Past and Future of Software Architectures for Context-Aware Systems: A Systematic Mapping Study

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Abstract. There is a growing interest on context-aware systems in recent years. *Context-aware* systems are able to change their behaviour depending on new conditions regarding the *user*, the *platform* and the *environment*. These systems are evolving towards interacting with the user in a transparent and ubiquitous manner, especially by means of different types of sensors, which can gather a wide range of data from the user, the platform the user is interacting with, and the environment where such interaction is taking place. It is worth noting that the software architecture of a system is a key artefact during its development and its adaptation process. Hence, the definition of the software architecture becomes essential while developing context-aware systems since it should reflect how the context is tackled for adaptation purposes. With the aim of studying this issue, we have designed and conducted a *systematic mapping study* to provide an overview about the different architectural approaches used in context-aware systems. One of the main findings of this study is that there are not many software architecture proposals that deal with context-awareness in an explicit way during the adaptation process. It was also detected that there are Human Computer Interaction (HCI) works that focus on context-aware adaptations but neglect partially or completely any possible change in the system architecture during the adaptation process. Due to this, we perceived a need to analyse what research works highlight the use of context and its relationship to the software architecture in existing context-aware systems. Therefore, this mapping study attempts to bridge the gap between Software Architecture and HCI in order to align the adaptation at the *architectural level* (changes in the configuration of architectural components) and at the *HCI level* (changes in the interaction modality or the user interface in general).

Keywords: human-computer interaction, user, platform, environment, quality of adaptation, quasi-gold standard.

1 Introduction

In recent years, we can observe a trend aiming at transforming the environment in which the user interacts with a software system into a smart environment so that the user can interact with the system in a transparent and seamless manner. In this sense, *context-awareness* emerges as a suitable approach for developing such systems since it provides them with flexibility, adaptability and capability of acting autonomously on behalf of users [22]. Context-aware systems pay attention to the *context* surrounding the user to adapt their behaviour to new conditions. Such context usually refers to the user, the platform he/she is interacting with, and the environment where such interaction is being done. As stated in [3], these three dimensions (*User*, *Platform* and *Environment*) represent the main cornerstones for defining the context.

As Perry and Wolf [35] already realized in 1992, the *Software Architecture* (SA) of every software system and its specification should be carefully considered during design. They defined the SA as “the selection of architectural elements, their interactions and the constraints on those elements and their interactions necessary to provide a framework in which to satisfy the requirements and serve as a basis for the design”. Therefore, SA becomes a key artefact whenever it is necessary to develop a system that offers complex capabilities.

Given the importance of context and its different dimensions in context-aware systems for adapting its behaviour, as well as the importance of the SA while designing a system, it could be thought that most of the proposals in the area have been defined exploiting SA mechanisms to provide such context-aware adaptations. However, we did not find many software architecture proposals that deal with adaptation based on the context of use. Most of the architectural proposals focus on some specific kind of adaptation, but mostly from the point of view of software architecture and the possible configurations of its components. Consequently, such architectural approaches do not deal with context-awareness in an explicit way during the adaptation process, usually not considering the user at all and hence neglecting the adaptation from the point of view of Human-Computer Interaction (HCI). There are also HCI works that focus on context-aware adaptations, but they do not pay much attention to the required software architecture support.

As a result of these observations, we perceived *a need to analyse what research works highlight the use of context and its relationship with the software architecture in existing context-aware systems*. To the best of our knowledge, no literature study exists yet that carries out such analysis, so that the execution of a systematic mapping study emerged naturally. As Kitchenham and Charters state [29], these type of studies provide a broad review of primary studies in a specific topic area that aims at identifying what evidence is available on the topic. Thus, by performing such a mapping study, we will be able to provide an overview about the different approaches used in *context-aware systems* in order to align the adaptation at the *architectural level* (changes in the configuration of architectural components) and at the *HCI level* (changes in the interaction modality or the user interface). Moreover, we will also identify the gaps existing till now with regard to *the deficiencies and weaknesses of systems when dealing with context and its different dimensions*. These findings will help the research community by providing guidelines for modelling, retrieving and managing context and its different dimensions. In addition, guidelines to know how to consider such context by the software architecture will be also provided in order to produce proper adaptation experiences to the final users.

This paper is structured as follows. Section 2 presents the *research methodology* applied to perform this systematic mapping study. Next, Section 3 describes how the *data collection* for this mapping study was carried out. Section 4 shows the *results* obtained from the search process of the mapping study by answering the research questions previously established. Section 5 presents the *discussion* derived from the analysis of the different results. Our main *conclusions* are presented in Section 7. Finally, the *selected papers* of this mapping study are listed in Appendix A.

2 Research Methodology

As aforementioned, this article presents a systematic mapping study that focuses on providing an overview about the state of the art on software architecture concepts when used for developing context-aware systems. A *systematic mapping study* [36] is an evidence-based form of secondary study that provides an overview of a research area, identifying common publication venue types (e.g. conference, journal or workshop), quantitative analyses (e.g. number of published studies per year), and research findings in the investigated research field. Kitchenham and Charters [29] also provide a definition of a systematic mapping study, considering it as broad review of primary studies in a specific topic area that aims to identify what evidence is available on the topic.

This mapping study has followed several guidelines [50][7][29] for conducting systematic studies, especially in the field of software engineering. Moreover, we have also taken into consideration the work by Zhang et al. [55][56] while performing our search strategy, since it was driven by a concept introduced by these authors: the Quasi-Gold Standard. The *Quasi-Gold Standard* [55] refers to a set of known studies extracted from related venues, such as domain-specific conferences and journals perfectly recognized by the research community in the field, and for a given period of time. Our mapping study is composed of the following six stages, being each one of them described separately in the following sections:

1. The *rationale* for conducting the mapping study (Section 2.1).
2. The establishment of the *Research Questions* (RQs) that this mapping study answers (Section 2.2).
3. The *search process* we have followed relying on the Quasi-Gold Standard approach (Section 2.3).
4. The *categorization* we have followed to classify the results obtained (Section 2.4).
5. How the *data collection* has been done applying the selection criteria (Section 3).
6. The *results* obtained along with the answers to the RQs (Section 4).

2.1 Mapping Study Rationale

The first step while performing a systematic study is to define the main reason that has led to carry it out. In this case, we did not find much evidence in the literature about software architecture proposals that provide support for adaptation based on the context of use. On the one hand, most of the architectural frameworks are centred on supporting some kind of adaptation, but mostly from the point of view of the software architecture and the possible configurations of its components. Such proposals do not manage the *context-awareness* explicitly during the adaptation process, and hence they neglect the user completely as well as the adaptation from the point of view of HCI. On the other hand, there are HCI studies focused on context-aware adaptations which neglect partially or completely any possible change in the system architecture during the adaptation process to support such adaptation. In this sense, we have detected *a need to analyse which research works highlight the use of context and its relationship with the software architecture in existing context-aware systems*.

By doing so, we will be able to provide an overview about the different approaches used in *context-aware systems* in order to align the adaptation at both *architectural level* (changes in the configuration of architectural components) and

HCI level (changes in the interaction modality or the user interface in general). Moreover, we will also identify the existing gaps up to now, i.e. *what are the deficiencies and weaknesses of systems when dealing with context and its different dimensions*. These findings will help the research community to define guidelines for modelling, retrieving and managing context and its different dimensions, as well as to establish how the software architecture may support the context in order to provide the final user with a good adaptation experience. Therefore, the *main objectives* of our study are the following:

- **Objective 1.** Review *software architecture concepts*, such as designs, frameworks, components, styles, patterns, infrastructures and specifications, proposed for designing and building *context-aware systems* with the aim of understanding the relationships between them.
- **Objective 2.** Review how *context-based adaptations* are considered by those software architecture concepts proposed for context-aware systems.
- **Objective 3.** Review the *maturity* of the different software architecture concepts proposed for context-aware systems, as well as the maturity of the methods for assessing context-based adaptations.

2.2 Research Questions

Based on the objectives from Section 2.1, we defined the following *Research Questions* (RQs), which will be answered throughout this paper:

- **RQ 1.** Which *architectural designs*, *frameworks*, *components*, *styles*, *patterns*, *infrastructures* and *specifications* are used in the existing context-aware systems? (Related to **Objective 1**)

  Rationale. Architectural designs, frameworks, components, styles, patterns, infrastructures and specifications (i.e., *software architecture concepts*) have been used as artefacts to guide the development of software products and establish a certain level of claimed quality. However, there is no overview of primary studies on defining and/or exploiting those software architecture concepts in relation to the existing context-aware systems. In this article, we aim at offering such an overview in order to help researchers and practitioners to analyse which of those architectural topics are the most relevant and the most used.

- **RQ 2.** How do the software architecture concepts proposed for context-aware systems consider the three main *dimensions of context* (User, Platform and Environment) to support adaptation? (Related to **Objective 2**)

  Rationale. In the field of context-aware computing, there are many different proposals for modelling the context. However, as stated in [3], there is a consensus that the three main cornerstones for defining the context are: *User*, *Environment* and *Platform*. Therefore, we want to discover how each dimension of context is addressed and taken into account within the different architectural proposals to carry out the adaptations based on these three dimensions of context. In this sense, we propose three different sub-research questions where each one of them refers to a different dimension of context for the sake of clarity.

