Information and Software Technology 111 (2019) 122–130

Contents lists available at ScienceDirect

Information and Software Technology

journal homepage: www.elsevier.com/locate/infsof

State of the art in hybrid strategies for context reasoning: A systematic literature review

Roger S. Machado[a,*], Ricardo B. Almeida[a], Ana Marilza Pernas[a], Adenauer C. Yamin[a]

Computer Science Graduate Program, Federal University of Pelotas, Pelotas - RS, Brazil

ARTICLE INFO

Keywords:
Context awareness
Reasoning strategy
Hybrid context reasoning
Internet of Things

ABSTRACT

Context: Several strategies have been used to implement context reasoning, and a strategy that can be applied satisfactorily in different smart systems applications has not yet been found. Because of this, hybrid proposals for context reasoning are gaining prominence. These proposals allow the combination of two or more strategies.

Objective: This work aims to identify the state of the art in the context awareness field, considering papers that use hybrid strategies for context reasoning.

Method: A Systematic Literature Review was explored, contributing to the identification of relevant works in the field, as well as the specification of criteria for its selection. In this review, we analyzed papers published between 2004 and 2018.

Results: During the process, we identified 3241 papers. After applying filtering and conditioning processes, ten papers about hybrid strategies for context reasoning were selected. We described, discussed, and compared the selected papers.

Conclusion: The Systematic Literature Review showed that some researchers explore hybrid proposals, but these proposals do not offer flexibility regarding the reasoning strategies used. Thus, we noted that research efforts related to the topic are still necessary, mainly focusing on the development of dynamic approaches that allow the applications to choose how they want to use the different resources available.

1. Introduction

Due to the rapid development of the Internet of Things (IoT) and its use in different aspects of everyday life, the amount of context data used in smart systems has been increasing [1]. These data can represent the state of the environment over time. The effective use of this large volume of contextual data can introduce new possibilities for human development, through computational solutions that are autonomous, responsive, and context-adaptable [2].

Context awareness becomes an essential approach for providing adaptable services in smart systems. It can be used, for example, to select the most appropriate services according to the contextual information that is relevant to the user or to change operational parameters of services in execution [3]. Thus, context-aware applications must be able to adapt their changing behaviors reducing human intervention, and resulting in additional challenges for their developers [4].

The operation of context-aware systems involve a significant amount of context information that needs to be: continuously collected; efficiently interpreted; quickly processed; disseminated to the interested applications; stored in context repositories [5,6]. Therefore, to minimize development efforts, robust mechanisms for context management must be adopted. Furthermore, it is necessary to use context representation schemes to deal with the heterogeneity of the data involved.

Investigating context management related to contextual information modeling approaches and reasoning strategies is part of a significant research effort. Besides, it is necessary to examine the use of context awareness for developing applications that are adaptable according to the interests defined by the users [7].

Some modeling approaches and strategies for context reasoning have recently been developed. However, they are not versatile enough to individually meet the reasoning requirements of different ubiquitous applications in the IoT scenario. Thus, the need of a combination of different methods for context reasoning is identified by means of hybrid strategies [2,8].

The use of hybrid strategies for context reasoning is a growing area of research in the scientific community due to its potential for better predictive accuracy. Hybrid strategies aim to provide adequate approaches

* Corresponding author.
E-mail addresses: rdsmachado@inf.ufpel.edu.br (R.S. Machado), rbalmeida@inf.ufpel.edu.br (R.B. Almeida), marilza@inf.ufpel.edu.br (A.M. Pernas), adenauer@inf.ufpel.edu.br (A.C. Yamin).

https://doi.org/10.1016/j.infsof.2019.01.010
Received 14 June 2018; Received in revised form 17 January 2019; Accepted 22 January 2019
Available online 14 February 2019

to computer-based solutions, regarding complex problems, such as those faced by IoT applications [9,10].

The goal of this work is to identify the state of the art in the field of context awareness, considering papers that explore hybrid strategies for context reasoning. To achieve such goal, we have performed a Systematic Literature Review (SLR), whose are discussed herein, thus allowing its reconstruction with other exclusion/inclusion criteria. As a product, we identified representative works published between 2004 and 2018 and recorded the obtained papers from different digital libraries. At the end of the SLR, ten papers were selected, described, and compared.

The remainder of this paper is organized as follows. Section 2 discusses the context awareness design and aspects regarding its definition. In Section 3 we present the SLR performed. Section 4 describes the selected papers in this SLR, exhibiting the main characteristics of each paper. In Section 5 we discuss the main features explored by the selected papers. Section 6 presents our conclusions and future work.

2. Background in context awareness

Context is any information that can be used to characterize the situation of an entity (person, place, or object) considered relevant to the interaction between user and application, including the user and the application [4,11]. Context awareness is the ability of a system to use context to provide relevant information and services to the user [11,12].

The construction of a context-aware system occurs mainly through four steps [13]:

- Acquisition - refers to the process of monitoring and capturing contextual information. This step aims at abstracting from context-aware applications the complexity of data collection, enabling the reuse of sensors and the separation between obtaining and using contextual information [14];
- Modeling - refers to the process of designing a model of real-world entities, their properties, the state of their environment and situations. The purpose of creating a context model is to provide a uniform, machine processable context representation scheme, facilitating context sharing and interoperability between different applications. The uniformity of the model between acquisition, reasoning, and utilization of context information is considered vital [12];
- Distribution - refers to the step that allows the injection of context into the context-aware application and its delivery to all entities that have expressed any form of interest in this data [5];
- Reasoning - can be defined as a method of deducing new knowledge, and better understanding, based on the available context [15]. It can also be explained as a process of providing knowledge deduction from a set of contexts [16].

The task of context reasoning is to transform raw data into knowledge associated with some basic functionalities such as validating context values, filling in missing values, removing outliers, checking context inconsistencies and applying calculations to obtain new values [6].

In the literature, we can identify different strategies for context reasoning, which have advantages and disadvantages considering the distinct domains of application. In this way, different applications will require distinct strategies to implement context reasoning, since each application has its own criteria and requirements that need to be fulfilled [2]. Bellow, we present some of the main strategies used to perform context reasoning [2,12,13,17].

