects, tools, devices, vehicles, or software systems. These resources can be essential to the development of the activity (for instance, a driving activity needs the resource car) or can affect the activity in some manner (a *traffic light* can affect the activity *driving*).

Some works associate a type to an activity, model the situation before and after the execution of the activity (activities can change the environment state), and also define properties to specify the effects of an activity (such as changes in the environment or the event triggering). Some works are concerned with modeling the requisites of an activity (what is necessary or desirable for the activity development). Activities can need a specific place to occur, or they can need a specific resource. The activities also can require that actors are not in specific places or do not use a specific resource.

Finally, there are properties related to the composition of activities. Some works divide an activity into small parts, called *actions* or *tasks*. These parts can be viewed as smaller activities that can themselves be partitioned. Activities themselves can be part of other larger activities. The parts compound a sequence of actions that is specified in a set of properties that define what are the next activities and/or what are the previous ones. Some properties were used to specify sequencing numbers or indexes to define what is the position of specific parts in the sequences.

RQ4: Is there any specific approach for smart environments? Most analyzed approaches (62,5%) are applied to smart environments. As described in the response for RQ2, most solutions are related to smart homes. Four works are focused on smart cities (S15, S17, S18, S32), and one on smart buildings (S24).

Therefore, there are ontologies defined in the literature for activity modeling in smart spaces. However, they are specific for certain types of environments and their application in other domains is restricted.

S1 and S22 present upper-level ontologies that contain a multi-domain specification for activities. However, these ontologies present a restricted set of properties (S1 provides properties for the specification of actors and the activity's environment and S24 provides properties for location and objects used in the activity).

3. Ontology

The systematic mapping study showed common model decisions for human activities modeling using ontologies. The analyzed works present an interesting set of different properties that can be associated with activities to model related information (as described in the discussion about RQ3). However, there are no analyzed ontologies that present a complete set of classes and relationships that can model activities and their contexts in different smart environments.

Therefore, as far as we know, no work in literature presents an ontology that can model human activities in different smart environments. This work intends to fill this gap. From the collected information, we developed an ontology called ActivEOn (Activity in Smart Environment Ontology) that models high-level concepts and properties related to activities and can be extended to represent specific domain terms.

An overview of the ontology is shown in Figure 1. The presented diagram uses OntoUML [Guizzardi et al. 2018] language to model the ontology.

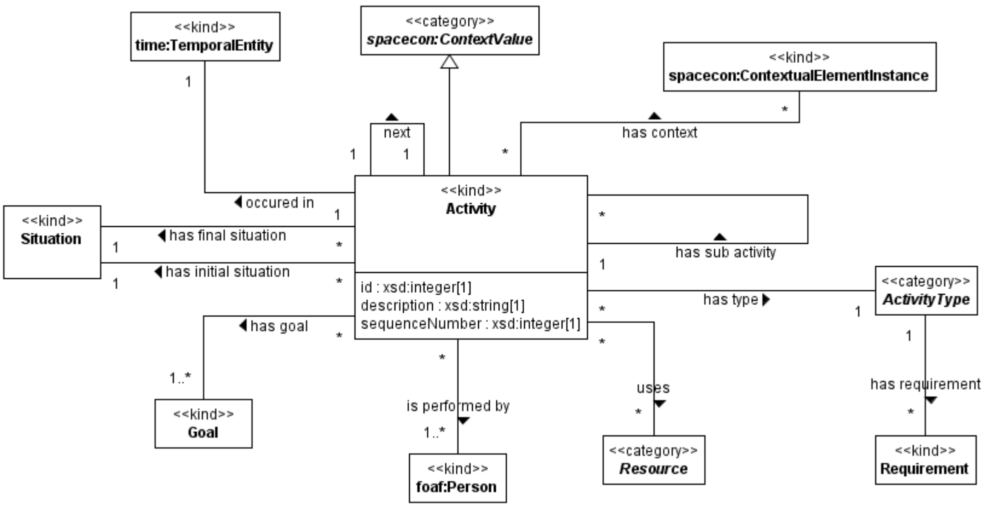

Figura 1. ActivEOn ontology concepts and properties.

The main concept in the ontology is *Activity*. This concept is related to an activity that occurred or is occurring. Each activity is associated with a unique numerical identifier (ID) and a description. We considered an activity as part of the user's context. Therefore, use modeled the Activity class as an extension of the *ContextValue* concept, defined in the SpaceCOn [Nascimento and de Oliveira 2023] ontology. The goal of SpaceCOn ontology is to model context information in general. An activity is a context category and, therefore, is related to a subset of context information. The SpaceCOn ontology is not concerned with the representation of activities, but define general concepts that can be extended to model activities. The extension of SpaceCOn *ContextValue* concept allows an activity to be part of contextual information related to an entity.