  - **RQ 2.1.** How do the software architecture concepts proposed for context-aware systems consider the *user dimension of context* to support adaptation?

    Rationale. The *user* dimension here refers to all characteristics related to the user of the system: preferences regarding the user interface (colour, font size, presentation, content, etc.), profile features (name, age, job, etc.), physical impairments (blind, single-handed, etc.), health condition, physiological data (heart rate, blood pressure, etc.), skills, expertise, contacts, etc. Thus, we are interested in studying the *user* dimension of context as a separate concern to identify how the different software architecture concepts proposed for context-aware systems are addressing it to carry out adaptation.

  - **RQ 2.2.** How do the software architecture concepts proposed for context-aware systems tackle the *platform dimension of context* to support adaptation?

    Rationale. As stated in [4], this particular dimension of context is related to the software side of a system, such as the operating system, the technology infrastructure represented by a well-defined programming language, applications supported, etc. However, the platform is not only limited to the software, but also it refers to hardware elements, such as the screen size of the monitor, a temperature sensor, or the network characteristics (bandwidth, speed, etc.). Therefore, we want to analyse, separately from the other context dimensions, how the different software architecture concepts proposed for context-aware systems tackle the platform dimension of context to support adaptation.

  - **RQ 2.3.** How do the software architecture concepts proposed for context-aware systems take into account the *environment dimension of context* to support adaptation?

Rationale. Along with the user and platform, the *environment* is also considered as one of the main dimensions of context. This dimension includes the ambient noise, light level, temperature, weather, date, nearby people, etc. in the location where the interaction between the user and the system is taking place. Thus, similarly to the other dimensions of context, we are interested in studying this context dimension too with the aim of identifying how the different software architecture concepts proposed for context-aware systems are addressing it to carry out adaptation.

- **RQ 3.** What *evaluations* have been performed so far for validating the different *context-aware adaptations* proposed for context-aware systems? (Related to **Objective 3**)

  Rationale. Every software artefact, such as a user interface or a software architecture, should guarantee a certain degree of quality when delivered to prevent the final user from rejecting it. Therefore, context-aware adaptation should also ensure a certain degree of quality whenever they are applied. In this sense, proposals supporting context-aware adaptation should provide some mechanisms to estimate the degree of quality of these adaptations, i.e. to evaluate whether context-aware adaptations are perceived positively by the final user or the entity the adaptation was designed for. With this purpose, we aim to discover to what extent the evaluation of context-aware adaptation in context-aware systems has been tackled in the literature. By doing so, we will be able to estimate the *maturity* of the proposals for adaptation.

- **RQ 4.** What *evaluations* have been performed so far for validating the different *software architecture concepts* proposed for context-aware systems focused on adapting the system using the surrounding context (user, platform and environment)? (Related to **Objective 3**)

  Rationale. We want to find out what evaluations have been carried out until now to validate the software architecture concepts proposed for context-aware systems. These evaluations may range from informal evaluations, just showing some examples, to more formal empirical evaluations. In this sense, we want to categorize the different software architecture concepts, depending on the type of evaluation presented. This will enable us to determine the *maturity* of such software architecture concepts for developing context-aware systems.

2.3 Search Process Based on the Quasi-Gold Standard

There have been two main reasons that have led us to use the systematic search strategy presented by Zhang et al. [55][56]: first, i) *to identify the most relevant works in the literature with regard to our topic in an objective and systematic way*, and second ii) *to properly assess the search performance*. These authors stated that most of the systematic studies in Software Engineering apply a subjective search process based just on the expertise and knowledge of the team on the research topic and tested on supposedly "well-known" studies previously gathered by such team to assess the search performance. Zhang et al. claimed that this set of "well-known" samples depends on the knowledge of the searchers on the particular topic and, thus, it cannot replace the *Gold Standard* (i.e. the known set of identified primary studies in a collection according to the definition of the Research Questions) for evaluation, since it is not possible to have a complete set of primary studies before the execution of the systematic study. Therefore, these authors introduced the concept *Quasi-Gold Standard* (QGS) [55] that refers to *a set of known studies extracted from related venues*, such as domain-specific conferences and journals perfectly recognized by the research community in the field, *for a given period of time*. Thereby, the QGS acts as a Gold Standard substitute, but with the only restriction of *where* (venues) and *when* (during a period of time).

In this sense, with the aim of providing *objectivity* to the search process, Zhang et al. integrate the QGS method into the systematic search process that relies on the analysis of information from the works collected, i.e. from the QGS, instead of using a subjective set of studies which depends on the perceptions of the people who carry out the search. Besides the support for objectivity, another benefit of applying the QGS method is that it can be used to evaluate the search strategy performance, that is, to evaluate the search results in order to guarantee a certain quality level of the automated search. Zhang et al. propose to carry out this assessment by means of the *Sensitivity* which is defined as the proportion of relevant studies retrieved for a given topic:

$$Sensitivity = \frac{Number\ of\ relevant\ studies\ retrieved}{Total\ number\ of\ relevant\ studies} \cdot 100\%$$

However, as the gold-standard is unknown, the sensitivity cannot be calculated so that the QGS is used to measure the *Quasi-sensitivity* of the search universe. Fig. 1 depicts the different steps that integrate this systematic search strategy. The first step consists in *identifying the most relevant venues* (both conferences and journals) regarding our research topic in order to *discover the QGS* (Step 2), and also *identifying the engines* (libraries and databases) that will be used for our *automated search* (Step 4). In step 3, *the search strings are built* to use them as input for the automated search. These strings can be defined either by researchers, thanks to their knowledge on the matter or, more objectively, they can be elicited from the studies in the QGS by means of the analysis of word frequency or content. In step 5, *the search results* *from the automatic search are evaluated* regarding the quasi-sensitivity and compared with a threshold previously established. If the search performance is found acceptable (usually when quasi-sensitivity ≥ 80%), then the results obtained by the automated search are combined with the QGS, finishing the search process. Otherwise, the flow must go back to step 3 to refine the search strings until the search performance reaches an acceptable level. In Section 3.2, each one of these steps are explained in more detail regarding our systematic study on software architectures for context-aware systems.

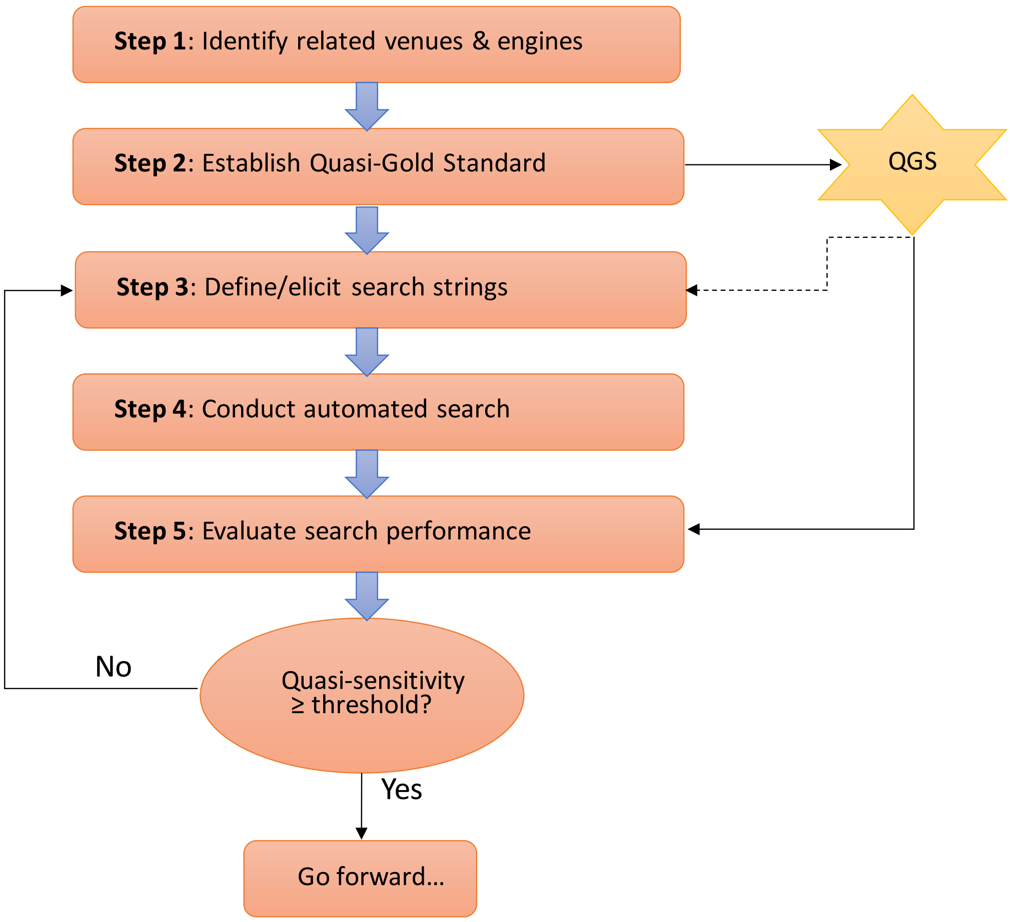

Fig. 1. Workflow of the systematic search strategy (adapted from [56])

2.4 Categorization of Results

Several well-defined and widespread taxonomies have been used in this work to classify the selected papers obtained from our search process. One of them is the categorization originally proposed by Wieringa et al. [52] for classifying papers regarding the *research type*. Table 1 shows these research types along with its description proposed by Kuhrmann et al. [32]. Note that one result can be categorized as more than one research type.