- Case-based is a strategy that uses the specific situational knowledge of a concrete problem previously experienced (cases) to solve a newly identified problem [18]. An important feature of case-based reasoning is its incremental learning ability from new experiences, which are retained each time a problem is solved, making it immediately available for future situations [19].
- Fuzzy allows approximate reasoning instead of a fixed value, being able to reason values between 0 and 1 [14]. This strategy can be used to reason about the uncertainty or imprecision of the context, allowing real-world scenarios to be represented more naturally [13].
- Probabilistic logic enables decisions to be made based on probabilities associated with events [20]. This strategy is especially applicable in context-aware environments due to potential temporary failures in communication with sensors and the possibility of imprecise measurements of physical sensors.
- Ontology proposes the semantic modeling of concepts (classes), roles (properties and relations), and individuals, allowing the specified knowledge to be machine interpretable [21]. This strategy is computationally intensive and the response time will depend largely on the size of the data and axiom sets contained in the ontology [22].
- Rules are constructed from facts, which are certain statements that are considered descriptions of a situation [23]. This strategy can be used with the support of a Complex Event Processing (CEP) mechanism, enhancing the capabilities to execute reasoning on context data [24].
- Supervised learning uses training examples that are collected, labeled according to the expected results and then a function is derived to generate the results by utilizing the training example data [25].
- Unsupervised learning can find hidden structures using a training set based on unlabeled data [26]. Techniques of this strategy analyze training data and attempt to discover patterns in the data used.

Table 1 presents a comparative analysis of the different reasoning strategies based on the papers [12,13]. The analysis focuses on the main positive and negative aspects of each strategy, as well as on examples of applicability, that benefit from the characteristics of the reasoning strategies analyzed.

The literature review indicates that the reasoning strategies are not versatile enough to individually meet the reasoning requirements of different ubiquitous applications in the IoT scenario. This situation has stimulated the use of hybrid strategies to perform context reasoning [8].

Hybrid strategies have the characteristic of using two or more strategies for reasoning, with the motivation to explore the strengths of each strategy and minimize weak points [2,7].

3. Systematic literature review in hybrid strategies for context reasoning

SLR is a research methodology that comprises the execution of a series of procedures to generate a literature review in an area, in order to identify a set of papers that precisely summarizes the addressed state of the art [27]. A property of this research methodology is that all of its procedures are registered, allowing the study to be reproduced by other researchers.

3.1. SLR: research questions

The first step in the development of an SLR is the definition of the research questions that support the SLR [28]. In this way, the research questions that support this SLR and guided the study were:

RQ1: What strategies for context reasoning are used together?

We want to investigate if there is a pattern of using two or more different reasoning strategies together, since many works explore distinct strategies. Thus, we intend to analyze, for example, if one reasoning strategy is considered complementary to another.

RQ2: In what domains are hybrid strategies for context reasoning applied?

Our goal is to identify domains that have potential to explore hybrid strategies for context reasoning. Furthermore, we want to investigate if there is any trend in the domains explored in the selected works.

RQ3: What evaluation approaches are used?

We want to investigate if there is one approach that is used by most of the selected works. Thus, we expect to identify what approach is con-

Table 1
Comparison between reasoning strategies.

Strategy	Positive aspect	Negative Aspect	Applicability
Case-based	Handles unknown issues and uses prior knowledge to solve new problems	Demands a careful specification of what the cases are and their similarity	Definition of actions based on a given situation and diagnostic tasks
Fuzzy	Allows natural representation, not resource intensive and ability to deal with uncertainty	Prone to errors due to manual labor and no quality check or validation	For situations where context needs to be converted into more natural information
Ontology	Definitions of complete concepts about objects and their relations	Not able to find missing values or ambiguous information and need a significant computational power	Definition of relationships and for validation and verification
Probabilistic logic	Allows to combine evidences, handle uncertainty, and achieves moderately significant results	It is necessary to know the probabilities and handle with numeric values only	For situations in which probabilities are known and can be used to situation recognition
Rules	Simple definition and interpretation, can be easily extendable	May be prone to errors due to manual labor and has complex maintenance	Definition of actions, policies, and preferences based on conditions
Supervised learning	Discovers the relationships between inputs and outputs and achieves good precision level	Requires a lot of data and labeled training data	Where the feature set is identifiable, and possible outputs are known
Unsupervised learning	Can learn without the need of an expected response in the training data	Difficult to validate and find predictable results	Detection of unusual behavior, being used for application in sensor networks

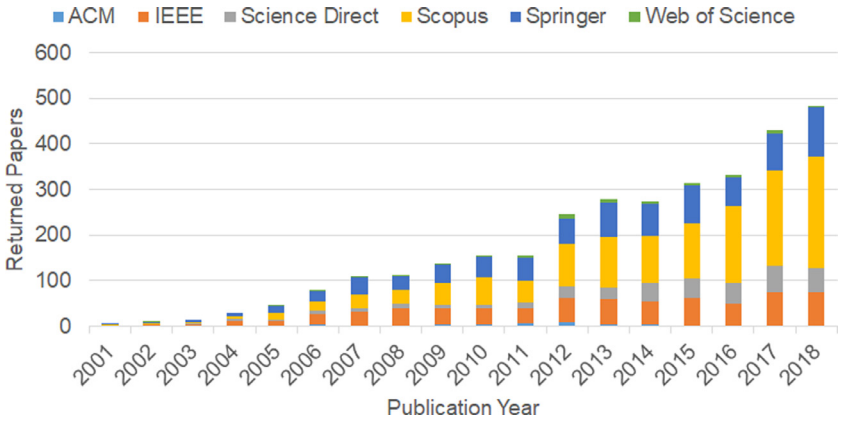

Fig. 1. Number of documents returned from the chosen digital libraries.

sidered adequate to evaluate the hybrid reasoning strategies, facilitating the evaluation of new works.

3.2. SLR: papers search process

The conceived search string to use in the systematic literature review process was:

((“hybrid reasoning”) OR (“hybrid approach”) OR (“hybrid framework”)

OR (“hybrid strategy”)) AND ((“context aware”) OR (“context awareness”)).

We have written the search string considering only hybrid strategies, so the first part of the string has all the terms accompanied by the word hybrid, since hybrid is a widely used term in the literature [8]. The second part of the search string (after AND) is used to search only for strategies that are context-aware.

In order to identify which period we should analyze in this SLR, we have applied the conceived string to search in full-text of papers contained in on six digital libraries: (i) ACM; (ii) IEEE; (iii) Science Direct; (iv) Scopus; (v) Springer; and (vi) Web of Science. The choice of these digital libraries was based on the predictability of long-term paper availability, as well as to the fact that these digital libraries cover most of the journals and conferences in the field of computer science, focusing on context-aware applications.

