Applied Ontology 16 (4) 421–452
DOI 10.3233/AO-210255
IOS Press

Ontologies in Human-Computer Interaction: A Systematic Literature Review

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Abstract. Human-Computer Interaction (HCI) is a multidisciplinary area that involves a diverse body of knowledge and a complex landscape of concepts, which can lead to semantic problems, hampering communication and knowledge transfer. Ontologies have been successfully used to solve semantics and knowledge-related problems in several domains. This paper presents a systematic literature review that investigated the use of ontologies in the HCI domain. The main goal was to find out how HCI ontologies have been used and developed. 35 ontologies were identified. As a result, we noticed that they cover different HCI aspects, such as user interface, interaction phenomenon, pervasive computing, user modeling / profile, HCI design, interaction experience and adaptive interactive system. Although there are overlaps, we did not identify reuse among the 35 analyzed ontologies. The ontologies have been used mainly to support knowledge representation and reasoning. Although ontologies have been used in HCI for more than 25 years, their use became more frequent in the last decade, when ontologies address a higher number of HCI aspects and are represented as both conceptual and computational models. Concerning how ontologies have been developed, we noticed that some good practices of ontology engineering have not been followed. Considering that the quality of an ontology directly influences the quality of the solution built based on it, we believe that there is an opportunity for HCI and ontology engineering professionals to get closer to build better and more effective ontologies, as well as ontology-based solutions.

Keywords: human-computer interaction, ontologies, systematic literature review

1. Introduction

Human-Computer Interaction (HCI) is interested in the design, implementation and evaluation of interactive computer systems for human use, along with the phenomena related to this use (Preece et al., 2015; Carroll, 2014). It is a multidisciplinary area that aggregates a vast and multifaceted community, bound by the evolving concept of usability, and the integrating commitment to value human activity and experience as the primary driver in technology (Carroll, 2014). In the last years, the HCI area has expanded to include a myriad of interaction techniques and devices, becoming a host for emerging ubiquitous, handheld and context-aware interactions. Being such a diverse area, it involves a diverse body of knowledge and the landscape of HCI concepts is complex. In addition, as the HCI area continues to mature, new terms are proposed and new meanings are assigned to existing terms, which can result in semantic problems, hamper communication and knowledge transfer (Carroll, 2014; Preece et al., 2015).

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Ontologies have been successfully used to solve semantics and knowledge-related problems in several domains (e.g., (Ethier et al., 2018; Rodrigues et al., 2020; Zárate et al., 2020; Fonseca et al., 2017)). An ontology is a formal and explicit specification of a shared conceptualization (Gruber, 1995; Studer et al., 1998). It can be used for conceptual description, communication purposes, knowledge management solutions, semantic interoperability, semantic web, reasoning, among others.

Ontologies can be used as conceptual models (reference ontologies) as well as computational artifacts (operational ontologies) that can be read and interpreted by machines (Guizzardi, 2007) allowing automated solutions. The HCI area has benefited from the use of ontologies in many contexts, such as knowledge management in user interface design (Suàrez et al., 2004), accessible web applications engineering (Martín et al., 2010), elicitation of user interface design recommendations (Tourwé et al., 2011), reasoning about the usability of interactive medical devices (Bowen and Hinze, 2012), modeling of user interactions in virtual reality environments (Sokolowski and Walczak, 2018), consistency between user requirements and GUI (graphical user interface) (Silva et al., 2019), among others.

Considering the HCI knowledge diversity and the successful use of ontologies to solve knowledge-related problems in several domains, we decided to investigate the use of ontologies in the HCI context. Our main goal was to find out (i) how ontologies have been used to support HCI and (ii) how they have been developed. With (i), we intended to understand which portions of the HCI domain have been supported by ontologies and the types of ontology-based solutions that have been adopted to solve HCI problems. With (ii), we aimed to verify the quality of the ontologies used in the HCI domain. This is important because the quality of an ontology directly influences the quality of the solution that uses it. Therefore, we investigated how ontologies have been developed, evaluated and the quality characteristics they exhibit. To achieve our goal, we performed a systematic literature review (SLR).

A SLR aims to evaluate and interpret available research studies relative to a topic, area or phenomenon of interest (Kitchenham and Charters, 2007). By performing a SLR, we want to use a trustworthy and auditable method to make a review about ontologies in HCI and investigate specific aspects about their characteristics and their use in the HCI area. Considering that we also want to provide a panorama of this research topic with some general questions (e.g., about publications year and vehicle) and by means of classification and counting contributions in relation to categories of classification schemas, our SLR also presents characteristics common in systematic mappings (Kitchenham and Charters, 2007; Petersen et al., 2015).

As a result of our study, we found 35 ontologies. These ontologies cover different (and sometimes overlapping) HCI aspects related to user interface (UI), HCI phenomenon, pervasive computing, user modeling/profile, HCI design, interaction experience[1] and adaptive interactive systems. The ontologies have been adopted as conceptual models as well as computational artifacts. They have been used mainly to structure and infer knowledge, support reasoning, serve as a basis for developing systems (e.g., recommender systems) or other approaches (e.g., frameworks) and describe portions of the HCI domain. By analyzing the ontologies, we noticed that many of them do not exhibit important quality characteristics, which can hamper the quality of the produced ontology-based solutions.

The study results contribute to researchers and practitioners interested in HCI and ontologies by providing information about ontologies that have been used in the HCI context and how they have been used. This information allows one to reuse existing ontologies or be inspired by the ontology-based solutions to propose new ones. Moreover, the results reveal how ontologies have been developed, pointing

[1]Interaction Experience (IX) is a higher-level concept that encompasses user experience, usability and accessibility (Sauer et al., 2020)

out ontology engineering practices that should be considered when developing HCI ontologies, which can indicate opportunities for collaboration between HCI and ontology engineer professionals. Furthermore, gaps that arose from the study results can be addressed in new research, providing advances in the state of the art.

This paper is organized as follows. Section 2 presents the background for this paper and discusses some related works. Section 3 presents the followed research protocol. Section 4 addresses data extraction and synthesis. Section 5 discusses the findings. Section 6 regards the study limitations. Finally, Section 7 concludes the paper.

2. Background

In this section, we briefly present the background for the paper. Section 2.1 concerns HCI and ontologies and Section 2.2 discusses some related works.

2.1. HCI and Ontologies

HCI interest in interactive systems and their impact on people's life has promoted the study and practice of usability, a key aspect related to user efficiency and satisfaction when interacting with the computer. HCI is also concerned with other important qualities characteristics such as user experience, accessibility and communicability. It is a multidisciplinary area, involving knowledge from multiple fields, such as ergonomics, cognitive science, user experience, human factors, among others (Carroll, 2014; Preece et al., 2015; Sutcliffe, 2014). Since HCI is a complex knowledge area, ontologies can be useful to capture, organize and share the involved knowledge.

According to Scherp et al. (2011), ontologies can be organized in a three-layered architecture that discriminates between foundational, core and domain ontologies. *Foundational ontologies* aim at modeling the very basic and general concepts and relations that make up the world (e.g., objects, events, participation, parthood). *Core ontologies* provide a refinement to foundational ontologies by adding detailed concepts and relations in a specific field (such as service, process, organizational structure) that still spans across various domains. Finally, *domain ontologies* describe knowledge that is specific for a particular domain, such as a domain-specific medical ontology describing the anatomy of the human body. Its concepts and relations can make use of or be based on foundational ontologies or core ontologies by specializing their concepts.

In another classification, orthogonal to the one proposed by Scherp et al. (2011), Guizzardi (2007) differentiates between reference and operational ontologies. A *reference ontology* is a conceptual model, whose aim is to make a clear and precise description of the elements (concepts, relations, properties) of a conceptualization for the purposes of communication, learning and problem-solving. A reference ontology is to be used in an offline manner to assist humans in tasks such as meaning negotiation and consensus establishment. Such a consensual conceptual model can be coded in a computational language (e.g., OWL) to be then deployed in a computational environment. This implementation version is an *operational ontology*. Unlike reference ontologies, operational ontologies are not focused on representation adequacy, but are designed with the focus on guaranteeing desirable computational properties. In the HCI domain, ontologies have been used for several purposes. Some works (such as the ones by Storrs (1994), and Mezhoudi and Vanderdonckt (2015)) have used ontologies as a conceptual model to conceptualize the HCI domain. Others have used only operational ontologies. For example, in the work by Garay-Vitoria et al. (2019), an operational ontology about affective computing was used as a basis for developing Affective Interactive Systems. There are also works that take advantage of both reference and operational ontologies. Bakaev et al. (2019), for example, used a reference ontology about UI and UI measurement to structure and organize knowledge, while an operational version of the ontology was used in a tool to assess web UI using different metrics.

2.2. Related Work

In the literature, some works describe secondary studies that investigate aspects related to HCI. For example, Guerino and Valentim (2020) conducted a systematic mapping study to investigate usability and user experience evaluation technologies used by researchers and developers in software with natural user interfaces. Li et al. (2020), in turn, carried out a systematic literature review and investigated the essence, process and result of how tangible interaction with light is conceptualized. Other examples of systematic literature review in the HCI domain are the work by Maalej and Kallel (2020), which reports the effectiveness of using keystroke dynamics biometrics in recognizing emotions, and the paper by Gubert et al. (2020), which addresses the use of context-awareness in health, defining a taxonomy and identifying challenges and open questions.

We did not find a secondary study that focuses on ontologies in HCI. Hence, in the following paragraphs, we summarize some secondary studies that provide reviews of the use of ontologies in embedded systems (Sousa et al., 2016), software process assessment (Tarhan and Giray, 2017), higher education (Tapia-Leon et al., 2018) and liver diseases (Messaoudi et al., 2020).

Sousa et al. (2016) report a systematic mapping study performed to collect evidence about the need for ontologies in embedded systems development and the benefits of using ontologies in that context. The authors investigated the software processes in which ontologies were applied, the used ontology languages, the purpose of using ontologies, the obtained benefits, among others. 19 publications were selected for data extraction. Considering the purpose of use, ontologies were applied mainly to domain knowledge representation and to provide a common vocabulary to communication between the engineers and requirements representation. The benefits of using ontology in embedded systems were to guide requirements elicitation, deal with ambiguity and inconsistencies between the requirements, facilitate communication between engineers and promote non-functional requirements standardization.