Table 1. Research types categorization

Research type	*Description*
Evaluation research	It is shown how the technique is implemented in practice (solution implementation) and which are the consequences of the implementation in terms of benefits and drawbacks (implementation evaluation). This also includes identifying problems in industry. An example for evaluation research is reporting of an industrially hosted case study.
Solution proposal	A solution for a problem is proposed. The solution can be either novel or a significant extension of an existing technique. The potential benefits and the applicability of the solution are shown by a small example or a good line of argumentation.
Validation research	Techniques investigated are novel and have not yet been implemented in practice. Techniques used are, for example, experiments, that is, work done in the lab.

Philosophical papers	These papers present a new way of looking at existing things by structuring the field in the form of a taxonomy or conceptual framework.
Opinion papers	These papers express the personal opinion of somebody whether a certain technique is good or bad or how things should be done. They do not rely on related work or research methodologies.
Experience papers	These papers explain on what and how something has been done in practice. It should be the personal (informal) experience of the author.

Another categorization, which has been applied to the selected papers when analysing the RQ 4, is the one presented in Table 2 to classify the *evaluation strategies* presented in the papers. These evaluations include the empirical strategies proposed by Wohlin et al. [54], such as *Survey*, *Case study* and *Experiment*, as well as the evaluation by means of an *Example* when no formal empirical strategy is applied. In this last case, the paper has not been classified neither as a Validation nor Evaluation research because of the lack of formalism and empirical evidence those papers presented.

Table 2. Evaluation strategies categorization

Evaluation strategies	*Description*
Survey	A *survey* is a system for collecting information from or about people to describe, compare or explain their knowledge, attitudes and behaviour by means of interviews or questionnaires. Surveys are conducted when the use of a technique or tool already has taken place or before it is introduced.
Case study	A *case study* is an empirical enquiry that draws on multiple sources of evidence to investigate one instance (or a small number of instances) of a contemporary phenomenon within its real-life context, especially when the boundary between phenomenon and context cannot be clearly specified.
Experiment	An *experiment* is a formal, rigorous and controlled investigation. Based on randomization, different treatments are applied to or by different subjects, while keeping other variables constant, and measuring the effects on outcome variables. During an experiment, quantitative data is collected and then *statistical methods* are applied.
Example	When no formal empirical strategy is applied to evaluate the proposal, but there is some kind of illustration.

Finally, we have also classified the results with regard to the following criteria in order to facilitate the later analysis and discussion. Note that it is not possible to predefine the different categories that belong to each one of these criteria before analysing the papers.

- The *country* denotes the country of the institution of the first author of the paper. It is a single value per paper.
- The *venue* indicates whether the paper is a Journal, a Conference or a Workshop. It is a single value per paper.
- The *research topic* represents the main research topic throughout the paper, e.g. context modelling, context inference, service delivery, context-aware applications development, UI adaptation, etc. A paper can be classified according to more than one topic.
- The *application domain* represents the main application domain/s of the proposal, e.g. healthcare, e-learning, smart home, etc. Not every paper is oriented to an application domain, but it is possible to have more than one domain for some papers.
- The question *what is adapted?* indicates which element of the context-aware system is the subject of the adaptation, e.g. services, UI, architecture configuration, content, presentation, navigation, etc. Not every paper expresses what is adapted. In contrast, it is possible to have more than one element that is adapted during the adaptation process in the same work.
- The *software architecture concept* (RQ 1) indicates the type of software architecture concept employed, e.g. service-oriented-architecture (SOA), multi-agent system, multi-layered architecture, etc. Every paper selected should describe some software architecture concept in the proposal, or even more than one.
- The *user dimension of context* (RQ 2.1) determines the different characteristics of the user considered in the proposal for performing the adaptation of the system, e.g. preferences, profile, physiological data, social profile, abilities,

disabilities, etc. Not every paper deals with this dimension of context. In contrast, one work can present more than one user characteristic.

- The *platform dimension of context* (RQ 2.2) determines the different characteristics of the platform considered in the proposal for performing the adaptation of the system, e.g. network, bandwidth, battery level, screen size, etc. Not every paper deals with this dimension of context. In contrast, one work can present more than one platform characteristic.
- The *environment dimension of context* (RQ 2.3) determines the different characteristics of the environment considered in the proposal for performing the adaptation of the system, e.g. location, noise, light, temperature, weather, date, nearby people, etc. Not every paper deals with this dimension of context. In contrast, one work can be classified according to different characteristics.
- The *other dimensions of context* (RQ 2) determines if the proposal makes use of other dimensions of context different from User, Platform or Environment. Not every paper deals with other dimensions of context. In contrast, one work can be classified according to more than one category for this RQ. For example, some other dimensions of context are the following:
    - *Historical data*, such as the interaction history of the user. It is usually used to know the evolution of the user and hence making changes and adaptations in the system that improve the user experience
    - *User activity*, refers to the activity the user is performing at a specific moment of time, e.g. sleeping, cooking, brushing the teeth, etc.
    - *Interaction task*, refers to the task of interaction the user is making with the system, e. g. opening a new window, clicking a link, typing in the keyboard, etc.

3 Data Collection

In this section, the procedure for collecting all data of this mapping study is presented. Section 3.1 presents the different criteria used to select only the relevant results from the search process. The related venues and engines identified for this study are described in Section 3.2.1. Section 3.2.2 presents the most relevant articles that define the QGS. Section 3.2.3 depicts the definition of the search string for the automated search. Section 3.2.4 presents the outcomes obtained from the automated search. Finally, Section 3.2.5 exhibits the evaluation of the search performance by means of the quasi-sensitivity calculation.

3.1 Selection Criteria

Generally, the search process in a systematic study returns a great deal of results, but not all of them are usually considered relevant. For this aim, we have defined the following criteria to filter out the papers returned and select only the relevant ones.

The *inclusion criteria* are:

- **I1**. The study presents any kind of software architecture concept that supports the development, design, etc., of context-aware applications.
- **I2**. The study reports an example or similar that shows how a particular software architecture concept supports context-aware adaptations.
- **I3**. The study presents some type of evaluation for validating a specific software architecture concept regarding a particular context-aware system.
- **I4**. The study presents some type of evaluation for assessing the adaptation in context-aware systems considering the supporting architecture.

On the other hand, the *exclusion criteria* are:

- **E1**. The study is not written in English.
- **E2**. The study is not related to Computer Science research field at all.
- **E3**. The study is related to Computer Science research field, but not to Software Engineering or Human-Computer Interaction fields, or to a software architecture concept applied on context-aware systems.
- **E4**. The study is an older publication from the same authors about the same approach.

- **E5**. The study is a short one, less than three pages.
- **E6**. The study is a very large one, e.g. a PhD thesis or a book.
- **E7**. The study is a secondary or tertiary study (e.g. a systematic mapping study or literature review), not a primary one.
- **E8**. The study is a non-peer reviewed publication such as a technical report, editorial note, preface, index, introduction, presents a special/theme issue, or it is unreferenced, illegible or inaccessible (e.g., paper is not available through the search engines used).
- **E9**. The study has been published after 2017.

Regarding the last exclusion criterion, note that 2017 was chosen as end date because the search was conducted at the beginning of 2018. The query could return inconsistent results whether it was rerun during the process if 2018 were also considered.

3.2 Quasi-Gold Standard-Based Search Strategy

This section details the steps of the search strategy we have followed to find the primary studies to be used in this mapping study. We would like to remind that we have based our search strategy in the Quasi-Gold Standard concept presented by Zhang et al. [56].

3.2.1 Identifying related venues and engines

The first stage of the search process is related to the identification of the most relevant *related venues* used in the next step for establishing the QGS (see Section 3.2.2), as well as the identification of the *engines* for the automated search in step 4 (see Section 3.2.4).