We have applied the conceived string to search the full-text of papers contained in the digital libraries. Fig. 1 shows the number of papers returned in each library.

As we can see in Fig. 1, there is an increase in the number of papers returned starting from 2004. Thus, we have decided to perform the SLR in the period between 2004 and 2018.

The selection of the papers followed the execution flow of Fig. 2, where we can see that it was executed in four steps. The first step applies the search string to the full-text of the papers contained in the digital libraries. The remaining steps execute the filters applied in this SLR which attend the following exclusion criteria:

1. Papers that were not published between 2004 and 2018;
2. Papers that do not contain the search string specifically in the title, abstract, or keywords;
3. Duplicate papers;
4. Documents that are not papers published in conferences or journals;
5. Papers not written in English or Portuguese;
6. Papers that do not present reasoning strategies;
7. Papers that propose the use of only one strategy for context reasoning;
8. Papers with small differences from previous work of the same research group.

In the second step, we applied the first filter using the first exclusion criterion, which eliminated papers that were not published between 2004 and 2018.

In the third step, we executed a filter based on the second exclusion criterion which excludes papers that do not contain the search string specifically in the title, abstract, or keywords. Several papers present in the literature use this criterion to limit the search process and avoid the false positive results of a full-text search [29–31].

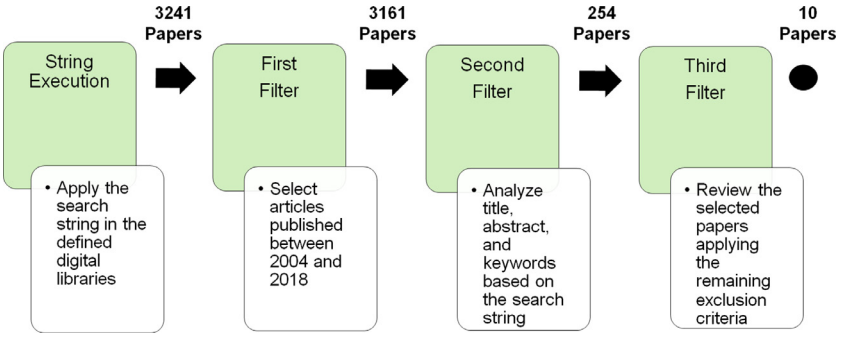

Fig. 2. Execution flow of this systematic literature review.

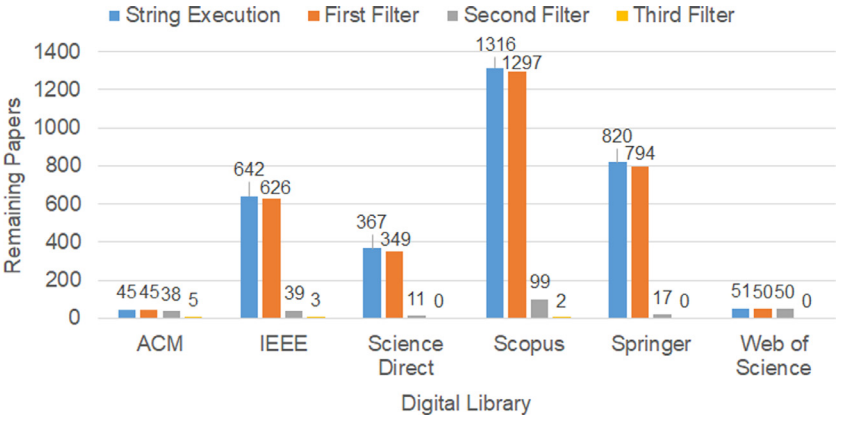

Fig. 3. Number of papers after each selection step.

In the last step, we performed a full-text analysis of the papers based on the remaining exclusion criteria. The third exclusion criterion removes duplicate papers, while the fourth exclusion criterion excludes studies that are books, book reviews, conference review, or lecture notes [32].

The fifth exclusion criterion removes papers that were not written in English or Portuguese. The sixth exclusion criterion excludes papers that do not present reasoning strategies, while the seventh exclusion criterion removes papers that propose the use of only one strategy for context reasoning

The last exclusion criterion eliminates preliminary work from the same research group, selecting only the most complete and recent work [29]. In order to apply this criterion, we identified which papers were related to the same research study and had only small differences between them.

3.3. SLR: number of analyzed papers

Fig. 3 shows the number of papers of each digital library after the execution of each step.

Table 2 shows an overview of the number of papers that were excluded based on each exclusion criteria. As we can see, the criterion that excluded the most significant number of papers was the analysis of the title, abstract, and keyword based on the search string, excluding 2907 papers.

In the last filter of this SLR, we analyzed 254 documents, in which 140 duplicate papers were detected. Considering the 114 remaining articles, we removed sixteen documents by the exclusion criterion of documents that are not papers published in conferences or journals. After, we excluded 2 papers because they were not written in English or Portuguese.

Regarding the 96 remaining papers, we performed a detailed review of them. Firstly, we decided to apply the criterion to exclude works that do not propose strategies for context reasoning, resulting in the exclusion of 38 papers.

Table 2
Number of excluded papers by each exclusion criteria in each digital library.

	Exclusion criteria							
Digital Library	1	2	3	4	5	6	7	8
ACM	0	7	0	0	0	16	14	2
IEEE	16	587	14	0	1	12	9	1
Science Direct	18	338	5	0	0	2	3	1
Scopus	19	1198	69	15	1	4	9	1
Springer	26	777	12	1	0	0	3	0
Web of Science	1	0	40	0	0	4	5	0
Total	80	2907	140	16	2	38	43	5
Remaining papers	3161	254	114	98	96	58	15	10

Considering the 58 remaining papers, we tried to exclude papers that propose the use of only one strategy for context reasoning, which resulted in the exclusion of 43 works. Among these papers the following strategies for reasoning were detected:

- Nineteen utilize ontology;
- Eight use unsupervised learning;
- Seven utilize rules;
- Six explore supervised learning;
- Two explore fuzzy;
- One uses probabilistic logic.

Regarding the 15 remaining papers, we applied the exclusion criterion which verifies papers that present small differences from previous work from the same research group, also analyzing the completeness of the work, which resulted in the exclusion of 5 papers.

Table 3 shows the selected papers in this SLR, where we can see: authors; title; digital libraries that returned the paper; and conference or journal where the paper was published.

Table 3
Summary of selected papers.