Tarhan and Giray (2017) performed a systematic literature review to investigate the state of the art of the use of ontologies in software process assessment. Similar to the work by Sousa et al. (2016), the study investigated the software processes where ontologies were applied, the used ontology languages, the purpose of using ontologies, among others. Data was extracted from 14 publications. OWL[2] was the predominant representation language and ontologies were used mainly in general software process (i.e., there is no indication of any specific process), whereas some of the ontologies were applied in testing, project management and quality processes. Regarding the purpose of ontology use, most of the studies focused on knowledge representation, followed by ontology mapping and knowledge reasoning over their represented knowledge.

Tapia-Leon et al. (2018) carried out a systematic mapping focusing on uses of ontologies in higher education, as well as the methods, tools, languages and vocabularies used in the ontology development process. 52 publications were selected for data extraction. The results showed that ontologies were used mainly in higher education enterprise (i.e., to represent knowledge regarding components of a higher education institution), e-learning and academic recommendation. Concerning ontology development,

[2]World Wide Web Consortium (W3C) Web Ontology Language, https://www.w3.org/OWL/

the authors said that most of the papers (81%) do not specify the method used to develop the ontology. Moreover, most of the times, it was not possible to identify reused ontologies. Protegé[3] was the most cited tool, but most of the papers do not specify the used tool. Domain ontologies are the most common type of ontology, being represented by computable models in most of the analyzed works. As such, OWL is the primary used language, followed by RDF[4]/RDFS[5]. Most proposals define a theoretical or conceptual framework for the application or use of ontologies. Only 21% of the papers presented a partial implementation or testing in a specific use scenario.

Finally, Messaoudi et al. (2020) report a systematic literature review focusing on the use of ontologies to represent liver diseases. As in the aforementioned studies, the authors investigated the purpose of using ontologies in this context. The authors also looked for concepts with higher frequency rates. As a result, after extracting data from 39 publications, the authors noticed that the majority of the found ontologies were computational models. Therefore, the most recurrent uses were to process large medical data volumes, support decision system in some cases and also diagnosis process acceleration and assistance. Concerning the concepts, “TypesLiverDisease”, “RiskFactors”, and “Symptoms” had the highest frequency rate and, thus, the authors considered them the most useful ones.

Our study presents some similarities and also differences when compared to the ones cited in this section. As for similarities, as the works by Gubert et al. (2020), Guerino and Valentim (2020), Li et al. (2020), and Maalej and Kallel (2020), our work is a secondary study that investigates aspects in the HCI domain. Moreover, like in the works by Messaoudi et al. (2020), Sousa et al. (2016), Tapia-Leon et al. (2018), and Tarhan and Giray (2017), our work regards the use of ontologies in a particular domain. However, there are important differences between our work and the others. Although the studies carried out by Gubert et al. (2020), Guerino and Valentim (2020), Li et al. (2020), and Maalej and Kallel (2020) are secondary studies investigating HCI aspects, different from our work, they are not concerned with the use of ontologies in HCI. On the other side, even though the works by Messaoudi et al. (2020), Sousa et al. (2016), Tapia-Leon et al. (2018), and Tarhan and Giray (2017) concern the use of ontologies, they are not focused on the HCI domain. Nevertheless, since these studies investigated the use of ontologies in a particular domain, some investigated questions are similar to the ones investigated in our study. For example, all the studies investigated the purpose of using ontologies. As in the works by Tapia-Leon et al. (2018) and Sousa et al. (2016), we also investigated which portions of the domain of interest have been addressed by ontologies. Like Tapia-Leon et al. (2018), we also investigated aspects related to ontology engineering aiming to verify the quality of the proposed ontologies. However, we used a set of quality characteristics different from that work. Some results obtained in these studies can also be compared to ours. For example, similar to Tapia-Leon et al. (2018), we also noticed that many publications are not clear about the method used to develop the proposed ontologies. Considering domain coverage, like Sousa et al. (2016), we noted that an ontology can address different portions of the domain of interest. As for ontology use, aligned to the works by Sousa et al. (2016) and Tapia-Leon et al. (2018), our study showed that ontologies have been used mainly for knowledge management, which includes knowledge representation. Moreover, OWL has also been the main language to represent ontologies as computational artifacts in the HCI domain.

[3]Open-source ontology editor, https://protege.stanford.edu
[4]Resource Description Framework, https://www.w3.org/RDF/
[5]RDF Schema, https://www.w3.org/wiki/RDFS

3. Research Protocol

To perform our study, we followed the process defined by Kitchenham and Charters (2007), which comprises: planning, when the research protocol is defined with the purpose of supporting study replicability as well as helping researchers to avoid bias when conducting the study; conducting, when the protocol is executed and data are extracted, analyzed and recorded; and reporting, when the results are recorded and made available to potential interested parties. In this section, we present the main parts of the research protocol used in the study.

The ***study goal*** was to understand how ontologies have been used in the HCI domain and how they have been developed. In our study, we refer to these ontologies as HCI ontologies. By understanding how ontologies have been used in the HCI domain, it is possible to verify if they have been used like in other domains (e.g., for reasoning, classification), if new applications have been explored and if there are opportunities for the HCI area to benefit from ontologies use. For example, by identifying if there is an HCI sub-domain favorable to the use of ontologies and that has not explored ontologies use yet, one can be inspired to propose ontology-based solutions to aid HCI practices in that sub-domain. By investigating how HCI ontologies have been developed, it is possible to verify if there has been concern with a ontology quality issues and if there is room for closer interaction between HCI and ontology engineer professionals. For achieving the study goal, we defined the ***research questions*** presented in Table 1.

Table 1
Research questions and their rationale

RQ	Research Question	Rationale
RQ1	When and in which type of vehicle have the studies been published?	Provide an understanding on when and where (journal/conference/workshop) publications addressing HCI ontologies have been published, to analyze the maturity of the research topic.
RQ2	Which aspects of the HCI domain have been covered by the existing ontologies?	Identify the portions of the HCI domain covered by the ontologies to analyze the comprehensiveness of the HCI ontologies and of their use in HCI domain.
RQ3	What have been the uses of HCI ontologies?	Identify the types of solutions that have been supported by ontologies and understand the purposes of using ontologies in the HCI domain.
RQ4	Have the HCI ontologies been developed by following ontology engineering methods?	Understand how HCI ontologies have been developed, aiming to analyze if good ontology engineering practices have been adopted.
RQ5	How have the HCI ontologies been evaluated?	Verify if (and how) HCI ontologies have been evaluated to analyze if ontology evaluation has been a concern in HCI ontologies.
RQ6	Which quality characteristics have HCI ontologies exhibited?	Identify the HCI ontologies quality characteristics to verify if the ontologies used in the HCI domain present good quality level.

The ***search string*** adopted in the study contains two groups of terms joined with the operator AND. The first group includes terms related to HCI. The second group includes terms related to Ontology. Within the groups, we used OR operator to allow synonyms. The following search string was used: *(“user interface ontology” OR “user interface ontologies” OR “UI ontology” OR “UI ontologies”) OR ((“human-computer interaction” OR “HCI” OR “user interface design” OR “user interaction design” OR “user centered design” OR “human-centered design” OR “UI design” OR “user interface evaluation” OR “user interface assessment” OR “user interaction evaluation” OR “user interaction assessment” OR “UI evaluation” OR “UI assessment” OR “user interaction”) AND (“ontologies”*

OR "ontology")). For defining the search string, we followed the strategy of iteratively improving the search string until obtaining satisfactory results in terms of the number of publications and their relevance (Petersen et al., 2015). We started with a very general search string including terms such as "human-computer interaction", "HCI", "user interface" and "ontology". After running some tests, we noticed that the term "user interface" caused many irrelevant papers to be returned. Thus, we refined the search string by combining the term "user interface" (and synonyms) with other terms such as "ontology", "design", "evaluation" and "assessment".

The ***sources*** used in the study were digital libraries that satisfy the following criteria (Costa and Murta, 2013): (i) it allows using logical expressions or a similar mechanism for performing searches; (ii) its search mechanism supports full-length searches; (iii) it is available in the researchers' institution; and (iv) it covers the research area of interest, namely Computer Science. The following sources were selected: Scopus and Engineering Village. Scopus is one of the largest databases of peer-reviewed literature. It indexes papers from other important sources such as IEEE, ACM and Science Direct, providing useful tools to search, analyze and manage scientific research. Engineering Village is also a citation indexing platform, which indexes complementary sources. Initially, we have also selected the Web of Science database. However, it did not return any additional paper when we searched publications until 2018. Thus, we decided to exclude it from the set of sources.

Publications selection was performed in four steps. In *Preliminary Selection and Cataloging (S1)*, the search string was applied in the search mechanism of each digital library used as source of publications (we limited the search scope to title, abstract and keywords metadata fields). After that, we performed the *Duplications Removal (S2)*, i.e., publications indexed in more than one digital library were identified and duplications were removed. In *Selection of Relevant Publications – 1st filter (S3)*, the abstracts of the selected publications were analyzed considering the following inclusion (IC) and exclusion (EC) criteria: (IC1) the paper presents an ontology about the HCI domain; (EC1) the paper does not present an ontology about the HCI domain; (EC2) the paper does not have an abstract; (EC3) the paper was published only as an abstract; (EC4) the paper is a secondary study, tertiary study, editorial, summary of keynote, tutorial or the proceedings of a scientific event; (EC5) the paper is not written in English. Finally, in *Selection of Relevant Publications – 2nd filter (S4)*, the full text of the publications selected in S3 was read and analyzed considering the aforementioned criteria plus the following: (EC6) the paper is an older version (outdated) of another paper already considered; and (EC7) we did not have access to the full text of the paper. The (EC6) served to avoid repetition and (EC7) to treat publications whose full text was not available for the researchers.

We used the StArt tool[6] to support publications selection. To consolidate data, publications returned in the publication selection steps were cataloged and stored in spreadsheets. We defined an id for each publication and recorded the publication title, authors, year, and vehicle of publication. Data from publications returned in S4 were extracted and organized into a data extraction table-oriented to the research questions. The spreadsheets produced during the study can be found in our SLR package (Costa et al., 2020).