Regarding the *related venues*, they are usually selected without difficulty considering both the research questions previously established and the expertise and knowledge of the researchers on the subject under study. However, for this mapping study, this selection was challenging because our study is focused not only on one research field, but on two research fields clearly different: *Software Engineering* (SE) and *Human-Computer Interaction* (HCI). On the one hand, we are interested in *architecture* concepts, such as designs, frameworks, components, styles, patterns, infrastructures and specifications (derived from the research questions described in Section 2.2), which are obviously connected to the area of Software Architecture (SA). On the other hand, we are only interested in those architectures designed for *context-aware systems*, which are directly connected to the Pervasive and Ubiquitous Computing area in the HCI field. Although our first thought was to include conferences and journals related to both research fields, after a quick review of the literature and a thorough discussion, we realized that most of the relevant works related to context-aware systems were published in specialized venues of HCI and Pervasive and Ubiquitous Computing for establishing the QGS. Thereupon, by considering all the aforementioned issues, we finally decided to set as related venues those connected to HCI and Pervasive and Ubiquitous Computing. Moreover, those works published in venues related to SA and SE fields will be discovered during the automatic search stage given that they are also indexed in the selected search engines. Table 3 shows the final set of relevant venues selected for establishing the QGS, along with their associated publisher, digital library or engine. Note that five different venues focused on HCI and Pervasive Computing have been identified, namely the journals *Human-Computer Interaction*, *IEEE*[1] *Pervasive Computing*, *Personal and Ubiquitous Computing*, and *User Modeling and User-Adapted Interaction*; as well as the *ACM*[2] *International Joint Conference on Pervasive and Ubiquitous Computing* (UbiComp). Note that this last conference, UbiComp, is the result of merging the most renowned conferences in the field during the last few decades, such as PERVASIVE[3], UbiComp[4] and HUC[5]. These five venues have been selected since they are considered the most relevant and referenced ones with regard to HCI and Pervasive Computing.

Table 3. Related venues identified

Type of venue	*Venue*	*Publisher*	*Digital libraries/Engines*

[1] Institute of Electrical and Electronics Engineers
[2] Association for Computing Machinery
[3] International Conference on Pervasive Computing
[4] International Conference on Ubiquitous Computing
[5] International Symposium on Handheld and Ubiquitous Computing

Journal	Human-Computer Interaction	Taylor & Francis	ACM Digital Library Scopus
	IEEE Pervasive Computing	IEEE Computer Society	ACM Digital Library IEEE Xplore Scopus
	Personal and Ubiquitous Computing	Springer London	ACM Digital Library Springer Link Scopus
	User Modeling and User-Adapted Interaction	Springer Netherlands	ACM Digital Library Springer Link Scopus
Conference	ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp)	ACM	ACM Digital Library Springer Link Scopus

Regarding the selection of *engines* for the automated search, Zhang et al. [56] stated that it depends on several factors, such as whether they publish the selected the venues or not, the degree of coverage among them, and also the availability and accessibility of the different articles through such engines. Furthermore, they observed that ACM Digital Library and IEEE Xplore constitute a must-have when talking about the engines to be selected for any automatic search for systematic studies in SE. Although our initial intention was choosing the minimum set of search engines for avoiding as much overlapping as possible, we noticed that many works were only indexed by one of these search engines, especially those indexed by Scopus and Springer Link. Therefore, for the sake of completeness, our final set of selected search engines include *ACM Digital Library* and *IEEE Xplore*, as recommended by Zhang et al., as well as *Scopus* and *Springer Link*. Note that when searching with ACM, we have chosen the option *Guide to Computing Literature* instead of *ACM Full-Text Collection* as the former includes a wider set of articles. Table 4 shows the search engines finally chosen for conducting the automated search (see Section 3.2.4).

Table 4. Selected engines for the automated search

Selected search engines	*Web reference*
ACM Digital Library	[2]
IEEE Xplore	[28]
Scopus	[17]
Springer Link	[48]

Zhang et al. stated [55,56] that authors can also employ other search engines not directly derived from the related venues while performing a systematic study, but, in such a case, the QGS is *only* valid for the assessment of the search performance through those engines inferred from the nominated venues.

3.2.2 Establishing the Quasi-Gold Standard

The second stage of the search process is the establishment of the QGS. Zhang et al. [55,56] recommend a manual search through the related sources identified in the previous step for finding the most relevant and most referenced works regarding our research topic. In this manner, all these relevant papers will be part of our QGS. However, this manual process is very time-consuming since all articles published in such venues have to be analysed one by one. To facilitate such work, we propose a *semi-manual search* which consists in using a generic search engine, such as Google Scholar [19], to identify a good initial set of studies related to our topic, and then applying the snowballing technique, screening one by one the resulting articles, to find the most relevant and most cited works.

The semi-manual search followed here is based on the guidelines for snowballing in systematic studies provided by Wohlin[53]. This author proposes among others the following tips that we have used to identify a *good initial set*, i.e. a set of papers to use for the snowballing procedure:

i. A good initial set of studies can be identified by using, for example, Google Scholar, with the aim of avoiding bias in favour of a specific publisher.

ii. If too many papers are found, then the most relevant and highly referenced ones should be identified.

iii. The initial set should cover different publishers, different years and different authors.

iv. The initial set should be formulated taking into account the keywords used in the RQs.

Therefore, the semi-manual search was conducted by using Google Scholar with an initial search string composed of the keywords *architecture* and *context-aware* extracted from the RQs (see Section 2.2). Seventeen papers were obtained from this first search, ordered by relevance according to Google algorithms, including various PhD dissertations related to relevant authors on the subject, such as Dey's PhD dissertation [15], as well as some technical reports. However, these types of articles, such as PhD theses and technical reports, were not included because of our exclusion criteria (see Section 3.1). Nevertheless, some specific vocabulary and synonyms related to the terms *context* and *context-aware* were gathered. For instance, in Dey's PhD dissertation [15], some context-aware synonyms were found, such as *adaptive* [5], *reactive* [12], *responsive* [16], *situated* [26], *context-sensitive* [40] and *environment-directed* [18]. Some of these terms have been used in the construction of the search string for the automated search (see Section 3.2.3).

Afterwards, the snowballing strategy was applied, looking for articles that cite those included in the initial set (*forward snowballing* [53]), and also looking for articles cited by the works in the initial set, i.e. those which appear in the references list (*backward snowballing* [53]). Thereby, all works found were filtered by their number of references, and also by their publication venue given that we are only interested in those ones published in the venues previously selected (see Section 3.2.1). Finally, we obtained a set of *17 relevant papers* which are indeed focused on architectures for context-aware systems and hence they constitute our QGS. Table 5 presents the distribution of the relevant papers selected from the related venues. Notice that the QGS covers the publication period between *1999* and *2011* so that 1999 was selected as the starting date for the automated search (see Section 3.2.4).

Table 5. Quasi-Gold Standard distribution

Venues	*Papers of the QGS*
Human-Computer Interaction	[13][23]
IEEE Pervasive Computing	[20][30][39][43]
Personal and Ubiquitous Computing	[25][41]
User Modeling and User-Adapted Interaction	[9][10][11][21][24][37][49]
ACM Int. Joint Conf. on Pervasive and Ubiquitous Computing (UbiComp)	[1][46]

3.2.3 Defining the search string for the automated search

As presented in Fig. 1, the search process at this point can be carried out in two different ways in order to obtain the final search string for the automated search. On the one hand, as Zhang et al. stated [3][4], most systematic studies found in the literature in SE conduct automated search in a subjective manner, i.e. researchers build search strings for automated search based on their knowledge and experience about the research topic. On the other hand, these search strings can also be elicited in a more objective way based on the QGS (dashed lines in Fig. 1). In this sense, text mining techniques are used to discover the most frequently occurring words or sentences within the QGS. By doing so, the search strings can be elicited using such candidate search terms, producing a higher search performance rather than using a subjective search string definition.

In our case, we started with the definition of the search string in a subjective manner, only depending on our knowledge, expertise and manual findings. Subsequently, different keywords and terms repeatedly found during the establishment of the QGS were incorporated to our search string to offer a more objective perspective to the search process. Obviously, the definition of the *search string* should be as useful and accurate as possible with the aim of extracting the most relevant papers related to the scope of the study. Nevertheless, the process of defining an adequate search string is neither an easy task nor a quick one because this study is focused on analysing the different *architectures* proposed for *context-aware* systems. Moreover, as mentioned before in the RQs (Section 2.2), we are especially interested in studying the three dimensions of context: *User*, *Environment* and *Platform*. Therefore, our final search string should take into account all these keywords, i.e. *architecture*, *context-aware*, and also the dimensions of context: *user*, *environment* and *platform*, as well as the most common synonyms for such terms.