Paper	Title	Digital libraries	Conference/Journal
[33]	Hybrid reasoning in the CARE middleware for context awareness	ACM and Scopus	International Journal of Web Engineering and Technology, 2009
[34]	COSAR: Hybrid reasoning for context-aware activity recognition	Scopus and Web of Science	Personal and Ubiquitous Computing, 2011
[35]	A context-aware middleware for ambient intelligence	ACM and Scopus	12th International Middleware Conference, 2011
[36]	A distributed architecture for dynamic contexts composition in Ubicomp	IEEE, Scopus, and Web of Science	Latin American Computing Conference, 2012
[37]	Hybrid reasoning technique for improving context-aware applications	ACM, Scopus, Springer, and Web of Science	Journal Knowledge and Information Systems, 2012
[38]	Context-aware hybrid reasoning framework for pervasive healthcare	ACM, Scopus, Springer, and Web of Science	Journal Personal and Ubiquitous Computing, 2014
[39]	Context-aware hybrid classification system for fine-grained retail product recognition	IEEE, Scopus, and Web of Science	Image, Video, and Multidimensional Signal Processing Workshop, 2016
[40]	An ontology-based hybrid approach for accurate context reasoning	IEEE, Scopus, and Web of Science	Asia-Pacific Network Operations and Management Symposium, 2017
[41]	Towards a hybrid approach to context reasoning for underwater robots	Scopus and Web of Science	Journal Applied Sciences, 2017
[42]	A hybrid architecture to enrich context awareness through data correlation	ACM and Scopus	ACM Symposium on Applied Computing, 2018

4. Hybrid strategies systematization considering the selected papers

In this section, we present aspects regarding reasoning strategies, about the ten papers selected with the SLR protocol.

4.1. Reasoning based on ontology and rules

In this section, we present the papers [33,36] which propose hybrid reasoning based on ontology and rules.

4.1.1. Hybrid strategy for the CARE middleware

In [33], the Context Aggregation and REasoning (CARE) middleware that aims to support the context-aware adaptation of internet services in a mobile computing environment was proposed. One of the key requirements of the middleware is to support reasoning on context data efficiently.

In order to perform the context reasoning, the authors proposed a hybrid strategy exploring ontology and rules. Ontological reasoning is performed for deriving particular classes of context data that cannot be expressed using rules.

The interaction between the strategy based on ontology and rules is provided by the possibility to define policy rules whose preconditions involve context data that may be derived by ontological reasoning. These data are used in preconditions of policies for determining new information, such as user preferences and adaptation directives.

In order to evaluate the proposal, the authors present experiments on ontological reasoning, wherein the ontology models the sociocultural environment of mobile users. Thus, the authors only evaluate the strategy based on ontology, which is used to derive the specific activity performed by the user.

4.1.2. Hybrid strategy for the DynamiCC architecture

The paper [36] proposes an architecture for context awareness called DynamiCC. The proposal focuses on the conception of a context model and a software architecture that allow the interpretation and the dynamic composition of the information acquired by sensors positioned in different locations of the ubiquitous environment. Thus, DynamiCC seeks to make feasible the construction of complex contexts, whose contextual information can be obtained in a distributed way, as well as having its processing rules changed without the need to interrupt the execution of the applications.

A hybrid strategy for reasoning was proposed to perform the processing of contextual information. DynamiCC uses semantic reasoning provided by the ontology, through axioms and rules to infer new knowledge based on the ontology instances. The ontology is represented in OWL-DL (Description Logics), using the rule language provided by the Jena framework. In addition to this, DynamiCC uses reasoning based on rules such as ECA (Event-Condition-Action), which performs the processing of contextual information provided by a relational model.

Although using a hybrid strategy for context reasoning, DynamiCC uses the two strategies proposed individually. When the data collected are sent to the relational model, DynamiCC uses the rule-based strategy, if the data were transmitted to the ontological model, DinamiCC explores the ontological reasoner. Context-aware applications should inform which monitored information will be processed by each strategy at the time of DynamiCC architecture configuration.

In order to evaluate the architecture proposed, the authors present four scenarios illustrating in only one of them the application of reasoning strategy using an ontology. While the other three scenarios cover the following aspects: (i) data acquired from the environment and action on it; (ii) communication between the architectural components; and (iii) composition of dynamic contexts.

4.2. Reasoning based on ontology and supervised learning

In this section, we present the papers [34,35,40] which propose hybrid reasoning based on ontology and supervised learning.

4.2.1. Hybrid strategy for the COSAR architecture

The paper [34] defines an architecture for a mobile context-aware activity recognition system named COSAR. The architecture performs the monitoring of body-worn sensors and spread in the environment. Data provided are merged to build a feature vector that is used to predict the user's activity.

In order to predict the user's activity, a hybrid reasoning was proposed, exploring a strategy based on ontology and supervised learning. To perform the ontological reasoning, the authors defined an ontology that models activities, artifacts, people, communication routes and symbolic locations, and that expresses relations and constraints among these entities. The same ontology is used to describe and recognize complex social activities that would be hardly identifiable by a purely supervised learning strategy.

The strategy based on supervised learning performs the inference based on raw data retrieved from body-worn sensors to predict the most probable activities. While the ontology is applied to refine the results of supervised learning inferences by selecting the set of possible activities performed by a user based on his/her current context. Thus, the context

information is mostly exploited by the ontological reasoner, and only in limited cases by the supervised learning strategy.

In order to evaluate the proposal, the authors present an experiment based on the identification of physical activities performed both indoor and outdoor by six volunteers. In the evaluation, the authors compare the accuracy and the computational cost of the hybrid strategy proposed with the use of supervised learning individualized. The results obtained show the superiority of the hybrid strategy.

4.2.2. Hybrid strategy for the IMERA middleware

In [35], a context-aware middleware called IMERA was proposed to support ambient intelligence. The middleware architecture is divided into four layers: (i) sensor layer has access to different computational entities and diverse sensors and actuators devices; (ii) interface layer that allow two ways exchange between devices and middleware management layer; (iii) middleware management layer which is based on sensors data fusion, a reasoning engine, a context knowledge base, a context database and a context query engine; and (iv) high-level interface layer which performs the communication between the middleware and the application.

Hybrid reasoning was proposed using a strategy based on ontology and supervised learning with the use of decision tree technique. In this way, the authors emphasize that the proposed strategy provides a more flexible, robust, and efficient problem resolution in complex ambient intelligence situations [35].