The first author performed publications selection and data extraction. The second and third authors reviewed both. Once data has been validated, the first author carried out data interpretation and analysis, and again second and third authors reviewed the results. Discordances were discussed and resolved. Quantitative data were tabulated and used in graphs and statistical analysis. Finally, the three authors

[6]http://lapes.dc.ufscar.br/tools/start_tool

performed qualitative analysis considering the findings, their relation to the research questions and the study purpose.

4. Data Extraction and Synthesis

The study considered papers published until 2019. Searches were conducted for the last time in January 2020. Figure 1 illustrates the followed process and the number of publications selected in each step. To search the digital libraries, the search string went through syntactic adaptations according to particularities of each source.

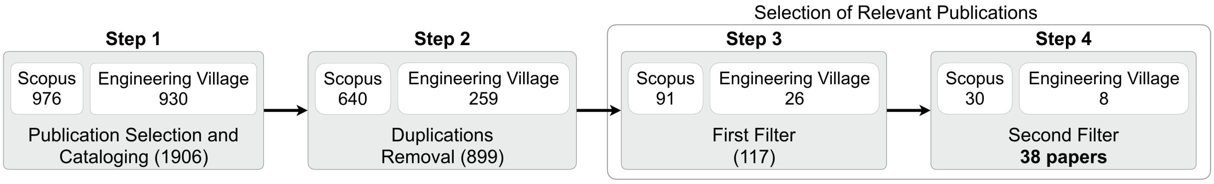

Figure 1. Search and Selection Process.

In the 1st step, as a result of searching the selected sources, a total of 1906 publications was returned. In the 2nd step, we eliminated duplicates, achieving 899 publications (reduction of approximately 53%). In the 3rd step, we applied the selection criteria over the abstract, resulting in 117 papers (reduction of approximately 94%). At this step, we only excluded publications that were clearly unrelated to the subject of interest. In case of doubt, the paper was taken to the next step. Finally, in the 4th step, the selection criteria were applied considering the full text, resulting in 38 publications (reduction of approximately 68%). It is important to highlight that the high number of excluded publications in the 3rd and 4th steps is because we decided to use a more comprehensive search string, which brings a higher number of publications that do not meet the inclusion criteria, but reduces the risk of not selecting relevant publications.

From the 38 selected publications, we identified 35 different ontologies because some publications present complementary parts of the same ontology. Table 2 shows the list of identified ontologies and corresponding publications. Along this and the next sections we refer to the ontologies by using the id listed in the table. Detailed information about the selected publications, including a brief description and extracted data, can be found in our SLR package (Costa et al., 2020). After Table 2, we present the data synthesis for each research question.

Table 2: Selected Publications and Ontologies.

ID	Ontology	Brief description and some concepts	Ref.
#01	Ontology of Multi-party Interaction	It is a conceptual model, based on references such as (Norman, 1986), which addresses the HCI phenomenon and involved parts (i.e., user and system). Includes concepts such as Participants, User and Interaction.	(Storrs, 1994)
#02	UI Design Process Ontology	It is a conceptual model on task modeling and interaction with a focus on UI design. Some concepts: Task, Interaction, Action.	(Suàrez et al., 2004)
#03	Impairment-User Interface Ontology	It is a conceptual model on UI and adaptation for user impairment. Addresses concepts such as Impairment, User, InterfaceAdaptation.	(Karim and Tjoa, 2006)

ID	Ontology	Brief description and some concepts	Ref.
#04	DREAMS Ontology	It presents a conceptual model and a small extract of the operational ontology implemented in OWL and RDF that addresses user stereotypes and related aspects for interaction and devices capabilities in massive networking scenarios. Includes concepts such as Social_Role, Device, Input_modality.	(Korfiatis and Constantiou, 2006)
#05	SOUPA Extension	It is a conceptual model which addresses multimodal pervasive systems, devices and environments in multimodal interaction. Some concepts: I/O Device, Sensor, Service.	(Coronato and De Pietro, 2007)
#06	HCI Frame-based Ontology	It is a conceptual model on task modeling and interaction with a focus on UI design regarding guidelines structures. Includes concepts such as Target User, Design Property, Usability Requirement.	(Bakaev and Avdeenko, 2010, 2012)
#07	Ontology for Interactive Adaptive Systems	It is an operational ontology, implemented in OWL, for adaptive interactive systems and its facets such as user, system, user-system interaction and adaptation. Includes concepts such as DialogSystem, Interaction, Adaptation, UserModelItem.	(Bezold and Minker, 2010)
#08	Interaction Ontology	It presents a small extract of an operational ontology implemented in OWL that addresses interaction patterns and web UI regarding structural and visual aspects. Some concepts: Widget, Event, Presentation Properties.	(Celino and Corcoglioniti, 2010)
#09	Abstract Widget Ontology	It is a conceptual model, addressing web UI elements and concepts such as Abstract Interface Element, Element Exhibitor, Variable Capture.	(Martín et al., 2010)
#10	User Interface Ontology	It is an operational ontology implemented using OWL/RDF. It addresses interface entities and relationships, including concepts such as Widget, Textual, Frame.	(Shahzad et al., 2011)
#11	Core HCI Ontology	It is a conceptual model of UI design addressing input and output modalities to be chosen according to the context of use. Some concepts: Location, Modality, Device.	(Tourwé et al., 2011)
#12	The name is not cited in the paper	It presents a conceptual model and an operational version that addresses interactive modal devices and situations of use. Includes concepts such as Device, DeviceRestrictedByLocation, Situation.	(Bowen and Hinze, 2012)
#13	Gesture Ontology	It is a conceptual model that addresses gesture interaction and aspects involved during the process of producing a gesture. Includes concepts such as User, Body Movements, Function-oriented Gesture.	(Chera et al., 2012)
#14	User Interaction Context Ontology	It is a conceptual model about user interaction and interaction context addressing the characterization of user actions and resources used during his/her interaction. It has an operational version implemented using OWL and includes concepts such as Action, Resource, Task, User.	(Devaurs et al., 2012)
#15	RaUL Ontology	It is a conceptual model, a markup ontology, about web UI elements related to the structure of a web form. It has an operational version implemented using RDF and includes concepts such as Page, Widget Element, Button.	(Haller et al., 2012)
#16	PersonasOnto	It is a conceptual model about persona characterization and personas aspects related to usability test. It has an operational version implemented using OWL. Some concepts: Person, Persona, Usability Test.	(Negru and Buraga, 2012, 2013)
#17	An ontology for Personas	It is a conceptual model about persona characterization. A small extract of an operational ontology implemented in OWL/RDF is presented. Includes concepts such as Person, Persona, Context, Goal.	(Salma et al., 2012; Salma and Marouane, 2016)
#18	Haptic Applications Software Modeling Ontology	It is an operational ontology, implemented using OWL/SWRL about haptic HCI and pathways that haptic information follows between the human and the machine haptic system. Some concepts: Haptic-Devices, Computer haptics, Haptic-Feedback.	(Myrgioti et al., 2013)
#19	End-to-End Interaction Ontology	It is a conceptual model and an operational ontology (implemented in OWL) that addresses elements of interaction under the WIMP (Windows, Icons, Menus, Pointer) UI perspective. Includes concepts such as Interaction, Interface, User.	(Zamzami et al., 2013)

ID	Ontology	Brief description and some concepts	Ref.
#20	Ergonomics of Human-Computer Interface Ontology	It is a conceptual model concerning ergonomics of UI and aspects such as recommendations, graphic design and evaluation. Includes concepts such as HCI Ergonomics, Interface_Evaluation, Design_And_Evaluation.	(Elyusufi et al., 2014)
#21	Interaction Event Ontology	It is a conceptual model about interaction event in social media, covering aspects related to users' (social) interactions. Some concepts: Event, InteractionEvent, SocialRole.	(Kabir et al., 2014)
#22	User's Feedback Ontology	It is a conceptual model that addresses user interaction feedback concerning aspects related to structure, credibility and information value. Includes concepts such as Role, Significance, Modality.	(Mezhoudi and Vanderdonckt, 2015)
#23	Web Design Domain Ontology	It is a conceptual model about web UI design property and web UI structure and elements. Some concepts: Interface element, menu, design property, Interface design property.	(Bakaev and Gaedke, 2016)
#24	Ontological Framework for Universal Acess to ICT	It is a conceptual model about universal accessibility in information and communication technologies according to the user needs and preferences. Includes concepts such as UserInterface, UserCharacteristic, UserCondition.	(Koutkias et al., 2016)
#25	Interaction Ontology	It is a conceptual model about craftswoman capacities and appropriated input/output (I/O) interaction modalities, modes and mediums. It is implemented using OWL/SWRL and includes concepts such as Craftswoman, Motor Capacity, Modality, Medium.	(Lebib et al., 2016)
#26	Ontological Model of Adaptive User Interface for People with Disabilities	It is a conceptual model about adaptive UI for people with disabilities, covering UI elements and user characterization. An operational version is implemented using Java and Jena. Includes concepts such as User, Disability, Interface Element Type.	(Kultsova et al., 2017)
#27	Usability Guideline Ontology	It is a conceptual model about usability guidelines description and structure. It is implemented using OWL and includes concepts such as Guideline, Guideline Element, Content Type.	(Robal et al., 2017)
#28	PG-Ontology	It is a conceptual model about pervasive game, concerning its description, elements/components and their relationships from the user experience perspective. Includes concepts such as Pervasive_game, Player, Game.	(Arango-López et al., 2018)
#29	Context Model Centre Ontology	It is a conceptual model about context-awareness, addressing context as the information that is used to characterize the relevant objects and entities that affect computing tasks. Some concepts: Context Domain, Environment Context, User Context.	(Meng, 2018)
#30	Accesibilitic Ontology	It is a conceptual model about characterization of user needs and capabilities, assistive devices/software tools used to support accessibility and the user's interaction taking into account capabilities. An operational version is implemented using OWL. Includes concepts such as User, Capacity, ActivityParticipation, SupportAssistance.	(Romero Mariño et al., 2018)
#31	Ontologies of Interaction Channels – Virtual Reality System and Environment	It is a conceptual model about characteristics of interaction channels of Virtual Reality system and environment. Includes concepts such as InteractionChannel, Forms_of_interaction, Spacial_navigation.	(Sokolowski and Walczak, 2018)
#32	Web UI Measurement	It is a conceptual model and an operational ontology (implemented in OWL) about the organization of UI metrics and services used in the UI measurement. Includes concepts such as Service, Metric, Attribute, Interface.	(Bakaev et al., 2019)
#33	Affinto Ontology	It is a conceptual model and an operational ontology (implemented in OWL) about affective HCI, which addresses affective states and different factors of its context of use. Some concepts: Environmental_property, System_property, AffectiveP_properties.	(Garay-Vitoria et al., 2019)