With regard to the term *architecture*, some synonyms were retrieved from the RQs, such as: *design*, *framework*, *component*, *style*, *pattern*, *infrastructure* and *specification*. We included all these words in the search string to find as many related works as possible but focusing on any type of architecture concept applied in context-aware systems. As aforementioned, this study deals with two different research areas, *Software Architecture* and *context-awareness*, that address the term of architecture in a different way, using different terminology. For this reason, we have used the following keywords to address the concept architecture in our search string:

architecture OR design OR framework OR component OR style OR pattern OR infrastructure OR specification

Regarding the concept *context-aware*, some synonyms have also been included in the search string as we noticed while establishing the QGS that this term appears in different forms. Some identified synonyms of context-aware were: *adaptive* [5], *reactive* [12], *responsive* [16], *situated* [26], *context-sensitive* [40] and *environment-directed* [18]. However, some of them, such as *adaptive*, *reactive*, *responsive* and *situated*, are too generic to use them as a single word. For solving this problem, we explored the literature in order to find out the most common terms used along with these generic concepts. The term *adaptive* usually is used along with *user interface*, *agent*, *application* and *wearable*; the term *reactive* is often used with *environment*; *responsive* is frequently used with the terms *environment* and *application*; and finally, the word *situated* is broadly used with *communication* and *application*, as well as the composed term *situation aware*. This led us to define the search string related to context-aware as follows:

"context-aware" OR "adaptive user interface" OR "adaptive agent" OR "adaptive application" OR "adaptive wearable" OR "reactive environment" OR "responsive environment" OR "responsive application" OR "situated communication" OR "situated application" OR "situation aware" OR "context-sensitive" OR "environment-directed"

With regard to the dimensions of context, *user*, *environment* and *platform*, some synonyms have also been used to build the search string, including several relevant words commonly used when referring to such dimensions of context:

user OR human OR device OR platform OR environment OR task

Finally, the final search string used for the automated search was defined as follows by gathering the previous ones connected by an AND operator:

Table 6. Search string (similar terms are included in brackets)

Concept	*Search*
Architecture	*(architecture OR design OR framework OR component OR style OR pattern OR infrastructure OR specification)*
Context-aware	***AND*** *("context-aware" OR "adaptive user interface" OR "adaptive agent" OR "adaptive application" OR "adaptive wearable" OR "reactive environment" OR "responsive environment" OR "responsive application" OR "situated communication" OR "situated application" OR "situation aware" OR "context-sensitive" OR "environment-directed")*
Dimensions of context	***AND*** (*user OR human OR device OR platform OR environment OR task*)

Note that we searched for papers published between 1st of January 1999 and 31st of December 2017. On the one hand, the selection of 1999 as our starting date was set during the establishment of the QGS (see Section 3.2.2), because we observed that the first relevant studies related to architectural approaches focused on context-aware systems dated from 1999 [1][46]. On the other hand, the selection of 2017 as end date was chosen because this systematic study started in 2016. Therefore, papers gathered from early 1999 till the end of 2017 may bring a full coverage of existing work on architecture concepts for context-aware systems.

3.2.4 Conducting the automated search

This section presents the steps followed during the search process, depicted in Fig. 2, to obtain the final set of relevant papers for this mapping study. The *automated search using all the four search engines* previously selected (see Section 3.2.1), i.e. ACM Digital Library, IEEE Xplore, Scopus and Springer Link, was firstly conducted using the final search string (see Table 6) and the limitation of the publication years from 1999 to 2017, both included. Note that the search string was differently coded depending on the search engine used, in order to fulfil the syntax requirements and capabilities of each search engine. Furthermore, the search process over each engine was conducted looking up in the *Title* and *Keywords* sections in order to keep the number of results obtained manageable. Table 7 shows the number of articles retrieved from each search engine, as well as the total of papers, 7836, after *merging all the results obtained*.

Table 7. Articles retrieved with the automated search

Search engine	*Articles retrieved*
ACM Digital Library	645
IEEE Xplore	139
Scopus	2747

Springer Link	4305
Total	*7836*

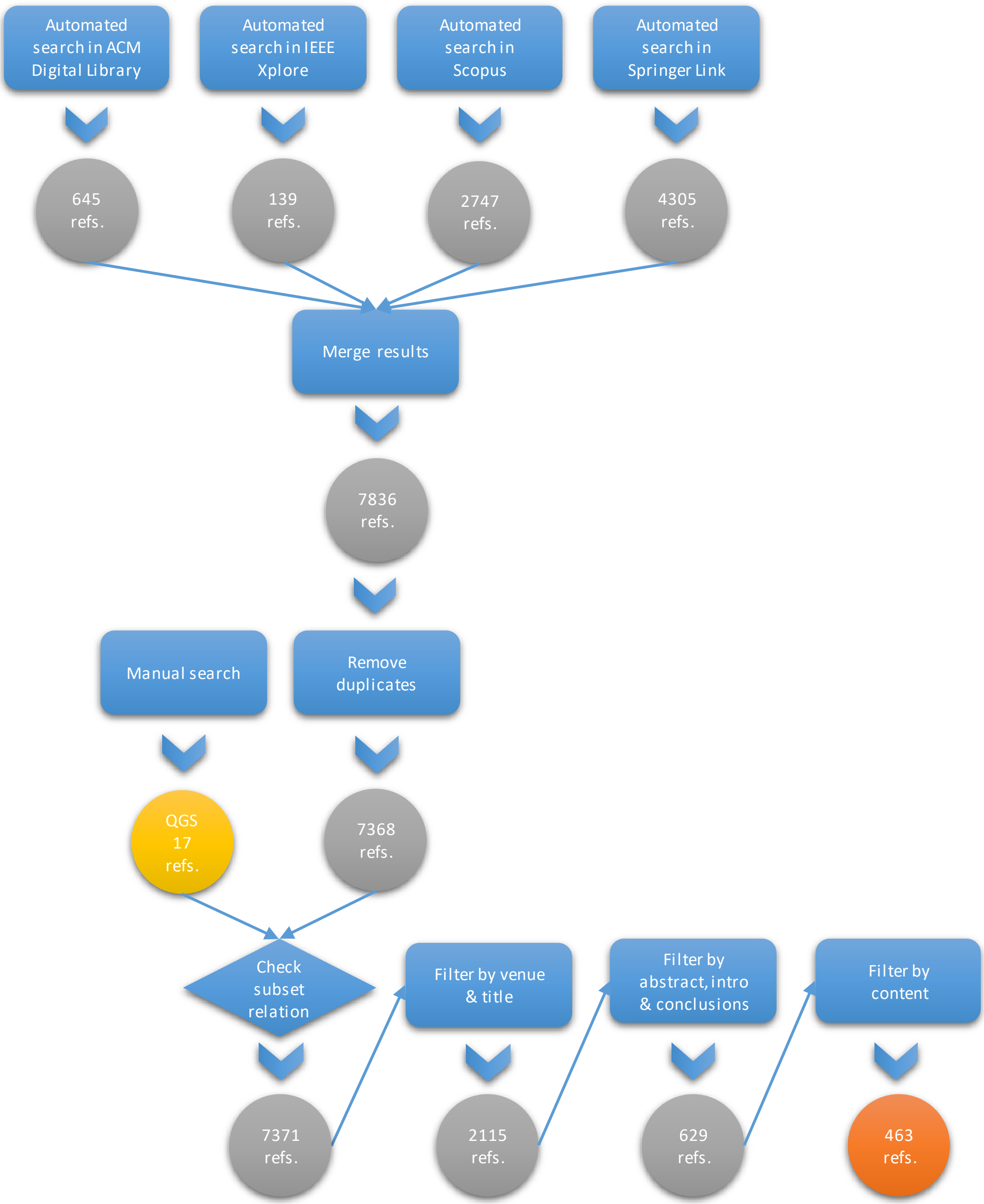

Fig. 2. Search process

Next step was to *remove all duplicates* as some papers appeared as a result in more than one search engine. We found 468 papers duplicated, so we continued the search process with 7368 articles. Then, we checked how many articles of the QGS (see Section 3.2.2) appeared in the set of papers provided by the automated search, identifying 14 articles out of 17 papers of the QGS. 3 articles were missing in our search results with respect to QGS. Therefore, they were also included in the set of papers to be used in the following steps.

Then, we applied several *filters* to the 7368 articles selected previously taking into account the exclusion and inclusion criteria defined in Section 3.1. First, we filtered out those papers whose *venue and title* revealed clearly that they were not related at all with the topic being addressed by this study, keeping as result 7368 articles. Second, we filtered out *by abstract, introduction and conclusions*, i.e. we kept those papers that, after reading their abstract, introduction and/or conclusions, we found enough evidence that they were relevant to our study, keeping 629 references. Finally, a filter *by content* was applied so that some more articles were excluded once they were read carefully. Obviously, all papers included in the QGS were never excluded when applying these type of filters as they must be part of the final selected papers. Note that the most common exclusion criteria at this point were: E3, as some papers were definitely not useful for this work; E4, since some papers were older publications from the same authors about the same approach; E8, because some articles were completely illegible, especially figures detailing software concepts; and E9, as some papers were published after 2017. Table 8 presents the number of papers excluded by exclusion criterion. Note that some of the papers excluded satisfied more than one exclusion criterion. At the end of this search process, we selected *463 references* for being analysed in this mapping study (see Appendix A for further details) as will be presented in Section 4.