A human activity is performed by one or more people. We decided to use the concept *Person* of the FOAF ontology[1]. FOAF define a set of several properties that can be used to describe an activity's actor.

Each activity goal can be modeled using the *Goal* concept (an activity can have one or more goals). This concept can be extended to include specific properties useful in some domains (for example, a desired final state).

The property "*occurred in*" allows us to specify the time information related to the activity. We chose to use the *TemporalEntity* concept from W3C Time ontology[2], which was reused by some of the analyzed ontologies. The *TemporalEntity* concept is generic enough to allows the inclusion of time intervals, time instants, or duration specifications in different ways.

Resources can be associated with activities through the use of property. The detailed modeling of resources can be different for each domain. For example, in a smart home domain, the SSN ontology can be used to model sensors and home objects can be modeled using some domain-specific concept. In smart cities, it is necessary to model resources such as vehicles, smartphones, and parking lots. Smart classroom resources can be modeled, for example, using the PLOM ontology [Atif et al. 2015].

Each activity can have a context that can be specified through one or more instances defined by the *ContextualElementInstance* concept from SpaceCOn. A contextual element instance is an attribute value of the activities' context. These attributes can be the location related to the activity, social context, environment context, and so on.

The situation before and after the activity can be specified through the "*has initial situation*"and "*has final situation*"properties. The modeling of situations is out of the scope of this work. However, there are works in literature that discuss the situation concept and its modeling [Almeida et al. 2018, Marilza Pernas et al. 2012]. Specific situation modelings can be defined as extensions of the *Situation* concept.

Activities can also be related to each other. An activity may have another activity that occurred immediately after (property *next*). It is also possible for an activity to be composed of other activities specified by the "*has sub activity*"property. The order of activity in a sub-activities sequence can be specified in the *sequenceNumber* property.

An activity has a type (for instance, walking, running, or driving), modeled in the *ActivityType* concept. This concept can be extended to model a specific taxonomy of activities used in a domain.

A type can have one or more requirements, represented by the *Requirement* concept. We decided to relate requirements to activity types and not to Activity concepts because requirements are conditions that should be true before an activity starts. As the Activity concept models an activity that occurred or is occurring, it is supposed that all

[1]http://www.foaf-project.org/

[2]https://www.w3.org/TR/owl-time/

the requirements have already been provided. Furthermore, all activities of a given type have the same requirements. For example, the *driving* activity type requires a resource *car*, while "*having breakfast*"must occur in the morning.

4. Case Studies

The ontology was implemented in OWL language using Protégé software [Musen 2015], version 5.5.0. The implementation used gUFO [3] as base ontology. The implementation of each class is summarized below.

- *Activity*
  - Subclass of *gufo:Kind*, *spacecon:ContextValue*
  - Restrictions:
    - activeon:isPerformedBy **min** 1 foaf:Person
    - activeon:hasInitialSituation **exactly** 1 activeon:Situation
    - activeon:hasFinalSituation **exactly** 1 activeon:Situation
    - activeon:hasGoal **min** 1 activeon:Goal
    - activeon:hasType **exactly** 1 activeon:ActivityType
    - activeon:next **exactly** 1 activeon:Activity
    - activeon:occuredIn **exactly** 1 time:TemporalEntity
- *Goal*
  - Subclass of *gufo:Kind*
- *Situation*
  - Subclass of *gufo:Kind*
- *ActivityType*
  - Subclass of *gufo:Category*
- *Resource*
  - Subclass of *gufo:Category*

To evaluate the capacity of the ontology to represent real-world situations, we used two case studies. The first one is based on the following scenario: *John is at a hotel in Technopolis downtown. It is noon and he is hungry. He opens a restaurant recommendation app on his smartphone and spends five minutes searching for vegetarian restaurants in the neighborhood. The app recommends three restaurants and John chooses one called Green Dreams. He takes his car and uses his navigation app to drive from the hotel to the restaurant. The restaurant is next to a public parking lot equipped with a panel that lists the available parking spaces. John uses the information provided by the panel to park in an available parking space. He spends fifteen minutes driving to the public parking lot and just two minutes parking the car. John spends one minute more walking to the restaurant. He enters the restaurant and spends thirty minutes having lunch.*