The authors do not show any information about the reasoning execution flow or how the applications can select the use of one strategy or another. Besides, in the paper is not presented examples of the strategy based on ontology, and if in this strategy they used axioms or ontological rules.

In order to evaluate the proposal, the authors present one scenario in which they say how both reasoners can be used. The ontology strategy processes the user's activity from collected contexts, while the supervised strategy constructs the decision tree based on the user's profile.

4.2.3. Hybrid strategy for the Mining Minds framework

In [40], a hybrid strategy for context reasoning is proposed for the Mining Minds, which is a framework that offers personalized support for health and well-being. In order to carry out the context reasoning, a new conjunctive approach is proposed, which is based on ontology and supervised learning. The supervised learning strategy supports the inference by classifying high-level contexts based on the data set instantiated in the ontology. In order to develop the ontology, the authors use OWL-DL and Pellet to perform reasoning.

In order to accomplish the storage of contextual data provided by the ontology the authors propose the use of a triple model. In the tests performed, an ontology-based strategy was combined with six different supervised learning techniques: Naive Bayes, KStar, IBK, J48, RandomForest, and RandomTree. The technique that presented the best result combined with the ontology was RandomForest, whereas KStar showed the worst performance.

The reasoning execution flow explored for the authors is always the same, where the ontology strategy checks the consistency of contexts, deduces knowledge on context information, and stores this information in the triple model. After, the supervised learning strategy uses the data stored in the triple model as a training dataset. Thus, with this combination, the authors improve the classification precision of the supervised learning strategy.

In order to evaluate the proposal, the authors present an experimental evaluation using a dataset collected from 20 users on different days and timings. Users were provided with smartwatch, smartphone, and skeletal postures were detected using indoors Kinect facilitated with a depth camera. The supervised learning strategy used together to ontological strategy enhanced the precision performance from 91.5% to 99.99%.

4.3. Reasoning based on cases and ontology

In [37], a service platform called Context-Aware Service Platform (CASP) was proposed. This platform has as main characteristics to be context-aware and deal with the aggregation and abstraction of context information using ontologies to represent them.

The CASP platform uses two reasoning strategies, one based on ontology and the other in cases. The authors use the Jena framework for implementation of the ontology strategy and jCOLIBRI framework for implementation of the case-based strategy.

High-level context information can be derived using ontology or cases. Ontology represents general knowledge of the domain, while the cases capture specific knowledge. Ontology reasoning evaluates the rules provided and adds the inferred information to the knowledge base. Case-based reasoning recovers similar situations and uses the corresponding solutions to update the data in the knowledge base represented by the ontological model.

The authors use the two reasoning strategies individually, they did not propose any combination of these strategies. Reasoning execution flow is always the same, where after occurring an update in the knowledge base, the strategies are notified, perform the reasoning process, and add the new information obtained in the knowledge base.

In order to evaluate the proposal, the authors present two use cases in which both reasoners are used to derive extra useful information. In the desk-sharing office use case, the combination of ontology-based and case-based reasoning allowed the typical trajectories of a user to be learned with a 42% improvement in the localization of such trajectories. In both use cases, the hybrid approach provided a significant improvement.

4.4. Reasoning based on cases and fuzzy

The paper [38] presents a framework for hybrid reasoning developed for the Context-Aware Real-time Assistant system. The framework performs the monitoring of an intelligent home environment, providing a fusion of context-aware data, as well as anomaly detection mechanisms that support the activity of analysis and generation of alerts.

The hybrid reasoning is based on the cases and fuzzy strategies, making it more robust and adaptable to an environment subject to changes [38]. The case-based reasoning is used to detect conditional anomalies for residential automation, and the fuzzy reasoning to deal with exceptions, as well as case retrieval and adaptation of query-sensitive cases [38].

The reasoning execution flow explored by the authors is always the same, where the fuzzy strategy is used to adapt the case-based reasoning. The authors apply fuzzy to the input query and use the crisp value of fuzzy output to adjust weights used for the features similarity measure. Besides, the outputs of both strategies are combined using the logical operator to produce response values.

In order to evaluate the proposal, the authors conducted an experiment to test the correctness of the system proposed in a pervasive healthcare environment. The reasoning strategy was evaluated based on its precision to detect the situation of interest. In the experiment performed the case-based with fuzzy dynamic weights and fuzzy rules adaptation obtained the best performance for anomaly detection.

4.5. Reasoning based on probabilistic logic and supervised learning

The paper [39] proposes a system that individually classifies the retail products on a shop shelf. The classification system combines the strengths of classifiers without context and with context information. The system objective is to design a probabilistic model that encodes the relationships between the products on the shelf and combine this with current methods of image classification based on vision.

In order to perform the contextual data reasoning, a combination of the supervised learning strategy and the probabilistic logic strategy is

proposed. Two different hybrid approaches are used, the first combines Support Vector Machines (SVMs) with Hidden Markov Models (HMMs). In the second, the SVMs are combined with Conditional Random Fields (CRF) aiming to form a new context. Probabilistic models are trained by learning from context-free classifier errors (SVMs) and neighboring relationships between retail products.

The reasoning execution flow explored for the authors is always the same, in which the outputs of the supervised learning strategy are used as inputs in the probabilistic logic strategy. Thus, with this combination, the authors improved the fine-grained retail product classification results.

In order to evaluate the proposal, the authors present an experimental evaluation using the Vispera[1] soft-drink products dataset, which consists of 3920 annotated images from retail shelves containing soft-drink products. The evaluation was based on detection of products by the reasoning strategies, and the results show that by combining of Context-free Classifier (SVMs) and the HMM method a 9.5% improvement was achieved. While the combination of SVMs with CRF achieved an 11.4% improvement.

4.6. Reasoning based on ontology and probabilistic logic

The paper [41] proposes a hybrid strategy for context reasoning for middleware Smart and Networking Underwater Robots in Cooperation Meshes. The strategy consists of two strategies for reasoning: (i) ontology modeled in OWL-DL using both axioms internal to the ontology and rules written in the SWRL language; and (ii) probabilistic logic using the Multi-Entity Bayesian Network, which consists of a logical system that integrates first-order logic with Bayesian probability theory[2].

The authors emphasize that with the incorporation of the two strategies, a better performance is provided for the context reasoning, taking advantage of the positive points of each strategy, with the intention of compensating the weaknesses of the same ones. The authors point out that the proposed hybrid strategy is useful in providing different reasoning capabilities and satisfying the diverse needs of the applications [41].