Table 8. Number of papers excluded by exclusion criterion

Exclusion criterion	*No. of papers excluded*
E1	13
E2	275
E3	6140
E4	25
E5	43
E6	10
E7	192
E8	228
E9	5

3.2.5 Evaluating search performance

The completeness and performance of the automated search has been assessed by means of the aforementioned *quasi-sensitivity* concept, whose formula is presented below:

$$\textit{Quasi-sensitivity} = \frac{Number\ of\ QGS\ studies\ retrieved\ from\ the\ automted\ search}{Total\ number\ of\ QGS\ studies} \cdot 100\%$$

A sensitivity threshold greater than 80% can be seen as an acceptable reference for sensitivity evaluation of search performance, as recommended by Zhang et al. [56]. The quasi-sensitivity has been calculated as follows, taking into account that the total number of studies in the QGS is 17 (see Section 3.2.2 for more details) and the number of QGS studies retrieved when performing the automated search was 14:

$$\textit{Quasi-sensitivity} = \frac{14}{17} \cdot 100 \cong 82{,}4\%$$

Therefore, with a quasi-sensitivity of 82,4%, we can state that the performance of the automated search proposed for this study is quite acceptable.

4 Results

A data extraction form was prepared that includes several fields to answer each of the RQs. We also collected other information of each paper, namely, keywords, country, venue type, research topic, application domain, research type, main contribution of the paper, and, finally, what elements are adapted during the adaptation process. All these data were collected from all the 463 selected papers (see Appendix A). In the next subsections, first, we present an overview of the selected papers regarding their publication venue (Section 4.1.1), year and country (Section 4.1.2), research topic, application domain and research type (Section 4.1.3), and what is adapted (Section 4.1.4). Afterwards, in Sections 4.2, 4.3, 4.4 and 4.5, some descriptive statistics and frequency analysis are presented to answer each research question introduced in Section 2.2.

4.1 Overview of Selected Papers

This section shows an overview of the selected papers in terms of their publication venue, year, country, research topic, application domain, research type as well as what is adapted by the system. Furthermore, at the end of this section, there is a summary about the different context dimensions covered by the SA concepts found in the selected papers, and the type of evaluation performed regarding those SA concepts.

4.1.1 By publication venue

Table 9 shows the top ten most popular publication venues for papers focused on context-aware systems regarding the number of papers published. As shown in this table, around 17,71% of the 463 selected papers are published in these publication venues: *Personal and Ubiquitous Computing*, *User Modeling and User-Adapted Interaction*, *Wireless Personal Communications*, *World Wide Web* journals, as well as the *International Conference on Embedded and Ubiquitous Computing*.

Table 9. Number of papers published in the top ten most popular publication venues

Ranking	*Venue*	*Type*	*No. of papers*	*% of papers*
1	Personal and Ubiquitous Computing	Journal	*20*	*4,32%*
2	User Modeling and User-Adapted Interaction	Journal	12	*2,59%*
3	Wireless Personal Communications	Journal	10	*2,16%*
4	World Wide Web	Journal	7	*1,51%*
5	International Conference on Embedded and Ubiquitous Computing	Conference	6	*1,30%*
6	Procedia Computer Science	Journal	8	*1,73%*
7	Journal of Systems and Software	Journal	5	*1,08%*
8	International Conference on Universal Access in Human-Computer Interaction	Conference	5	*1,08%*
9	Multimedia Tools and Applications	Journal	5	*1,08%*
10	IEEE Pervasive Computing	Journal	4	*0,86%*
		Total	*82*	*17,71%*

4.1.2 By year and country

Fig. 3 illustrates the distribution of the number of papers published from 1999 to 2017. It can be noticed that there is an increasing interest of the research community in context-aware systems and their architecture artefacts especially since 2007, that it is being sustained since then.

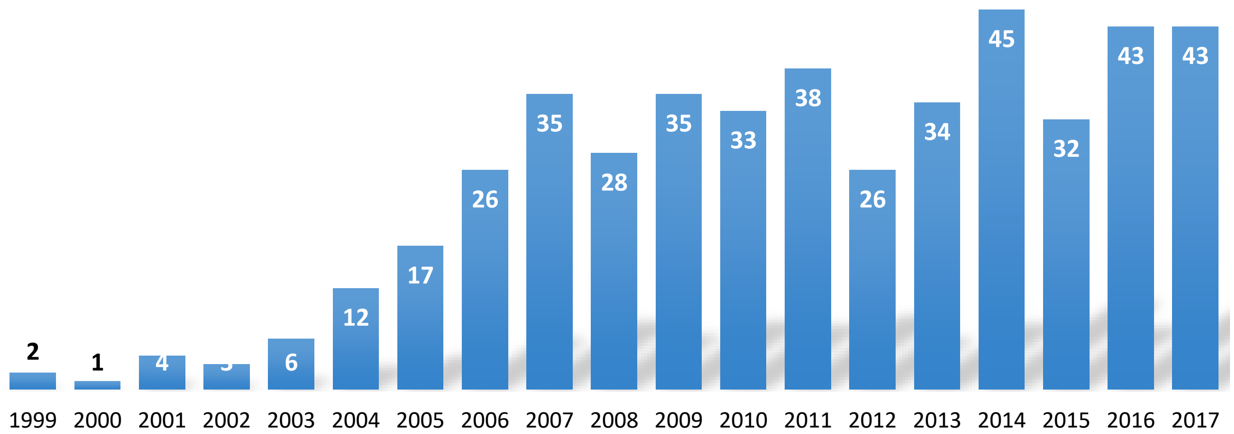

Fig. 3. Number of selected papers by year of publication

Moreover, Fig. 4 depicts the top ten countries that have devoted more effort into research in context-aware systems. Researchers from these ten countries have published a total of 277 papers out of the 463 selected ones, i.e. the 59,83% of all selected papers. As observed Asian countries, China and South Korea, lead this ranking significantly, followed by Germany, Spain and Italy.

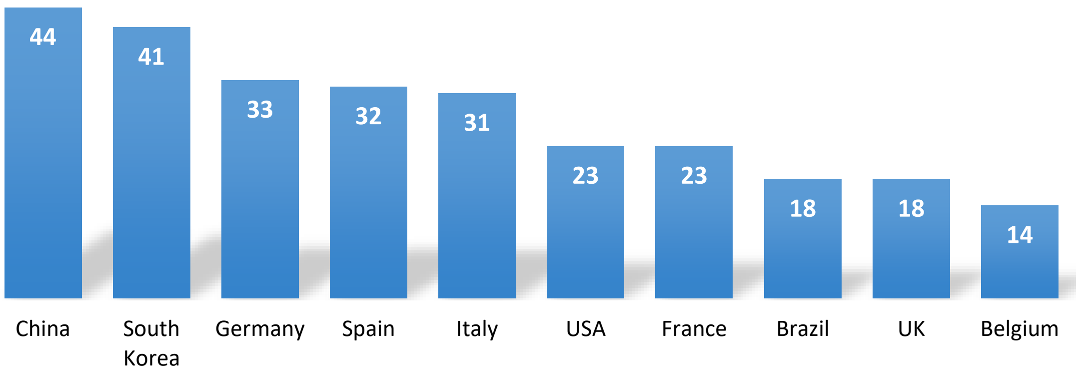

Fig. 4. Number of selected papers by top ten countries

4.1.3 By research topic, application domain and research type

By analysing the content of the selected papers more thoroughly, they can be classified by research topic, application domain and research type. Fig. 5 presents the *research topics* of the selected papers that have been addressed by at least 1% of the analysed papers. The research topics most frequently used are: *context inference*, *context management*, *context modelling* and *context gathering*. These terms have been described in a glossary in [42].