John was modeled as an individual of the class *Person* of FOAF ontology. We modeled five subclasses of *Resource*: *Smartphone*, *App*, *Car*, *ParkingLot*, and *InformationPanel*. We created individuals for each of these classes, representing resources used in the case study: *JohnsSmartphone*, *RestaurantRecommendationApp*, *NavigationApp*, *JohnsCar*, *PublicParkingLotNextToRestaurant*, and *InformationPanelAtPublicParkingLot*. We also created three subclasses of *ActivityType*: *Eating*, *Movement*, and *UsingApp*. An additional subclass of *Movement* was created called *Driving*. Six activity types have been

[3]http://purl. org/nemo/doc/gufo

modeled as individuals of these classes: one individual of class *Eating* (*HavingLunch*), two individuals of the class *Movement* (*GoingToPlace* and *Walking*), two individuals of the class *Driving* (*DrivingACar* and *Parking*), and one individual of the class *UsingApp* (*UsingRestaurantRecApp*).

We modeled three main activities in the scenario as instances of *Activity* class: "*searching for a restaurant*", "*going to the restaurant*", and "*having lunch*". These activities definitions in the Protégé software are shown in Figures 2 and 3. The activity "*going to the restaurant*"has been divided in three parts: "*driving to the restaurant*", "*parking*", and "*walking to the restaurant*". These activity properties can be viewed in Figures 4 and 5.

Figura 2. The modeling of the "searching for a restaurant"(b) and "going to the restaurant"(a) activities.

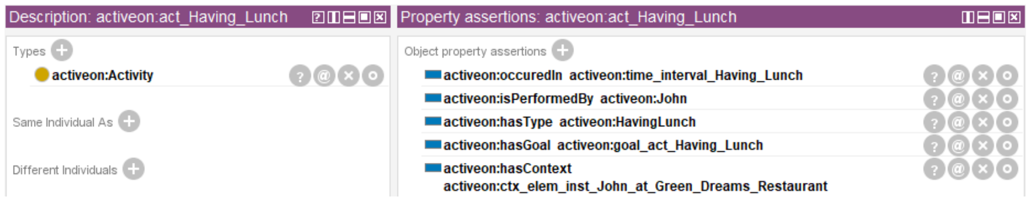

Figura 3. The modeling of the "having lunch"activity.

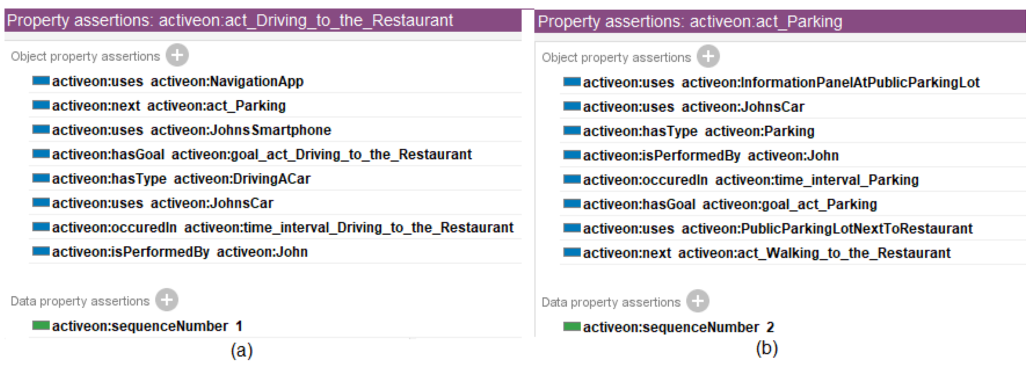

Figura 4. The modeling of the "driving to the restaurant"(a) and "parking"(b) activities.

The second case study is based on a home scenario: *Mary is sleeping on her bed when she is woken up by the alarm sound played by her home digital assistant at 07:00. She gets up and walks to the bathroom to take a shower of 15 minutes. The lights in the*

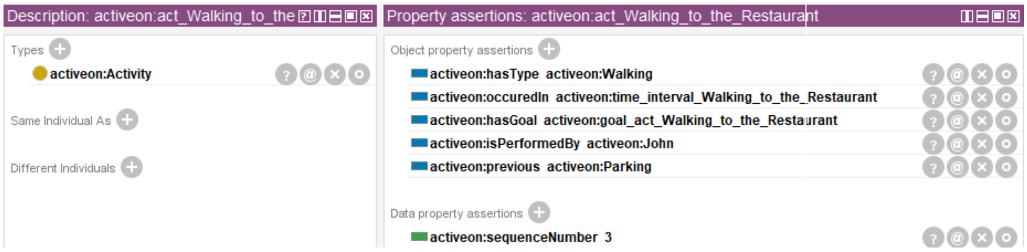

Figura 5. The modeling of the "walking to the restaurant"activity.

bathroom turn on automatically because of Mary's presence detection by a sensor. Then, she walks to the kitchen and makes coffee while she reads some messages on her phone and listens to her favorite music played by the home assistant.