ID	Ontology	Brief description and some concepts	Ref.
#34	IoRT Ontology	It is a conceptual model about the user characteristics and interaction in IoRT (Internet of Robotic Things), addressing relevant aspects for personalized, context-aware task generation. An operational version is implemented using OWL. Includes concepts such as Preferred Interaction, PreferredRobot Interactions, Task, Profile.	(Mahieu et al., 2019)
#35	The name is not cited in the paper	It is a conceptual model and an operational ontology (implemented in OWL) about the presentation and behavior of interactive components (graphical UI) used in web and mobile applications. It also addresses the structure of user stories, tasks, scenarios and prototypes. Some concepts: Event, Action, Condition, Menu, clickOn.	(Silva et al., 2019)

Publication year and vehicle (RQ1): Figure 2 shows the distribution of the 38 selected publications over the years and the distribution of publications considering the vehicle of publication. The oldest paper addressing ontologies in the HCI context we found in the study was published in 1994. Since then, papers addressing this subject have been published in journals and conferences (no workshop publication was found). Conferences have been the main forum, encompassing 68.4% of the publications (26 out of 38). 12 papers (31.6%) were published in journals. In Figure 2 we omitted years in which no publication was found. Hence, looking at the x-axis it is possible to notice some intervals where no publication was identified. The more expressive is the 9-years gap between 1994 and 2004.

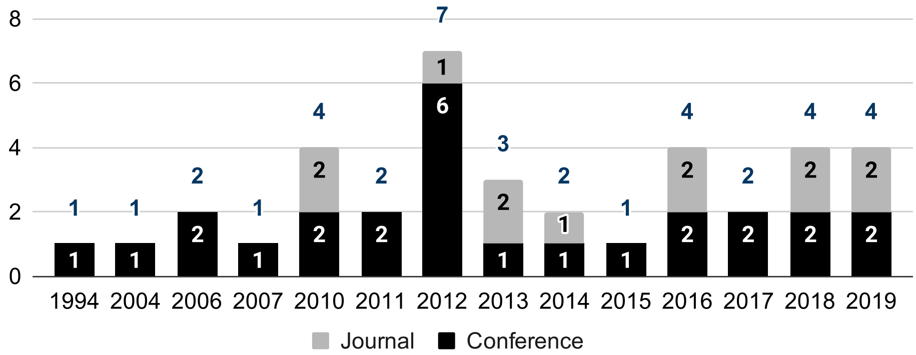

Figure 2. Publications over the years.

Coverage of the HCI domain (RQ2): Figure 3 shows the HCI aspects addressed by the ontologies identified in the study. The categorization used to classify the aspects was established based on the extracted data, HCI literature and also in topics of interest cited in important HCI conferences[7,8]. First, we analyzed each ontology to identify the aspects it addresses, according to the sub-domain (or sub-domain portion) covered by the ontology. In this first moment, we kept the terminology used in each publication. For example, ontology #13 addresses the HCI phenomenon by means of gesture, while #07 covers aspects related to adaptive interactive systems and user modeling. After that, we grouped similar aspects. For example, all ontologies addressing the HCI phenomenon, regardless of the mode of interaction, were

[7]INTERACT 2021, https://www.interact2021.org/
[8]CHI 2021, https://chi2021.acm.org/

grouped in HCI phenomenon. As a result, we reached 13 groups. Finally, we analyzed them and, considering HCI sub-domains found in the literature and topics of HCI conferences, we defined seven more general categories, namely: *User Interface* (addresses user interface types and elements, such as widget, graphical user interface); *HCI phenomenon* (deals with the interaction phenomenon regardless of the mode of interaction); *Pervasive Computing* (involves ubiquitous, context-aware, mobile and pervasive computing in the context of interactive computer systems) (Satyanarayanan, 2001; Surve and Ghorpade, 2017); *User Modeling / Profile* (addresses user characterization such as impairment, social roles, user modeling, persona, needs and preferences, capacity, disability) (Schiaffino and Amandi, 2009; Fischer, 2001); *HCI Design* (refers to aspects related to processes, methods and principles of the HCI design such as persona (as a method), usability testing, HCI evaluation and user interface measurement); *Interaction Experience* (addresses interactive computer system quality characteristics such as usability, user experience and accessibility) (Sauer et al., 2020); and *Adaptive Interactive System* (concerns adaptive and adaptable interactive computer systems). Each of the 35 ontologies was, thus, categorized according to the seven categories. For example: #07 was classified in the *Adaptive Interactive System* and *User Modeling / Profile* categories.

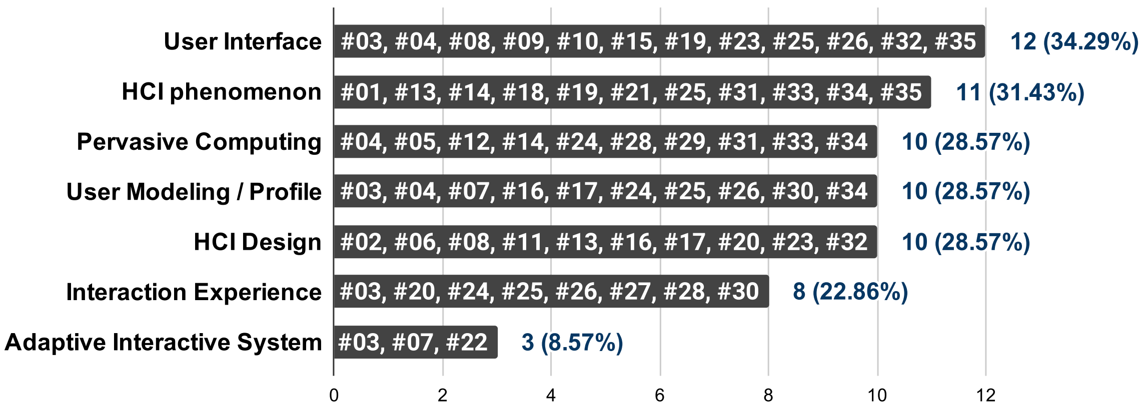

Figure 3. HCI aspects covered by the HCI ontologies.

User Interface (UI) has been the HCI aspect most addressed by the HCI ontologies, being covered by 12 of them (34.29%). In this context, some ontologies focus on the UI elements (#08, #09, #10, #15, #19, #23, #26, #35), addressing them from graphical (#10, #35), web (#08, #09, #15, #23, #26) and WIMP (#19) perspectives. Other ontologies address other aspects of UI, such as UI adaption (#03), interface modality (#04, #25) and UI measurement (#32). *HCI phenomenon* has been the second HCI aspect most addressed, being treated in 11 ontologies (31.43%). Some ontologies deal with specific modes of interactions such as gesture (#13), haptic (#18), virtual reality (#31), affective (#33) and IoRT (#34). #25, in turn, addresses several modes of interaction, representing them in categories such as direct manipulation, language, visual, hearing and tactile. #01 describes HCI as multiparty, concerning one or more participants. #14, #19, #21 and #35 represent HCI by means of events, actions and tasks.

Pervasive Computing, *User Modeling / Profile* and *HCI Design* were addressed by 10 (28.57%) ontologies. In *Pervasive Computing*, six ontologies treat context-awareness by means of interactive medical devices in multiple contexts and situations of use (#12), user interaction context for automatic task detection (#14), context-awareness in mobile adaptation (#29), context-based approach in virtual reality (#31), context of use factors that influence affective states (#33) and context-aware systems for personalized interaction tasks in IoRT (#34). Three ontologies treat mobile computing dealing with mobile devices capacities (#04), accessibility (#24) and performance (#29). Two ontologies treat pervasive systems by means of pervasive game description (#28) and proactive environments (#05).

In *User Modeling / Profile*, ontologies address user impairment (#03), social roles (#04), user modeling (#07), persona (#16, #17), user capacity (#25, #30), disability (#26), and needs and preferences (#24, #34). Concerning *HCI Design*, #13 focused on HCI design for gesture interaction, #02, #06, #08, #11, #16, #17, #20, #23 on user interface design. #16 encompasses usability testing under the persona perspective, #20 concerns user interface ergonomic guidelines and #32 focused on user interface metrics and measurement.

Eight (22.86%) ontologies address *Interaction Experience*, dealing with UI accessibility (#03, #25, #26) and user needs targeting accessibility issues (#24, #30). #20 addresses ergonomics by means of recommendations, #27 describes usability guidelines while #28 deals with user experience in the context of games. Three (8.57%) ontologies address *Adaptive Interactive System*, dealing with adaptive interactive system as a whole (#07), adaptive interactive system based on user feedback (#22) and UI adaptation for user impairment (#03).

By combining *when the studies have been published* (RQ1) and *HCI aspects covered by the ontologies* (RQ2) it is possible to identify changes of focus in the HCI domain regarding the use of ontology over the years. Figure 4 illustrates this information and presents trend lines showing increasing in some HCI aspects addressed by ontologies over the years. In order to not visually pollute the graph, in the figure we show only aspects that have been target of increasing interest. As in Figure 2, in Figure 4 we omitted years in which no publication was found. Hence, the figure considers only years where we identified publications about the investigated topic.