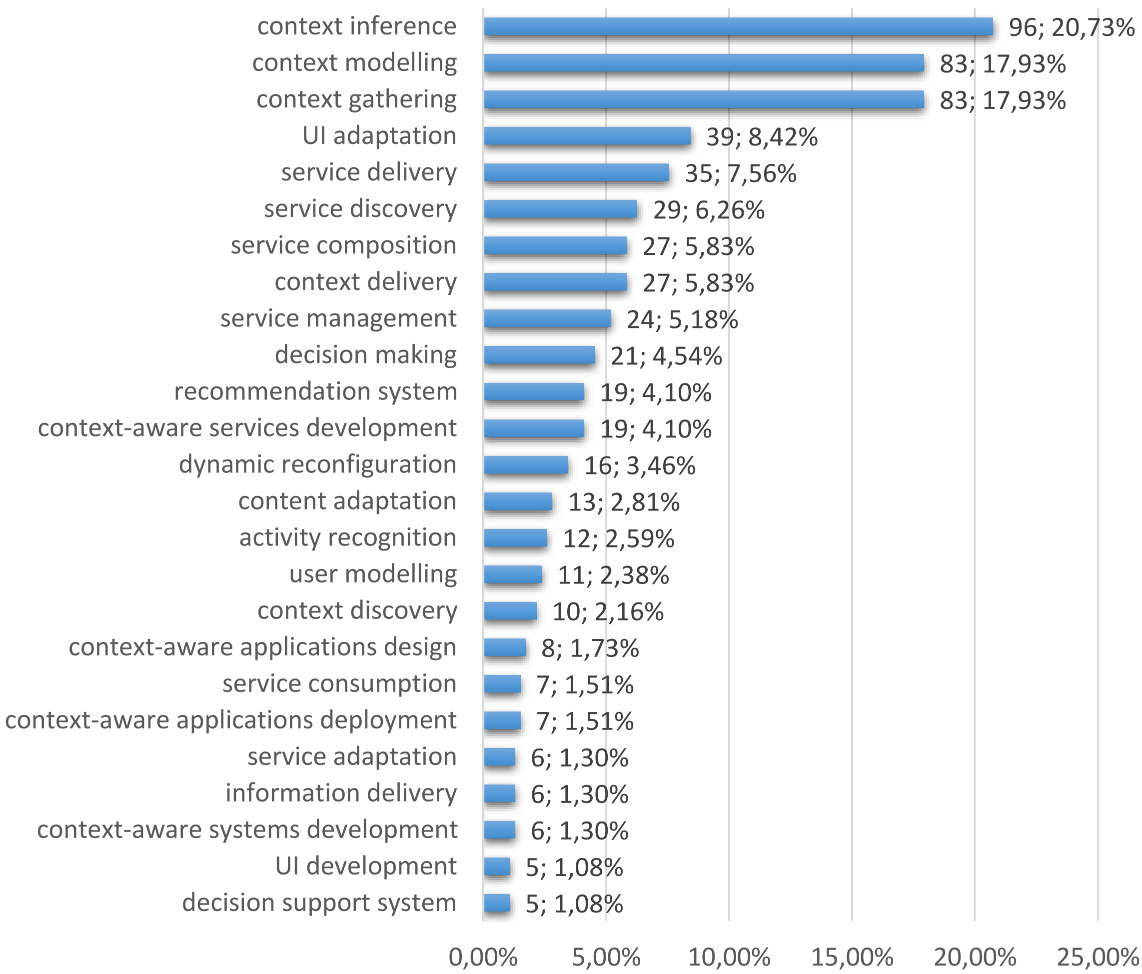

Fig. 5. Research topics addressed by the selected papers: number and percentage of papers

Furthermore, the most frequent application domains of context-aware systems were also identified. Fig. 6 shows these *application domains* (at least identified in 1% of the analysed papers) and groups of interest of context-aware systems, being *smart environment* and *healthcare* the most recurrent. It is worth noting the wide range of smart environments that have been considered under such category, such as smart home, smart hospitals, smart office, smart rooms, and even one paper devoted to smart kitchen. Related to healthcare several proposals have been defined for physical rehabilitation and tele-therapy.

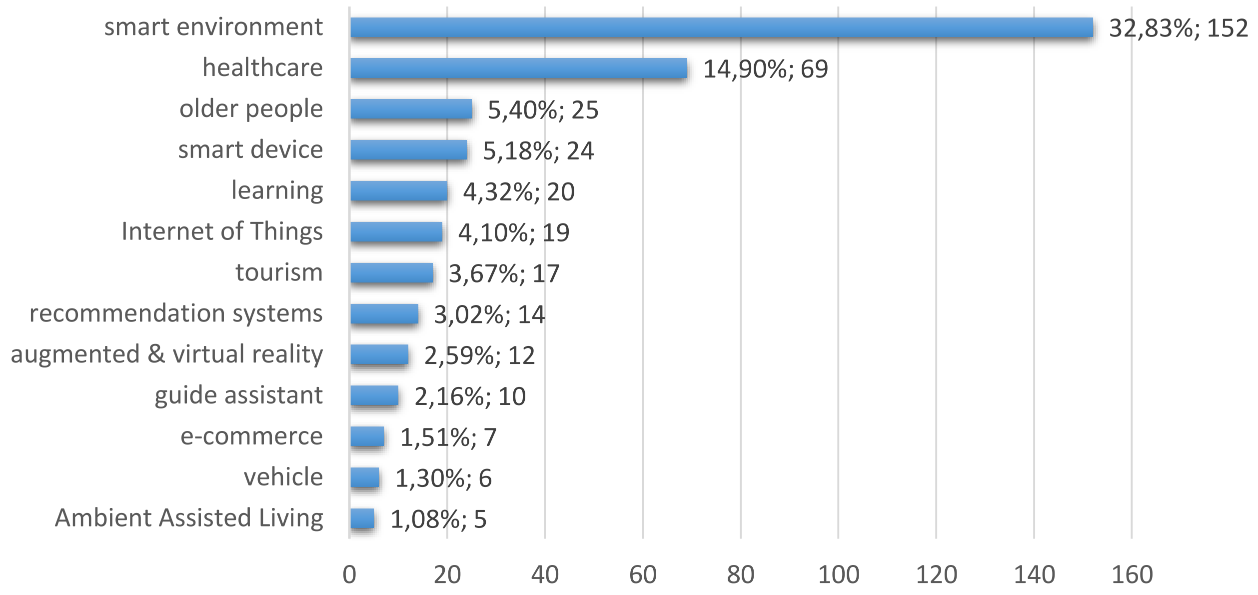

Fig. 6. Application domains of selected papers number and percentage of papers

Finally, Fig. 7 shows how the selected papers were classified according their *research types* using Wieringa et al. [52] taxonomy (see Section 2.4 for more details). Most of the selected papers are categorized as *Solution proposals* (424 papers, i.e. 91,5%), followed by *Validation research* (118 papers, i.e. 25,48%), *Experience paper* (10 papers, i.e. 2,1%), *Evaluation research* (3 papers, i.e. 0,64%), and finally *Philosophical paper* (1 paper, i.e. 0,28%). Some papers are categorized as both Solution proposal and Validation research, e.g. P004, P009, P012 or P433, and there are also some papers, e.g. P008 or P035, which are both Solution proposals and Experience papers. Other papers, such as P065 or P411 are just Validation research and the paper P359 is the only one classified as both Validation research and Experience paper. The paper P113 is the only one categorized as both Solution proposal and Philosophical paper. Finally, P036 is the only one classified as Solution proposal and Evaluation research.

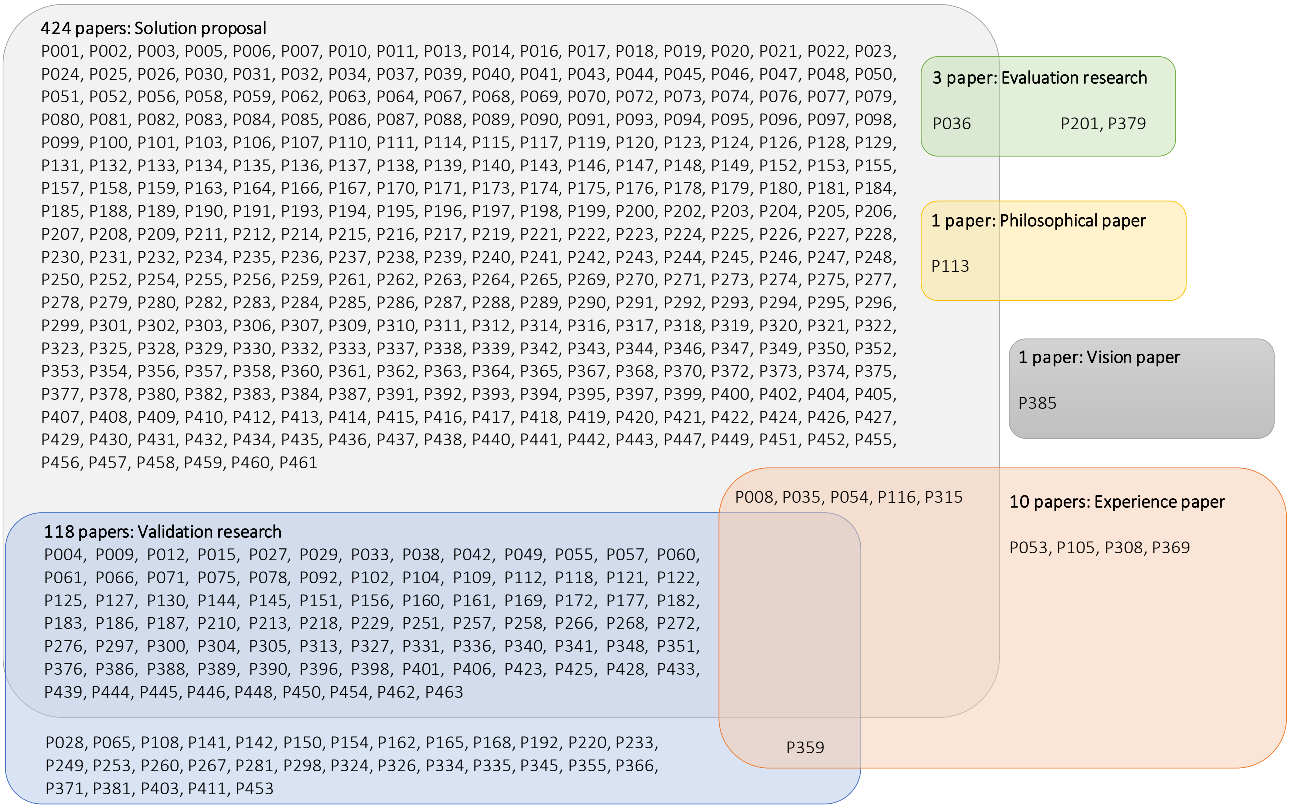

Fig. 7. Research types of selected papers

4.1.4 By what is adapted

Most of the papers analysed in this mapping study are focused on the adaptation process and, generally, they clearly identify what is adapted by the system. We considered this information very useful and a cornerstone when designing and developing context-aware applications. Therefore, Fig. 8 depicts an overview of the most frequently adapted elements that have been used by at least 1% of the analysed papers. As shown, *services* is the element of context-aware systems most frequently adapted, being used by 61,12% of the analysed paper. UI follows, considered by 47,73% of the papers. Some aspects of the UI that have been considered by at least 1% of the papers have been depicted in a different category, such as *presentation* or *interaction mode*. Moreover, it is worth highlighting that 9,72% of the analysed papers have considered some aspect of the adaptation of the architecture.