The authors use the two reasoning strategies individually, they do not propose any combination of these strategies. The reasoning execution flow is the same for both strategies: information stored in the ontology model is consulted; the reasoning process is performed; and the new information obtained is added to the ontology model.

In order to evaluate the proposal, the authors describe a case study on oil spill detection, in which they verify the usefulness and applicability of the hybrid context reasoning mechanism. The simulated results have shown that in theory, the hybrid context reasoning method can make logical inferences in specific contexts and also probabilistically reasoning under uncertainties in the underwater robot field.

4.7. Reasoning based on ontology, rules, and supervised learning

In the paper [42], a context-aware architecture to process information based on hybrid models is proposed. The architecture provides: acquisition of context; preprocessing of data; context processing with a hybrid reasoning strategy; data storage with the support of three database models; repository communication that enable access to contextual information; and correlation approach based on compositional rules that allow the combination of data stored in distinct models.

In order to perform the context reasoning, the authors propose the use of rules, ontology, and supervised learning. The strategy based on rules performs the correlation of events detecting patterns described in an easy interpret syntax. The ontology can be used in two forms, internal axioms and external rules written in SWRL. While supervised learning uses the decision trees technique to classify events.

The authors emphasize that the three strategies can be selected according to the demand, being able to be used individually or combined. However, the authors did not show the reasoning execution flow, and how the strategies can be combined.

In order to evaluate the proposal, the authors describe a usage scenario based on information security, in which they explore the ISO 27002, that contains a code of practice for the management of information security. To perform the context reasoning, the authors use only the rule-based strategy, and for mapping the structure of ISO 27002, an ontology.

5. Discussion of research efforts in selected papers

In this section, we discuss the main features explored by the selected papers to obtain context awareness. Afterwards, we examine the research questions based on the answers obtained with the execution of this SLR.

5.1. Context awareness steps

Table 4 presents a comparative analysis of the selected papers in the SLR performed. This analysis was based on: (i) types of sensors used in the acquisition step; (ii) models used to perform the context representation; (iii) model utilized to store the contextual data; (iv) reasoning strategies proposed; and (v) evaluation methodology used.

Concerning acquisition step, according to the information on Table 4 only one paper does not present how they collect contextual data. The remaining of papers have support to deal with different types of sensors, allowing the treatment of different applications.

Regarding the modeling step, we can see that six papers use the ontology-based model, mainly due to its semantic representation characteristic. It is worth mentioning that in [36] and [42] the use of hybrid modeling was proposed combining ontological and relational models.

Issues related to contextual information storage are not discussed by the majority of the papers, although it is important for context-aware applications. The work of Yuan and Herbert [38] uses the markup scheme model XML (eXtensible Markup Language), mainly because it can be utilized to transmit information between different components. The works of Lopes et al. [36] and Xu et al. [35] use a relational storage model, which is not considered a satisfactory model for the storage of data provided by the ontologies [43]. Besides, the work of Razzaq et al. [40] proposes the use of the triple model along with Jena TDB, being a more recommendable model to perform the persistence of information provided by ontologies. The paper [42] proposes the use of three storage models (non-relational, relational, and triple) offering better flexibility to deal with diverse types of data, semantic levels among other aspects.

Regarding context reasoning, despite using hybrid strategies, the solutions apply their strategies in a static way, not allowing the application to choose a strategy that better fits their needs. Besides, we have noted the absence of an approach that enables the combination of different strategies for context reasoning. The creation of this approach could increase the flexibility for the use of contextual data, facilitating the identification of situations of interest.

Concerning the evaluation methodology, we can see that the selected papers consider adequate the use of an approach based on usage scenarios.

5.2. Research questions

Based on the analysis of the selected papers, it is possible to answer the research questions that supported this SLR. The research questions and the answers are:

RQ1: What strategies for context reasoning are used together?

We have observed that there is no pattern for strategies combinations, for example, the strategy based on ontology is used with rules,

[1] www.vispera.co.

[2] http://www.pr-owl.org/mebn/index.php.

Table 4
The comparison performed among state of the art papers.

Paper	Acquisition	Model	Storage model	Reasoning strategies	Evaluation
[33]	Sensor Physical Logical	Ontological	Information Not Available	Ontology and Rules	Usage Scenario
[34]	Sensor Physical Logical	Ontological	Information Not Available	Ontology and Supervised Learning	Usage Scenario
[35]	Sensor Physical Logical	Ontological	Relational	Ontology and Supervised Learning	Usage Scenario
[36]	Sensor Physical Logical	Ontological and Relational	Relational	Ontology and Rules	Usage Scenario
[37]	Sensor Physical Logical	Ontological	Information Not Available	Case-based and Ontology	Usage Scenario
[38]	Sensor Physical Logical	Fuzzy	XML	Case-based and Fuzzy	Usage Scenario
[39]	Information Not Available	Information Not Available	Information Not Available	Probabilistic Logic and Supervised Learning	Usage Scenario
[40]	Sensor Physical Logical	Ontological	Triple	Ontology and Supervised Learning	Usage scenario
[41]	Sensor Physical Logical	Ontological	Information Not Available	Ontology and Probabilistic Logic	Usage Scenario
[42]	Sensor Physical Logical	Ontological and Relational	Non-Relational, Relational, and Triple	Ontology, Rules, and Supervised Learning	Usage Scenario

cases, probabilistic logic and supervised learning. However, the combination most used was ontology with supervised learning, while the strategy most used was the ontology, which appears eight times, followed by supervised learning with five, rules with three, and case-based reasoning and probabilistic logic with two.

RQ2: In what domains are hybrid strategies for context reasoning applied?

Among the ten selected papers, three of them [36,37,42] appear to be applied in different domains. The paper [36] shows four scenarios related to the agriculture domain, in which a rules-based strategy is utilized to verify if the temperature data collected are between predefined limits, and the ontology is used to identify an alert situation based on temperature and humidity data.

The paper [37] illustrated the applicability of their hybrid strategy in two application use cases, the first is a desk sharing office environment, and the second is an enhanced instant messaging. The paper [42] shows a scenario on information security, in which the proposed architecture was used to reinforce the password policy.

The papers [33,34] used the proposed strategies for the identification of physical activity, while, the remaining selected papers [35,38–41] used their strategies in the respective following domains: ambient intelligent; healthcare system; classification systems; a paradigm of health and well-being; and underwater robots.