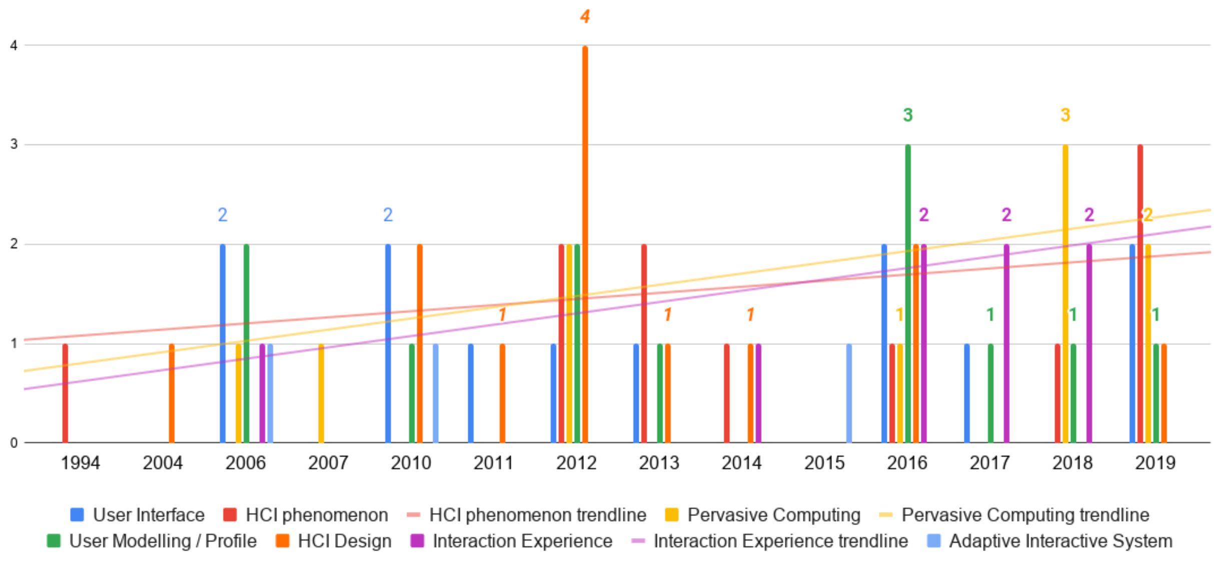

Figure 4. HCI aspects covered by the HCI ontologies over the years.

As showed in Figure 3, *User Interface* and *HCI phenomenon* have been the HCI aspects addressed in more ontologies. When looking at Figure 4, it is possible to notice an increasing tendency to address the

HCI phenomenon. On the other side, although *User Interface* has been target of many ontologies, when looking at the distribution of them over the years, it is possible to notice a stable trend in the number of ontologies addressing this aspect (trendline not showed in the graph), while *Pervasive Computing* and *Interaction Experience* have an increasing trendline.

In order to perceive information that may not be evident only by looking at Figure 4, we grouped data presented in Figure 4 by period of time. Thus, we grouped publications in periods of five and four years: 1994-2010 (1994, 2004, 2006, 2007 and 2010); 2011-2015 (from 2011 to 2015); and 2016-2019 (from 2016 to 2019).

In the 1994-2010 period there are nine (23.68%) papers (#01, #02, #03, #04, #05, #06 (2010), #07, #08, #09) with an average of 1.8 articles published by year. In this interval, *User Interface* stands out, being treated by four (44.44%) ontologies (#03, #04, #08 and #09). There is an average of 2.29 HCI aspects addressed per publication, showing that a single ontology often addresses more than one HCI aspect (as Figure 3 shows). Moreover, there is an average of three aspects addressed per year. For instance, ontology #03 was developed to help customize/adapt the UI according to user impairments, aiming to improve user interaction for people with special needs. Thus, it addresses UI (*User Interface*), UI adaptation (*Adaptive Interactive System*), user impairment (*User Modeling / Profile*) and accessibility (*Interaction Experience*). #09, in turn, addresses web user interfaces and web user interface design (i.e., *User Interface* and *HCI Design*), being used in an aspect-oriented approach for engineering web applications.

In the 2011-2015 period there was an increase of 66.67% of publications when compared to the previous period. There were 15 publications (39.47%) with an average of 3.0 publications per year, four HCI aspects per year, and an average of 3.14 HCI aspects addressed per publication. *HCI Design* was the aspect most treated by ontologies in this period, being covered by seven (46.67%) publications (#06, #11, #13, #16, #17, #20). Four of them (#06, #13, #16, #17) contributed to the high number of publications in 2012 (as shown in figures 2 and 4).

In the 2016-2019 quadrennium, 14 (36.84%) papers were published, with an average of 3.5 publications and 8.0 aspects per year and 3.43 HCI aspects per publication. Three aspects stand out equally (each one was treated by six (42.86%) ontologies): *Pervasive Computing* (#24, #28, #29, #31, #33, #34), *User Modeling / Profile* (#17, #24, #25, #26, #30, #34) and *Interaction Experience* (#24, #25, #26, #27, #28, #30).

Use of Ontologies in HCI (RQ3): When investigating how ontologies have been used in the HCI domain, we first looked at the types of ontology-based solutions that have been used and, thus, we investigated their use in the HCI domain. Figure 5 shows the identified types of ontology-based solutions.

The most common ontology-based solution has been *Knowledge Management*, which has been the use of 15 out of 35 ontologies (42.86%). In this category, ontologies have been used to support knowledge capture, representation, organization, use, sharing, among others. In this context, #06, #07, #12, #14, #23, #26, #27 and #33 were used to structure knowledge bases. For example, #06 was used in a recommender system supporting HCI design for web applications; #07 served as a semantic representation to an interactive system, enabling the UI to adapt itself to each user; #23 structured knowledge in an Evolutionary Algorithm approach, which combines Artificial Intelligence and design methods to automate development and improvement of web UI; #27 was used in a tool to support automatic evaluation of web UIs based on usability guidelines; and #33 was used as a basis of an affective multimodal conversational system. Some ontologies were used to knowledge capture and sharing. For example, #11 was used in an ontology-driven modeling framework to capture and manage design expert knowledge

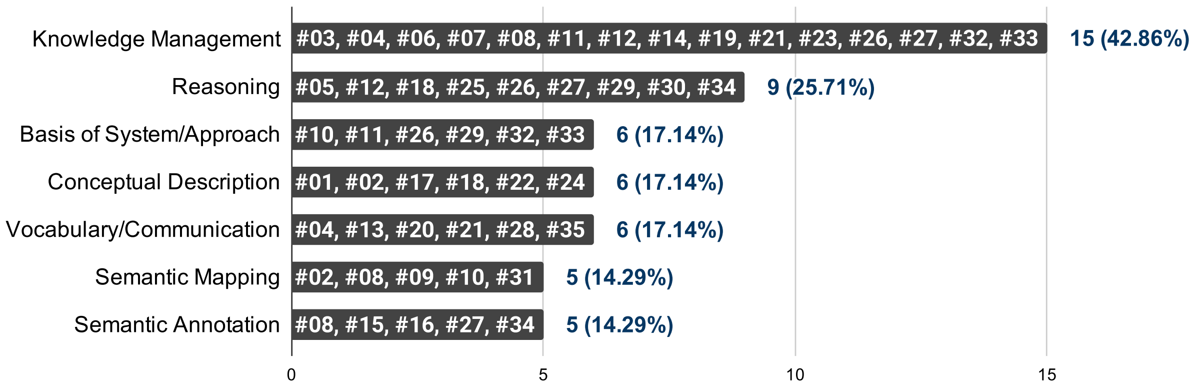

Figure 5. Ontology-based solutions.

to be provided as design-related recommendations. #03 was used in a user's personal information management system to capture knowledge and adapt the UI according to the user impairments. By using a template to capture knowledge, #19 supported reverse engineering requirements for systems without documentation or available source code. #14 was used to increase the performance of user task detection by capturing simple interaction events (key pressed and mouse clicks) from the user's computer desktop which are automatically stored into a repository for further inferences. The other three ontologies (#04, #21, #32) were used for knowledge representation. #04 regards the representation of social context and its surrounding activities to support the development of mobile service provision models, #21 represents knowledge about the user's interaction events in different social media and #32 structures knowledge about web UI metrics.

Nine (25.71%) ontologies were used to *Reasoning*, i.e., to derive information that is not explicitly expressed in the ontology or in the knowledge base (Victoria et al., 2008). For example, #25 was used to determine the most suitable and adaptable user interfaces to craftswoman (user) considering modalities and sensory and motor abilities; #34 was used to build services that generate interaction tasks for social robots in smart IoT environments; and #12 was used to reason about the usability of interactive medical devices in multiple situations of use.

The third main use of HCI ontologies, with six out of 35 (17.14%) ontologies, has been *Basis of a System/Approach*, *Conceptual Description* and *Vocabulary/Communication*. Being a *Basis of a System/Approach* means that the ontology is used as part (e.g., a module or a repository) of the proposed system/approach architecture. This is the case, for example, of #29 and #34. The former is part of a context-aware computing architecture, supporting architecture layers such as knowledge discovery and context-aware services. The latter is part of the reasoning service component of a semantic-based platform architecture conceived as a middleware.

Ontologies used for *Conceptual Description* aim to provide a formal specification of a portion of the domain of interest. In this context, #18 provides a conceptualization regarding haptic interaction; #01 describes the HCI phenomenon, #2 conceptualizes interaction based on task description; #17 provides a conceptual representation about personas; #22 presents a conceptual description about user feedback; and #24 provides a semantic representation of concepts that are required for addressing universal accessibility related to user interaction with Information and Communication Technologies.

Ontologies used for *Vocabulary/Communication*, as the name suggests, are used as a vocabulary or for communication purposes. In this sense, #35 was used as a common vocabulary in an approach to allow for automatic assessment of the graphical UI prototypes against user stories. #04 supported communication related to social context and its surrounding activities to aid the development of advanced models of mobile service. #21 represents user interaction events in different social media and it was used as a vocabulary for semantic event matching. #13 helped to inform the design of service-oriented architectures for engineering new systems and applications. #20 was used to support building user profiles. Finally, #28 served as a consensual instrument to talk about pervasive games from the user experience perspective.

Five out of 35 (14.29%) ontologies were used to *Semantic Mapping*, i.e., interrelate concepts from different sources (e.g., data bases, documents, ontologies, etc.). For instance, #31 was used to map concepts related to virtual reality (VR) system and VR environment, enabling the proposed system to assign interaction channels to the interaction capabilities of the VR environment. Finally, five (14.29%) ontologies were used to *Semantic Annotation*, meaning that semantic information was added to artifacts, allowing machines to read them. For example, in #27, each usability guideline was annotated enabling information to be accessed in a machine-processable form to automatically access the UI elements against selected UI guidelines and the associated metrics.