Mary was modeled as an individual of the class *Person* of FOAF ontology. We reused the classes *Smartphone*, *App* from the previous example and modeled other five subclasses of *Resource*: *Bed*, *Shower*, *Coffee Machine*, *Presence Sensor*, and *Home Assistant*. The *Presence Sensor* class is also a subclass of *Sensor*, a classe defined in the SOSA ontology[4]. We created individuals for each of these classes, representing resources used in the case study: *MarysSmartphone*, *MessageApp*, *MarysBed*, *MarysShower*, *MarysCoffeeMachine*, *MarysBathroomPresenceSensor*, and *MarysHomeAssistant*. We reuse the individual *Walking* from the first case study and also created the following instances of *ActivityType*: *Sleeping*, *WakingUp*, *TakingAShower*, *MakingCoffee*, *ListeningToMusic*, and *UsingMessageApp*.

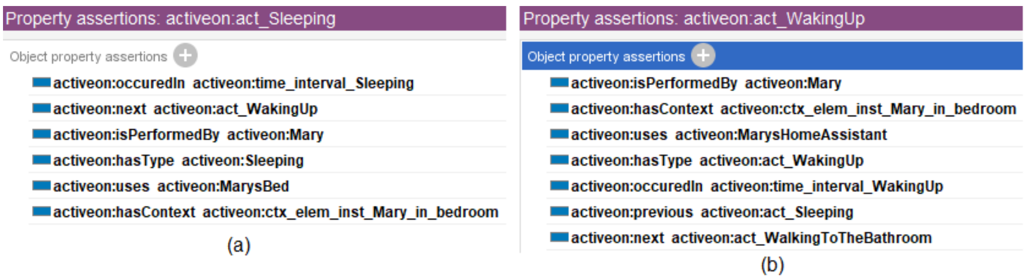

Figura 6. The modeling of the "sleeping"(a) and "waking up"(b) activities of the second case study.

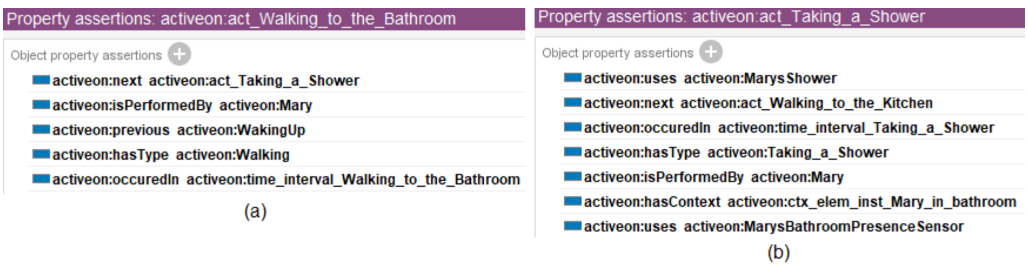

Figura 7. The modeling of the "walking to the bathroom"(a) and "taking a shower"(b) activities of the second case study.

[4] `https://www.w3.org/TR/vocab-ssn/#SOSASensor`

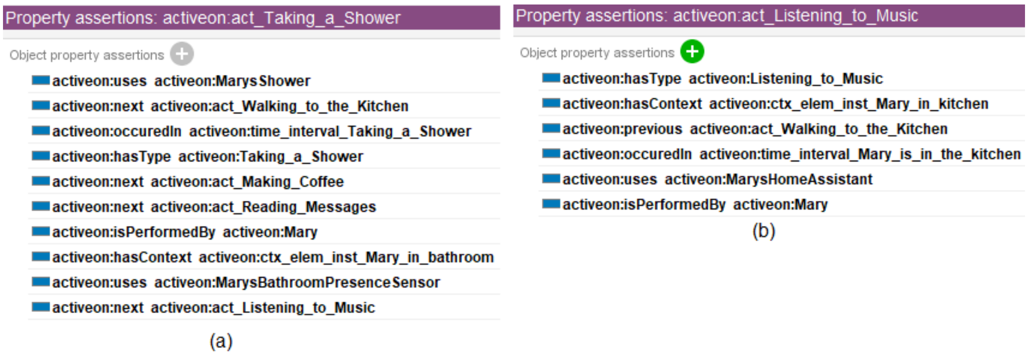

Figura 8. The modeling of the "walking to the kitchen"(a) and "listening to music"(b) activities of the second case study.