RQ3: What evaluation approaches are used?

We have observed that the selected works consider adequate the use of an approach based on usage scenarios to evaluate their hybrid reasoning strategies. Among the selected works that proposed the use of a supervised learning strategy, we can note that one of them [39] uses a public dataset, while the other two [34,40] produce their dataset, with six and twenty users respectively.

6. Conclusion

The main contribution of this paper is the systematization of research trends in hybrid strategies for context reasoning in smart systems which are built exploring the modern computational infrastructure provided by IoT. To achieve this contribution, we have explored Systematic Literature Review which is a methodology for the identification of the state of the art considering a determined scope. In this review, we have analyzed papers published between 2004 and 2018. During this process, we identified 3241 papers and selected ten of them, which proposed hybrid strategies for context reasoning. We described, discussed, and compared the selected papers.

In the comparison performed, we have discussed the resources offered by the studies to deal with acquisition, modeling, reasoning, and storage of contextual information, as well as their evaluation methodology. Furthermore, we have presented the main aspects of the strategies used for context reasoning on the papers.

Although there are several hybrid proposals in the literature, we have noted that research efforts related to the topic are still necessary, mainly focusing on the development of dynamic approaches. Once that current reasoning approaches are static, and each application needs to choose at the beginning of their execution, which strategy for context reasoning they will use. Thus, the conception of a dynamic approach can enable the applications to decide how they want to use the different available resources at run time. This way, the applications can determine which strategies for context reasoning they will use. Moreover, with the development of these approaches, applications can choose whether these different strategies will be utilized individually or combined, depending on application demand and the contextual data treated.

As future study, we highlight the conception of a proposal for the provision of context awareness for IoT applications. This approach should be dynamic in provisioning the necessary resources to obtain the context awareness. Among these resources, we can mention: (i) several storage models; (ii) an approach for correlating information stored in the distinct models; and (iii) a strategy for context reasoning that allows a dynamic composition of different strategies.

Acknowledgments

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and Fundação de Amparo á Pesquisa do Rio Grande do Sul (FAPERGS) - PqG. Roger da Silva Machado is a FAPERGS/CAPES - BRAZIL Scholarship holder.

References

[1] M. Razzaque, M. Milojevic-Jevric, A. Palade, S. Clarke, Middleware for internet of things: a survey, Internet Things J., IEEE 3 (1) (2016) 70–95, doi:10.1109/JIOT.2015.2498900.
[2] X. Li, M. Eckert, J.-F. Martinez, G. Rubio, Context aware middleware architectures: survey and challenges, Sensors 15 (8) (2015) 20570, doi:10.3390/s150820570.
[3] A. Sánchez Guinea, G. Nain, Y. Le Traon, A systematic review on the engineering of software for ubiquitous systems, J. Syst. Softw. 118 (C) (2016) 251–276, doi:10.1016/j.jss.2016.05.024.
[4] A.M. Khattak, N. Akbar, M. Aazam, T. Ali, A.M. Khan, S. Jeon, M. Hwang, S. Lee, Context representation and fusion: advancements and opportunities, Sensors 14 (6) (2014) 9628–9668, doi:10.3390/s140609628.
[5] P. Bellavista, A. Corradi, M. Fanelli, L. Foschini, A survey of context data distribution for mobile ubiquitous systems, ACM Comput. Surv. 44 (4) (2012) 24:1–24:45, doi:10.1145/2333112.2333119.
[6] C.G. Sahu, D.S. Adane, A survey on context-aware middleware, Int. J. Adv. Res.Comput. Commun. Eng. 4 (5) (2015) 650–656, doi:10.17148/IJARCCE.2015.45138.
[7] S.E. Bibri, Context modeling, representation, and reasoning: An ontological and hybrid approach, in: The Human Face of Ambient Intelligence, in: Atlantis Ambient and Pervasive Intelligence, 9, Atlantis Press, Paris, 2015, pp. 197–257, doi:10.2991/978-94-6239-130-7_5.
[8] C. Bettini, O. Brdiczka, K. Henricksen, J. Indulska, D. Nicklas, A. Ranganathan, D. Riboni, A survey of context modelling and reasoning techniques, Pervasive Mob. Comput. 6 (2) (2010), doi:10.1016/j.pmcj.2009.06.002.
[9] M.M. Cabrera, E.O. Edye, Integration of rule based expert systems and case based reasoning in an acute bacterial meningitis clinical decision support system, CoRR abs/1003.1493 (2010).
[10] R. Subbaraj, N. Venkataraman, Reasoning in context aware computing - a review, Int. J. Pharm.Technol. 8 (2016) 5021–5032.
[11] A.K. Dey, Understanding and using context, Pers. Ubiquitous Comput. 5 (1) (2001) 4–7, doi:10.1007/s007790170019.
[12] M. Knappmeyer, S. Kiani, E. Reetz, N. Baker, R. Tonjes, Survey of context provisioning middleware, Commun. Surv. Tutorials, IEEE 15 (3) (2013) 1492–1519, doi:10.1109/SURV.2013.010413.00207.