Table 3 summarizes the aspects addressed by each HCI ontology (RQ2) and the ontology-based solutions on which the ontologies were used (RQ3).

When extracting data to answer RQ3, we also extracted information about the benefits of using ontologies in the HCI domain. Table 4 summarizes the benefits reported in the publications and the ontology-based solutions they related to.

Ontology Development (RQ4): According to the publications, the development of only three (8.57%) out of 35 ontologies followed an ontology engineering method (see Figure 6): #25 adopted Methontology (Fernández-López et al., 1997), #28 used Methontology (Fernández-López et al., 1997) and NeOn (Gómez-Pérez and Suárez-Figueroa, 2009; Suárez-Figueroa et al., 2012) and #30 applied NeOn (Gómez-Pérez and Suárez-Figueroa, 2009; Suárez-Figueroa et al., 2012). Although other publications (#02, #11, #12, #13 and #18) mention the use of some guidelines to develop the ontologies, the methods are not clearly presented or referred to. Thus, we did not consider that they adopted an ontology engineering method.

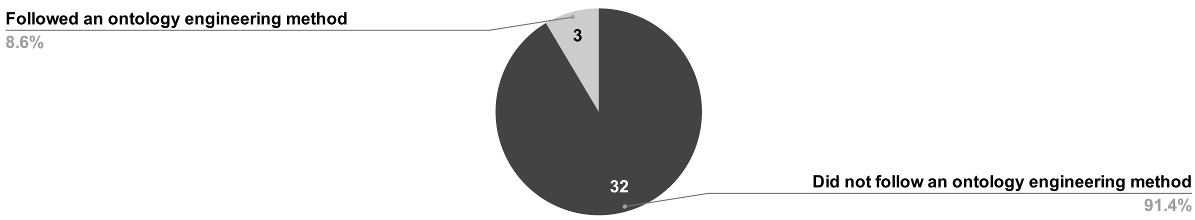

Figure 6. Ontology development.

Ontology Evaluation (RQ5): In this research question, we used the classification proposed by Brank et al. (2005), namely: task-based evaluation and data-driven evaluation. In a task-based evaluation, the ontology is used in some kind of application or task, and the outputs of the application, or its performance on the given task, are used to evaluate the ontology (Brank et al., 2005). This is an indirect way of evaluating an ontology and, depending on the complexity or subjectivity of the application, it is hard to say if the ontology is really correct. In a data-driven evaluation, the ontology is compared to existing data about the problem domain to which the ontology refers (Brank et al., 2005). As shown in Figure

Table 3: HCI ontologies: HCI aspects and ontology-based solutions.

	HCI aspects covered							**Ontology-based solution adopted**						
Id	UI	HCI phenomenon	Pervasive Computing	User Modeling / Profile	HCI Design	Interaction Experience	Adaptive Interactive System	KM	Reasoning	Basis of a System	Conceptual Description	Vocabulary	Semantic Mapping	Semantic Annotation
#01		√									√			
#02					√						√		√	
#03	√			√		√	√	√						
#04	√		√	√				√				√		
#05			√						√					
#06					√			√						
#07				√			√	√						
#08	√				√			√					√	√
#09	√												√	
#10	√									√			√	
#11					√			√		√				
#12			√					√	√					
#13		√			√							√		
#14		√	√					√						
#15	√													√
#16				√	√									√
#17				√	√						√			
#18		√							√		√			
#19	√	√						√						
#20					√	√						√		
#21		√						√				√		
#22							√				√			
#23	√				√			√						
#24			√	√		√					√			
#25	√	√		√		√			√					
#26	√			√		√		√	√	√				
#27						√		√	√					√
#28			√			√						√		
#29			√						√	√				
#30				√		√			√					
#31		√	√										√	
#32	√				√			√		√				
#33		√	√					√		√				
#34		√	√	√					√					√
#35	√	√										√		

Table 4: Benefits of using ontologies in the HCI domain and ontology-based solution.

Benefits of using ontologies in the HCI area		**Ontology-based solution adopted**						
Id	Main Benefits	KM	Reasoning	Basis of a System	Conceptual Description	Vocabulary	Semantic Mapping	Semantic Annotation
#01	Describe the HCI phenomenon				√			
#02	Acquire a task-based description of interaction				√		√	
#03	Customize / adapt the UI according to user impairments	√						
#04	Support user stereotypes through the concept of social roles to research on content negotiation and deployment of different interaction styles	√				√		
#05	Make pervasive computing environments smarter with multimodal system and services		√					
#06	Aid recommender system to support interface design for modern applications and websites	√						
#07	Assist in adapting interactive systems to user behavior	√						
#08	Support multiple and different views/compositions of Web applications according to a dataset	√					√	√
#09	Engineer accessible web applications						√	
#10	Assist user interface model for generating graphical user interface			√			√	
#11	Support designers' activities	√		√				
#12	Aid safety-critical interactive devices and their use within multiple locations	√	√					
#13	Assist in informing the design of Service-oriented Architectures for controlling smart homes with gesture commands					√		
#14	Automatic detect the tasks a user is performing on his/her interaction	√						
#15	Support designers' activities							√
#16	Link Persona and Usability test methods in User-Centered Design							√
#17	Support personas to be effective tools for design				√			
#18	Design effective user interfaces and assist in the development of software modeling for haptic devices		√		√			
#19	Recover requirements and reconstruct the software requirements document through observing the user interacting with the system	√						
#20	Recommend custom interfaces based on user profiles					√		
#21	Capture users' interaction activities in different social media	√				√		
#22	Improve User Interface adaptation through user's feedback				√			
#23	Support automated development and improvement of web user interfaces	√						
#24	Express personal user needs and preferences across ICT				√			
#25	Support suitable and adaptable interfaces for the user		√					
#26	Aid customization of user interface for people with disabilities	√	√	√				
#27	Assist Web user interface (UI) automatic evaluation	√	√					√
#28	Serve as a vocabulary of pervasive games from the user experience perspective					√		
#29	Support context-aware adaptation in mobile applications		√	√				
#30	Assist recommender system to suggest software adaptations related to user characterization		√					
#31	Build resilient virtual reality (VR) applications that can be automatically adapted to a particular VR system configuration						√	
#32	Support assessing Web User Interfaces using metrics from different providers	√		√				
#33	Guide the development of affective resources and/or applications	√		√				
#34	Build services that generate interaction tasks for social robots in smart IoT environments		√					√
#35	Perform automatic assessment of the Graphical User Interfaces prototypes against User Stories					√		

7, 15 (42.86%) ontologies (#02, #05, #06, #07, #08, #10, #12, #14, #15, #16, #21, #26, #29, #31, #35) were evaluated by following a task-based evaluation, two (5.71%) ontologies (#09, #30) used a data-driven evaluation method, five (14.29%) ontologies (#18, #19, #25, #27, #33) used both methods and 13 (37.14%) ontologies (#01, #03, #04, #11, #13, #17, #20, #22, #23, #24, #28, #32, #34) were not evaluated.

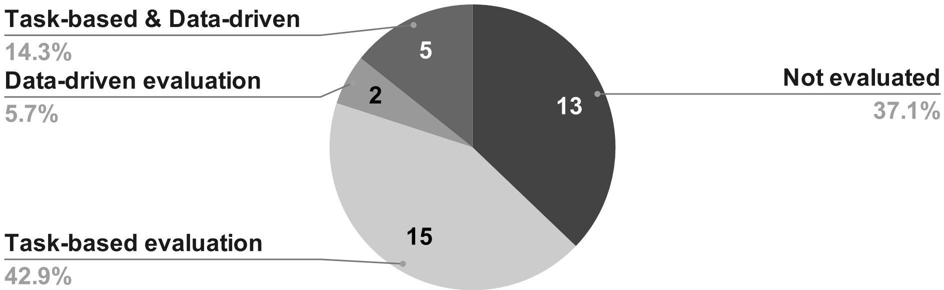

Figure 7. Ontology evaluation.

20 (51.14%) ontologies (#02, #05, #06, #07, #08, #10, #12, #14, #15, #16, #18, #19, #21, #25, #26, #27, #29, #31, #33, #35) were evaluated through a task-based method. In this kind of evaluation, ontologies are used to build solutions that are objects of evaluation. Thus, the ontology is indirectly evaluated. For example, the evaluation of #25 and #31 was carried out considering prototypes built using the ontologies. Analogously, systems built using the ontologies were used to evaluate #06 (university website and recommender system), #07 (interactive dashboard), #12 (safety-critical system), #26 (hospital device system) and #27 (interface customization system). #15 was evaluated through a RESTful Web Service that was used to deploy, generate and retrieve RDFa annotated web forms using the ontology. In #16, a semantic HTML template was applied in a small-scale experiment to build a web-based application for managing academic information (e.g., grades, schedule). #19 was evaluated by means of a template used to recover system requirements from the actions performed by the user.

Seven (17.5%) ontologies (#09, #18, #19, #25, #27, #30, #33) adopted a data-driven approach. All of them used some kind of instantiation to evaluate the ontology. For example, #19 was instantiated considering a real case of requirements recovery, while #27 was evaluated through the instantiation of 115 usability guidelines. #30 was the only ontology evaluated by using a data-driven approach and that used competency questions to represent the ontology requirements. In its evaluation, #30 instantiation was oriented to the competency questions.

Finally, 13 (37,14%) ontologies (#01, #03, #04, #11, #13, #17, #20, #22, #23, #24, #28, #32, #34) were not evaluated. In some cases, the authors stated that the ontology was under evaluation (e.g., #24). In others, toy examples or workshops were used to illustrate the ontology use (e.g., #11, #34). Based on the information provided in the publications, we did not consider that these ontologies were evaluated because they were not actually used in real situations nor instantiated real data.

Ontology Quality Characteristics (RQ6): in this research question, we considered some of the characteristics of "beautiful ontologies" defined by D'Aquin and Gangemi (2011)[9], namely: (i) reusing foundational ontologies; (ii) being formally rigorous; (iii) implementing also non-taxonomic relations; (iv)

[9]We did not consider characteristics such as commercial impact, which are difficult to evaluate based only on information provided in the publications.

being modular or embedded in a modular framework; (v) implementing an international standard; (vi) being based on competency questions, and (vii) following an evaluation method. Table 5 presents the quality characteristics identified in the ontologies.