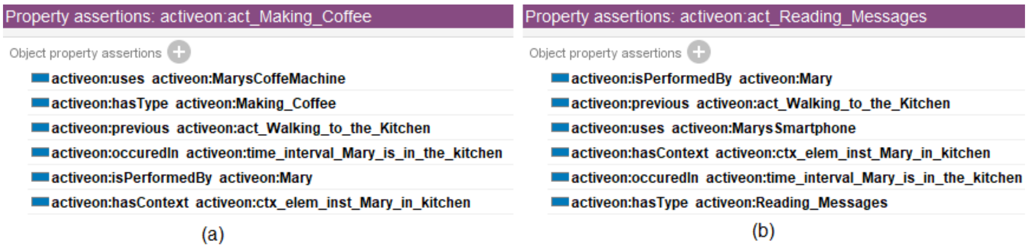

Figura 9. The modeling of the "making coffee"(a) and "reading messages"(b) activities of the second case study.

We modeled eight activities in the scenario as instances of *Activity* class: "*sleeping*"(Figure 6(a)), "*waking up*"(Figure 6(b)), "*walking to the bathroom*"(Figure 7(a)), "*taking a shower*"(Figure 7(b)), "*walking to the kitchen*"(Figure 8(a)), "*listening to music*"(Figure 8(b)), "*making coffee*"(Figure 9(a)), and "*reading messages*"(Figure 9(b)).

5. Discussion

Most ontologies identified in the systematic mapping study have been designed for specific domains: smart homes (S2, S3, S4, S5, S6, S8, S9, S16, S19, S23, S25, S26, S27, S29, S30), smart cities and smart buildings (S15, S17, S18, S24, S32). These classes and properties defined in these ontologies are useful to model activities that are specific to these domains, but that cannot be extended to other smart domains. For example, ontologies in smart homes are limited to modeling activities that occur inside homes and relating them to resources and locations that can be found in houses. Ontologies for smart cities relate activities to locations such as points of interest, and cannot be applied to domains where it is necessary to represent locations inside buildings, such as rooms. Furthermore, most of these ontologies have been designed with specific applications in mind, such as health care, elderly care, activities of daily living modeling, energy efficiency, mobile user context modeling, physical activities modeling, and work activities modeling. The case studies demonstrated that ActivEOn can be extended to model activities in different smart environments.

Seven analyzed ontologies are domain-independent (S1, S10, S11, S12, S22, S28, S31). Despite the possibility of application in different domains, these works lack properties for the representation of different resources (the focus is physical entities such as tools or objects) or different contexts (the focus is on location contexts) in a unique ontology. ActivEOn allows the association of activities with different resources (including non-physical ones, such as digital documents) and different contexts (such as user preferences, and weather conditions).

Few analyzed ontologies reuse others to model concepts such as time, context, or upper-level concepts. ActivEOn reuses ontologies such as W3C Time (for time-related concepts), SpaceCOn (for context-related concepts), gUFO (upper-level concepts), and FOAF (for actors modeling).

There are several practical uses of ActivEOn. As observed in Section 2, activities can be viewed as part of the user's context, and ActivEOn can be integrated with context modeling ontologies (such as SpaceCOn) to complement context modeling. ActivEOn is also an important tool to semantically describe activity-related terms in systems where there is data exchange, and it is crucial to ensure the correct interpretation of such concepts by all agents. There are several solutions for human activity recognition that can semantically enrich their results using ActivEOn. However, the time involved in processing the ontology can be an obstacle to the ActivEOn application in time-critical systems.

6. Conclusion

This paper presented a systematic literature mapping and an ontology called ActivEOn. The systematic mapping study analyzed recent literature on human activity modeling using ontologies. The analysis found several research papers that used ontologies to model human activities in smart environments, especially smart homes. The proposed ontologies defined several concepts and properties for activities, but each ontology failed to be generic enough to be applied to different smart environments, or the set of concepts and properties are limited. Therefore, the ActivEOn ontology has been proposed. The ontology defines a main concept called *Activity* and properties based on properties and concepts defined in the literature. The ontology is also extensible, and it allows the addition of new activity classes.

A case study was developed using the Protégé software. The developed scenario had reached the intended purpose of consistently representing context information. ActivEOn can be used with success to represent activities in a smart environment scenario. Furthermore, domain ontologies can extend ActivEOn to represent domain-specific concepts.

As future work, we intend to carry out new tests with the ontology in different usage scenarios. It is also intended to extend ontologies to model activities in specific smart environments, such smart campuses.

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