[13] C. Perera, A. Zaslavsky, P. Christen, D. Georgakopoulos, Context aware computing for the internet of things: a survey, Commun. Surv. Tutorials, IEEE 16 (1) (2014) 414–454, doi:10.1109/SURV.2013.042313.00197.
[14] U. Alegre, J.C. Augusto, T. Clark, Engineering context-aware systems and applications, J. Syst. Softw. 117 (C) (2016) 55–83, doi:10.1016/j.jss.2016.02.010.
[15] A. Bikakis, T. Patkos, G. Antoniou, D. Plexousakis, A survey of semantics-based approaches for context reasoning in ambient intelligence, Constr. Ambient Intell. (2008) 14–23.
[16] D. Guan, W. Yuan, S. Lee, Y. Lee, Context selection and reasoning in ubiquitous computing, in: The 2007 International Conference on Intelligent Pervasive Computing (IPC 2007), 2007, pp. 184–187, doi:10.1109/IPC.2007.102.
[17] O.B. Sezer, E. Dogdu, A.M. Ozbayoglu, Context-aware computing, learning, and big data in internet of things: a survey, IEEE Internet Things J. 5 (1) (2018) 1–27, doi:10.1109/JIOT.2017.2773600.
[18] A. Pla, J. Coll, N. Mordvaniuk, B. López, Context-aware case-based reasoning, Min. Intell. Knowl. Explor. (2014) 229–238.
[19] A. Aamodt, E. Plaza, Case-based reasoning: foundational issues, methodological variations, and system approaches, AI Commun. 7 (1) (1994) 39–59.
[20] A. Ranganathan, J. Al-Muhtadi, R.H. Campbell, Reasoning about uncertain contexts in pervasive computing environments, IEEE Pervasive Comput. 3 (2) (2004) 62–70, doi:10.1109/MPRV.2004.1316821.
[21] T.R. Gruber, A translation approach to portable ontology specifications, Knowl. Acquis. 5 (2) (1993) 199–220, doi:10.1006/knac.1993.1008.
[22] G. Guizzardi, On ontology, ontologies, conceptualizations, modeling languages, and (meta)models, in: Proceedings of the 2007 Conference on Databases and Information Systems IV: Selected Papers from the Seventh International Baltic Conference DB&IS'2006, IOS Press, Amsterdam, The Netherlands, 2007, pp. 18–39.
[23] E. Gilman, Exploring the use of rulebased reasoning in ubiquitous computing applications, University of Oulu, Oulu-Finland, 2015 Academic dissertation of the doctoral training committee of technology and natural sciences.
[24] A. Badii, M. Crouch, C. Lallah, A context-awareness framework for intelligent networked embedded systems, in: Proceedings of the 2010 Third International Conference on Advances in Human-Oriented and Personalized Mechanisms, Technologies and Services, in: CENTRIC '10, IEEE Computer Society, Washington, DC, USA, 2010, pp. 105–110, doi:10.1109/CENTRIC.2010.29.
[25] N. Khan, U. Alegre, D. Kramer, J.C. Augusto, Is 'context-aware reasoning = case-based reasoning'? in: Modeling and Using Context, 2017, pp. 418–431.
[26] M. Yan, X. Zhang, C. Liu, L. Xu, M. Yang, D. Yang, Automated change-prone class prediction on unlabeled dataset using unsupervised method, Inf. Softw. Technol. 92 (2017) 1–16, doi:10.1016/j.infsof.2017.07.003.
[27] B. Kitchenham, S. Charters, Guidelines for performing Systematic Literature Reviews in Software Engineering, Joint Report, Keele University and Durham University, 2007.
[28] K. Petersen, S. Vakkalanka, L. Kuzniarz, Guidelines for conducting systematic mapping studies in software engineering: an update, Inf. Softw. Technol. 64 (Supplement C) (2015) 1–18, doi:10.1016/j.infsof.2015.03.007.
[29] A. Dikici, O. Turetken, O. Demirors, Factors influencing the understandability of process models: a systematic literature review, Inf. Softw. Technol. 93 (2018) 112–129, doi:10.1016/j.infsof.2017.09.001.
[30] L.T. Heeager, P.A. Nielsen, A conceptual model of agile software development in a safety-critical context: a systematic literature review, Inf. Softw. Technol. 103 (2018) 22–39, doi:10.1016/j.infsof.2018.06.004.
[31] S. Hosseinzadeh, S. Rauti, S. Laurén, J.-M. Mäkelä, J. Holvitie, S. Hyrynsalmi, V. Leppänen, Diversification and obfuscation techniques for software security: a systematic literature review, Inf. Softw. Technol. 104 (2018) 72–93, doi:10.1016/j.infsof.2018.07.007.
[32] E. Zavala, X. Franch, J. Marco, Adaptive monitoring: a systematic mapping, Inf. Softw. Technol. 105 (2018) 161–189, doi:10.1016/j.infsof.2018.08.013.
[33] A. Agostini, C. Bettini, D. Riboni, Hybrid reasoning in the care middleware for context awareness, Int. J. Web Eng. Technol. 5 (1) (2009) 3–23, doi:10.1504/IJWET.2009.025011.
[34] D. Riboni, C. Bettini, Cosar: hybrid reasoning for context-aware activity recognition, Pers. Ubiquitous Comput. 15 (3) (2011) 271–289, doi:10.1007/s00779-010-0331-7.
[35] T. Xu, B. David, R. Chalon, Y. Zhou, A context-aware middleware for ambient intelligence, in: Proceedings of the Workshop on Posters and Demos Track, PDT'11 - 12th International Middleware Conference, 2011, doi:10.1145/2088960.2088970.
[36] J. Lopes, R. Souza, G. Gadotti, M. GusmÃ£o, C. Costa, J. Barbosa, A. Yamin, C. Geyer, A distributed architecture for dynamic contexts composition in ubicomp, 38th Conferencia Latinoamericana En Informatica (CLEI), 2012, doi:10.1109/CLEI.2012.6427253.
[37] M. Strobbe, O. Van Laere, B. Dhoedt, F. De Turck, P. Demeester, Hybrid reasoning technique for improving context-aware applications, Knowl. Inf. Syst. 31 (3) (2012) 581–616, doi:10.1007/s10115-011-0411-7.
[38] B. Yuan, J. Herbert, Context-aware hybrid reasoning framework for pervasive healthcare, Pers. Ubiquitous Comput. 18 (4) (2014) 865–881, doi:10.1007/s00779-013-0696-5.
[39] I. Baz, E. Yoruk, M. Cetin, Context-aware hybrid classification system for fine-grained retail product recognition, IEEE 12th Image, Video, and Multidimensional Signal Processing Workshop (IVMSP), 2016, doi:10.1109/IVMSPW.2016.7528213.
[40] M.A. Razzaq, M.B. Amin, S. Lee, An ontology-based hybrid approach for accurate context reasoning, in: 19th Asia-Pacific Network Operations and Management Symposium (APNOMS), South Korea, 2017, pp. 403–406, doi:10.1109/APNOMS.2017.8094159.
[41] X. Li, J.-F. Martínez, G. Rubio, Towards a hybrid approach to context reasoning for underwater robots, Appl. Sci. 7 (2) (2017), doi:10.3390/app7020183.
[42] R. Machado, F. Rosa, R. Almeida, T. Primo, M. Pilla, A. Pernas, A. Yamin, A hybrid architecture to enrich context awareness through data correlation, in: 33rd Annual ACM Symposium on Applied Computing, in: SAC '18, ACM, New York, NY, USA, 2018, pp. 1451–1453, doi:10.1145/3167132.3167405.
[43] O. Can, E. Sezer, O. Bursa, M.O. Unalir, Comparing relational and ontological triple stores in healthcare domain, Entropy 19 (1) (2017) 30.