Table 5

Research questions and their rationale.

id	reusing foundational ontologies	being formally rigorous	implementing also non-taxonomic relations	being modular	implementing an international standard	based on competency questions	following an evaluation method
#01			√				
#02		√	√	√			√
#03			√	√			
#04			√	√	√		
#05		√	√	√			√
#06		√	√				√
#07		√	√	√			√
#08			√	√			√
#09			√				√
#10			√	√			√
#11		√	√	√		√	
#12		√	√			√	√
#13			√	√		√	
#14				√			√
#15				√			√
#16			√	√			√
#17			√				
#18	√	√	√	√			√
#19			√	√			√
#20				√			
#21		√	√				√
#22							
#23				√			
#24		√	√	√	√		
#25		√	√				√
#26		√	√	√			√
#27			√				√
#28			√			√	
#29							√
#30		√	√	√		√	√
#31				√			√
#32			√	√	√		
#33		√	√	√			√
#34	√	√	√	√	√		
#35							√

Concerning the reuse of foundational ontologies, only #18 and #34 (5.71%) were developed based on a foundational ontology (Basic Formal Ontology – BFO[10] (Grenon et al., 2004) and Dolce Ultralight upper ontology[11] (Gangemi et al., 2002), respectively).

With respect to being formally rigorous, we considered two aspects: whether axioms/rules are defined, and how the ontology is presented (as a graphical conceptual model, as an operational ontology, using some formalism, or textual description only). Eight (22.86%) ontologies define rules (#02, #05, #06, #07, #11, #24, #25, #26), two (5.71%) ontologies define axioms (#30, #33) and four (11.43%) ontologies define both (#12, #18, #21, #34). Thus, 14 ontologies (40%) present some degree of formalism. Only one (7.14%) of those 14 ontologies (#02) is presented by means of textual description (since it defined rules, we consider that it presents some degree of formalism). Two (14.29%) (#07, #18) are operational ontologies, being represented as OWL and OWL SWRL artifacts, respectively. Five (35.71%) ontologies (#06, #11, #21, #24, #26) are presented as graphical conceptual models. The remaining six (42.86%) ontologies (#05, #12, #25, #30, #33, #34) are presented as both, graphical conceptual model and operational ontology.

Regarding the types of relations, 27 (77.14%) ontologies consider both taxonomic and non-taxonomic relations (although #01, #10 do not clearly represent them). Six (17.14%) ontologies (#14, #15, #20, #23, #29, #31) consider only taxonomic relations. In two (5.71%) ontologies (#22, #35) it was not possible to identify the types of relations.

As for modularity, we investigated if the ontology was organized in hierarchy, dimension, abstraction levels, structure of classes, or if it is non-modular. 12 (34.29%) ontologies are non-modular, while 23 (65.71%) ontologies are modularized according to one of the aforementioned modularization types.

Concerning the use of standards, only four (11.43%) ontologies mention their use as a reference to the ontology conceptualization: #04 used the Composite Capabilities/Preference Profiles part of the Device Independence activity of W3C (Klyne et al., 2004), #24 considered ISO/IEC 24751:2008 (ISO, 2008), ETSI TS 202 746 (ES, 2010) and ISO 9999:2011 (ISO, 2011), #32 used W3C Web Content Accessibility Guidelines[12] and #34 considered the vcard specification (RFC6350[13]) and the W3C Organization Ontology[14]. Other works (#01, #02, #03, #10, #13, #16, #17, #18, #28, #33) mention the use of references but do not specify which ones were used. #28 and #33 mention models found in the literature. Therefore, we did not consider that they use international standards.

Regarding the use of competency questions, only five (14.29%) ontologies (#11, #12, #13, #28 and #30) used competency questions to establish the ontology requirements.

5. Data Analysis and Discussion

In this section, we provide additional information about the analyzed HCI ontologies and make some discussion about the obtained results.

Considering *when the studies have been published*, HCI ontologies only became a regular research topic addressed in publications from 2010. We believe that this is due to the increasing use of ontologies in several domains in the last decade (Jean-Baptiste, 2021) (ontologies became particularly popular

[10] http://ontology.buffalo.edu/bfo/
[11] http://www.ontologydesignpatterns.org/ont/dul/DUL.owl
[12] https://www.w3.org/WAI/ER/tools/
[13] https://www.w3.org/TR/vcard-rdf/
[14] https://www.w3.org/TR/vocab-org/

because of Semantic Web) and the acknowledgment of the advantages of using them to solve knowledge-related problems. Regarding the peak of publications, in our study it appears in 2012 (7 studies), while in the study by Tarhan and Giray (2017) (2005-2016) it appears in 2008 (3 studies) and 2012 (3 studies), in the work by Tapia-Leon et al. (2018) (2012-2017) it appears in 2013 (14 studies) and 2014 (13 studies) and in the work by Sousa et al. (2016) (2006-2014) it appears in 2014 (4 studies) followed equally by 3 studies in 2006, 2011 and 2013.

Regarding the *type of vehicle*, we noticed a predominance of conference papers (26 out 38 papers, 68.42%). The shares in our study are close to the ones found in secondary studies investigating the use of ontologies in other domains (Sousa et al., 2016; Tapia-Leon et al., 2018; Tarhan and Giray, 2017), in which conference represents an average of 64% of the papers. Considering studies that investigate other aspects in the Computer Science field, the shares in our study are close to the ones found by Salamon et al. (2019), Quirino et al. (2018) and Real et al. (2019). Taking the period of publications into account, we noticed that the investigated topic has been target of researchers for more than 25 years. However, there is a predominance of conference papers, which, as in the aforementioned studies, can be seen as an indication that the research on this topic is not very mature yet, since journal publications usually require more mature works. We also noticed that there is no "home" or well-established forum for publications addressing HCI ontologies, since the 38 papers were published in many different conferences and journals. In fact, it seems that papers addressing HCI ontologies have been more welcome in vehicles of areas such as Information Technology and Artificial Intelligence than in vehicles devoted to HCI.

With respect to the *HCI aspects covered by the ontologies*, the top two aspects have been *User Interface* (12 ontologies) and *HCI Phenomenon* (11 ontologies). These aspects concern core knowledge of the HCI domain. When talking about HCI, it is often necessary to talk about the HCI phenomenon itself and the parts involved in it, i.e., the user and the system, which is perceived by means of the user interface. Thus, it was expected that these aspects were the focus of many ontologies. *Pervasive Computing*, *User Modeling / Profile* and *HCI Design* have also been addressed by many ontologies (ten) followed by *Interaction Experience* (eight) and *Adaptive Interactive System* (three). This shows that representing knowledge related to the design of interactive computer system based on user needs offers the potential to achieve personalized interaction and adaptive user interface, promoting a better user experience in times of pervasive systems. Although they are different aspects, there is an interrelation when we look at them in a holistic way. The evolution of one contributes to the evolution of the others, in a virtuous cycle, reflecting the core concerns of the HCI area and motivating the emergence of new technologies and studies for the benefit of people's daily lives. Even though there are ontologies that have addressed these aspects, there are some topics that have not been much explored (e.g., user feedback, usability) and others that have not even been considered (e.g., evaluation methods, prototype), suggesting that there are still many portions of the HCI domain that can be addressed by ontologies.

Considering *when the studies have been published* and *HCI aspects covered by the ontologies* we noticed that, although several HCI aspects have been addressed (Figure 4), the target of interest has changed over the years. For example, *User Interface* is the most addressed aspect in the first period (1994-2010), when ontologies started to be applied in HCI area. In the 2011-2015 period, which has the highest number of publications, *HCI Design* stands out, while in the 2016-2019 period, *Pervasive Computing*, *User Modeling / Profile* and *Interaction Experience* are the aspects addressed by more publications. We believe that, at first, ontologies were used to address more basic and perceptible aspects (e.g., User Interface) and, as the use of ontologies as a whole got more mature, other aspects were also addressed. The evolution and change of concerns in the HCI area can also have contributed to that. Despite the little use of ontologies in the first half of the 26 years considered in the study, the use of ontologies in the last decade reflects (in some way or to some degree) recent concerns in the area of HCI. Moreover, the increasing number of ontologies, the fact that HCI ontologies have addressed a wider range of HCI aspects associated with the increasing number of ontologies represented as both conceptual and computational models (which increases the range of possible ontology-based solutions) can be understood as an indication that the use of ontologies in HCI has been target of interest by the HCI community.

Considering *how ontologies have been used in the HCI domain*, there has been a predominance of knowledge management solutions (15 ontologies) and reasoning (9 ontologies). Ontologies are useful to structure data and knowledge (Jean-Baptiste, 2021). In this study, knowledge management encompasses issues such as knowledge representation, structuring, organization and sharing. As ontologies primarily serve to the representation purpose, it is not a surprise that most publications appear in this category. Knowledge management has been an ontology use of paramount importance in several domains (de Souza et al., 2015). The study results showed that the HCI domain has also benefited from the use of ontologies in this kind of application. Ontologies as conceptual models as well as operational ontologies have been used in knowledge management solutions. On the other hand, reasoning has involved the use of operational ontologies to support getting new information from data captured by an application or stored in a repository. By combining results from RQ2 and RQ3, we can notice that the two more used ontology-based solutions (knowledge management and reasoning) have been used only in the context of the four more addressed HCI aspects (UI, HCI phenomenon, User Modeling / Profile and HCI design). In line with what we said before, we believe that these aspects have been much explored because they are core aspects in the HCI domain. Thus, we think that it would be expected that they were addressed in the ontology-based solutions most used in the HCI domain. Although interactive computer system and user interface evaluation is an important aspect of the HCI domain (Preece et al., 2015), we noticed that it has not been much explored.

By analyzing the ontologies use and benefits reported in the selected publications, we can point out some advantages that have been obtained from the use of ontology-based solutions to solve HCI problems: (i) by using ontologies it has been possible to represent knowledge about the domain in a clear and explicit way, supporting communication and learning tasks. For example, #01 and #28 describe and make clear knowledge about HCI phenomenon and pervasive games, respectively. (ii) ontologies have allowed structuring knowledge, supporting the development of ontology-based systems, frameworks, approaches, architectures, etc. For example, #07 is used (both at design time and at runtime) in a framework for adapting interactive systems according to the user behavior. (iii) ontologies have enabled automated solutions and reasoning. For instance, #12 is used to reason about the usability of interactive medical devices in multiple situations of use. (iv) ontologies have supported semantic interoperability, enabling data/information from different sources to be integrated into HCI solutions (e.g., #16 it is used to semantically annotate a template about persona to integrate multiple data).

Concerning the *quality of HCI ontologies*, we noticed that although the ontologies present some quality characteristics (e.g., being modular and implementing non-taxonomic relations), others have not been a concern. For example, only one ontology (#34) is grounded in a foundational ontology. Foundational ontologies provide basic concepts and help domain ontologies to be truthful. Most of the HCI ontologies are not formally rigorous. For example, the ontologies presented in #13, #15, #20, #23, #29 and #31 are, in fact, taxonomies or lightweight ontologies, while #07, #08, #10 and #18 are just OWL artifacts (i.e., operational ontologies). Being formally rigorous makes the ontology more precise. As it was expected, Web Ontology Language (OWL) and Resource Description Framework (RDF) were the main languages used. This demonstrates that the publications may be concerned with using a language recommended by the World Wide Web Consortium (W3C) to specify and manipulate ontologies. Only four ontologies used international standards as a basis. Standards are important references to ontologies because they provide a consensual conceptualization of the domain of discourse. As for ontology development, only three were developed by following an ontology engineering method. By following an ontology engineering method, one adopts best practices to increase ontology quality. In this context, only three ontologies had their scope defined by means of competency questions. These questions help to elicit the ontology requirements and produce an ontology that meets the user's needs. Most HCI ontologies have been evaluated. However, evaluation has not been an explicit subject in the publications. Most of the times we considered that the instantiations or uses made of the ontologies were a way of evaluating them. The quality of an ontology directly affects the solution built using it. Thus, it is of paramount importance to use good practices to develop HCI ontologies. In general, the study results showed that ontology engineering practices and principles have not been a concern when developing HCI ontologies. We think that this can be seen as an opportunity for HCI and Ontology Engineer professionals and researchers to get closer.

Finally, by analyzing the ontologies coverage (we extracted the ontologies concepts, as it can be seen in our SLR package (Costa et al., 2020)), we noticed several overlaps. Although several ontologies address the same concepts or complementary portions of the HCI domain, they do not reuse each other's concepts. In fact, we noticed that HCI ontologies have been developed for solving specific problems, in specific contexts, without concern with integration to other existing HCI ontologies. This causes an increasing number of ontologies and makes it difficult to integrate different ontologies to produce a new ontology covering a larger portion of the domain. This, in turn, leads one to create new ontologies instead of reusing existing ones, feeding a 'vicious cycle' of many overlapping ontologies.

6. Limitations of the Study

Although the ambition of a systematic literature review is to summarize all relevant research in an area, different sets of publications can be obtained given a number of decisions and judgments taken (Wohlin et al., 2012). Thus, as any study, the study presented in this paper has some limitations, which must be considered together with the results. In addition, some challenges can reach the researchers during a systematic literature review, such as how to select a comprehensive and relevant source of publications, how to consistently apply the inclusion/exclusion criteria, how to classify data and how to interpret them. In this study, we experienced these challenges and carried out some actions aiming at minimalizing their influence on the results.

Publication selection and data extraction were initially performed by one of the authors. To reduce this subjectivity, the other two authors performed these same steps over a random sample of about 45% of the non-duplicated publications. Thus, at least 400 publications were evaluated by two researchers. The results of each reviewer were then compared. Discordances and possible biases were discussed in meetings. Concerning the 38 selected publications, all of them were evaluated by at least two researchers. An analysis of the degree of concordance was performed to measure the level of agreement between the results obtained from the researchers in the selection process. For this, we calculated the kappa coefficient (Landis and Koch, 1977). Kappa is a statistical measure of inter-rater agreement for qualitative (categorical) items. It is considered a more robust measure than simple percent agreement calculation, since it takes into account the agreement occurring by chance. Kappa maximum value is 1, representing total agreement. Values close to and below 0 indicate no agreement. Considering the set of publications analyzed by all the reviewers, the obtained kappa coefficient was 0.79, which, according to Landis and Koch (1977), means substantial agreement.

Terminological problems in the search strings may have led to missing some primary studies. In order to minimize these problems, we performed previous simulations in the selected databases. We decided not to search any specific conference proceedings, journals, or the grey literature (technical reports and works in progress). Thus, we have just worked with studies indexed by the selected electronic databases. The exclusion of these other sources makes the review more repeatable, but possibly some valuable studies may have been left out of our analysis. Although the digital libraries adopted represents a comprehensive source of publications, the exclusion of other sources and the fact that we did not perform snowballing may have left some valuable publications out of our analysis.

Applying the search string to the digital libraries engine can also interfere with the returned publications. First, because it is necessary to adapt the string syntax. The adaptation may result in a different search string. The string used in the study was adapted to each digital library and we double-checked the adapted string and ran tests to ensure that it was correct. Second, because of problems or changes in the engines. During the study, changes occurred in the engine of one of the used digital libraries. We ran some tests that showed us that the engine interface had changed, but the engine seemed to work as before.

Another limitation is related to the classifications we made for categorizing data. Some categories were based on classifications proposed in the literature (e.g., quality characteristics (D'Aquin and Gangemi, 2011), evaluation types (Brank et al., 2005)). Others were established during data extraction, based on data provided by the analyzed publications (e.g., categories used in RQ2 and RQ3). Classification schemas and data categorization were done by the first author and reviewed by the other two authors. However, determining how publications fit them involves a lot of judgment. Thus, different results could be obtained by other researchers.

7. Conclusions

In this paper, we presented a systematic literature review that investigated ontologies in the HCI domain. The results of this study provide a panorama of research related to the topic and go deeper in some aspects about the use of ontologies to solve HCI-related problems. A total of 899 publications were considered and 35 ontologies addressing different aspects of the HCI domain were identified in 38 selected publications. Six research questions were defined to investigate the following facets: (i) the distribution of the selected publications over the years and the type of vehicle; (ii) the HCI domain aspects addressed by the HCI ontologies; (iii) how ontologies have been used in the HCI domain; (iv) how HCI ontologies have been developed; (v) how HCI ontologies have been evaluated; and (vi) the HCI ontology quality characteristics.

According to Kitchenham and Charters (2007), the results of a systematic literature review help identify gaps that suggest future research. Therefore, this study contributes by providing a consolidated view of ontologies in HCI and pointing out some conclusions that can drive future research in the area. In this context, we can highlight: (i) The adoption of ontologies in the HCI domain is a research topic that still needs to be matured. Although the first publication found in this study is from 1994, only in the last decade ontology use became more regular in the HCI domain. (ii) Ontologies have focused on core HCI aspects, mainly on the interface and interaction. This suggests that several HCI sub-domains have not experienced the benefits of ontology-based solutions. For instance, in most cases, there are topics of the HCI aspects that have not been much explored (e.g., user experience, usability) and others that have not even been considered (e.g., prototype, brain computer interface). Moreover, although some works deal with HCI design and evaluation, there is still much to be explored. For example, we did not find any work addressing design or evaluation processes, documentation and evaluation methods. We also did not find any publication dealing with physiological computing, multiple users or smart home. (iii) Ontologies have been used mainly in knowledge management and reasoning solutions. Considering the diversity of knowledge involved in the HCI domain and the multiple artifacts used in this context, other important solutions, such as the ones related to semantic interoperability, can be further explored. (iv) The most sophisticated ontology-based solutions we found focus only on interface adaptation. There are many other HCI-related problems that can be addressed by using ontologies. (iv) There has been no concern with the quality of the developed ontologies. This suggests that HCI and ontology engineering professionals and researchers should work together to produce HCI ontologies. This can contribute to both areas: HCI can benefit from quality ontologies, while Ontology Engineering can find new opportunities and challenges to apply ontologies. (v) There has been a lack of reusing existing ontologies. Therefore, ontologies reuse in the HCI domain is an issue to be further explored. In summary, the study results show that although ontologies have been used in the HCI domain, the use has focused on only two types of ontology-based solutions and three core aspects of HCI. Moreover, HCI ontologies, in general, have not been developed by following ontology engineering good practices. Considering the advantages of using ontologies (as discussed in Section 6), we believe that it is worth investing efforts to improve HCI ontologies and ontology-based solutions to address problems in the HCI domain. Towards this direction, we propose to organize HCI ontologies as an ontology network to provide comprehensive and consistent knowledge of the HCI domain and support ontology-based solutions.

Concerning related works, we did not find any study investigating the use of ontologies in the HCI domain. Before performing our study, we searched for secondary studies investigating ontologies in the HCI domain. Since we did not find any, we decided to carry out our study. Therefore, there is a possibility that this study is a pioneering work investigating HCI ontologies.

As for the publications analyzed in this study, many times we faced difficulties to extract information about the ontologies, because it was incomplete or implicit in the paper. This makes it difficult to properly understand existing ontologies and hampers reuse them. We believe that the HCI community could achieve more benefits if the proposed ontologies were presented completely (even if through supplementary material). Another fundamental issue is to improve the visibility and ability to download ontologies and their documentation through the web.

Reuse is an important issue in ontology engineering and a desirable quality attribute of ontologies. Considering seven ontologies (#25, #27, #30, #32, #33, #34, #35) published in the last years and represented as both conceptual and computational models (which may contribute to reuse), we noticed that four of them were reused: #27, #32 and #34 in other works by the same authors; #30 and #34 by other authors. Since this is a small sample of the ontologies identified in our study, we cannot make conclusions about reuse considering only these ontologies. Thus, as future work, we intend to extend our study to investigate ontology reuse in HCI.

Finally, it is worth saying that, due to the successful use of ontologies in other areas, in this study, our focus was to investigate ontologies in HCI and verify if their potential has been explored to solve semantic and knowledge-related problems in that domain. Sometimes, ontologies can be used as taxonomies, but the opposite does not apply. Thus, since taxonomies can also be used to represent knowledge in the HCI area (e.g., (Dankov and Bontchev, 2020; Janssen et al., 2020; Jonas et al., 2019)) and support semantic and knowledge-based solutions, we consider in the future to investigate the use of taxonomies in HCI and compare the results with our study.

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