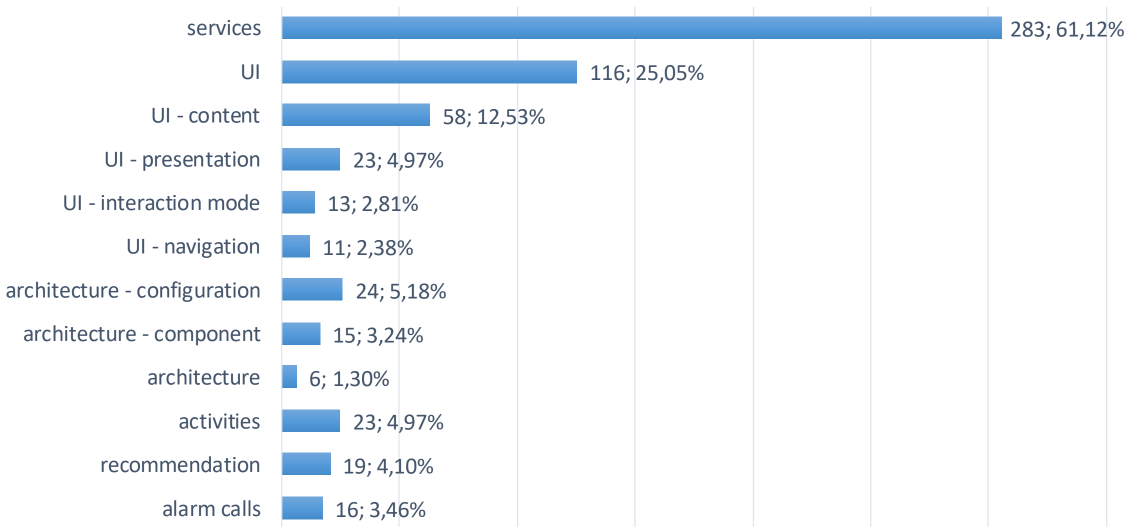

Fig. 8. What is adapted in the context-aware systems: number and percentage of papers

4.2 RQ 1 – Software Architecture Concepts

In order to provide an overview of software architecture concepts used for building context-aware systems, after going through all the 463 selected papers, we have identified the following 16 different software architecture concepts and patterns illustrated in Fig. 9 along with the number of selected papers that apply them. Notice that the same work can use more than one architecture concept. It is interesting to highlight that the *multi-layered* approach is the most commonly used one for building context-aware systems, followed by *component-based*, *SOA* and *MAS*.

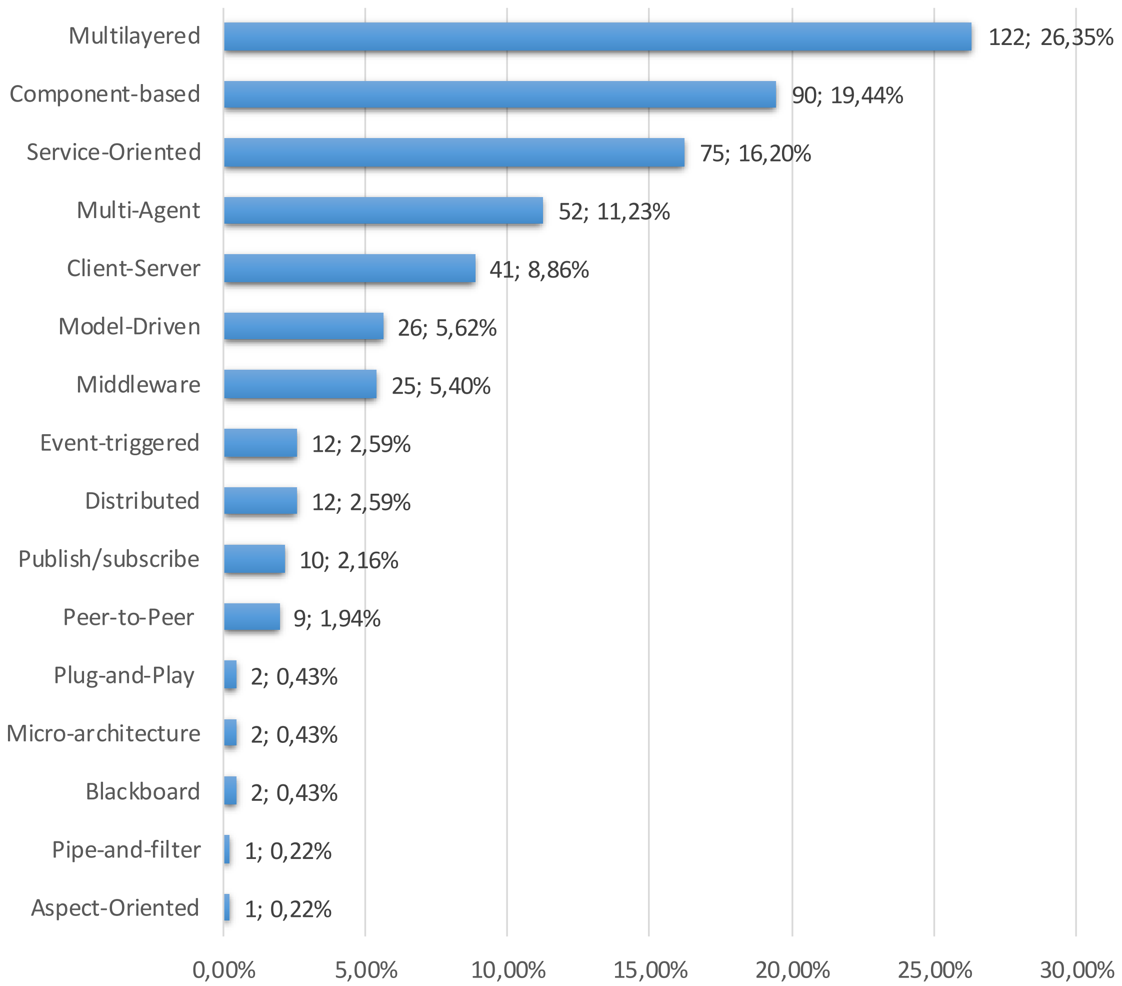

Fig. 9. Software Architecture concepts

In the following lines, we offer some examples of papers regarding these SA categories in more detail. For example, there are plenty of works that use SOA, among other approaches, such as the papers P178 which proposes the use of SOA along with a multi-layered and middleware approach. P331 also follows a SOA paradigm as it proposes the CAMPH system to provide a number of services for context data acquisition, context storage, context reasoning, service organization and discovery used to facilitate the development of pervasive homecare applications. This work also makes use of a multi-layered architecture, since the middleware infrastructure separates context data and context-aware services in different layers so that they can be used by the applications. P415 also uses SOA along with a P002P approach to provide an optimized context management.

Other works are only focused on applying a SOA approach. For instance, P065 makes use of Web services for designing context-aware applications mainly due to the loosely coupling benefit. P002 and P184 consider SOA too, as well as P108 that integrates services into widgets used for collecting data from sensors and acting like GUI interactors to make changes to the environment. For example, a Light widget can identify and change the light conditions of a specific location.

There are other proposals built using a MAS approach, such as P388 or P213. P177 proposes an agent-based framework along with a multi-layered approach for providing customized services based on context history and users' preferences. The proposed framework consists of the following layers: data gathering layer, context management layer, preference management layer and application layer. Some other papers present a component-based architecture for developing context-aware systems, e.g. P319 and P222. The architecture presented in P347 also follows the structure of a middleware and it is distributed.

With regard to multi-layered architectures, some examples are P361 and P416 which identify four layers: the *application layer* that consists of context-aware, proactive and mobile applications as well as sensors to provide application-specific context information to such applications; the *Event-Condition-Action (ECA) engine* that is responsible for the application behaviour; the *privacy enforcement layer* that ensures that privacy-sensitive information can only be accessed according to privacy policies; finally, the *infrastructure layer* entails functionality for context management and reasoning. P362 follows a multi-layered approach having several layers, such as the *ontology editor* for modelling ontologies, the *authoring tool* for creating learning objects from existing content and contextualize them with references to the ontology, and the *delivery platform* for context-aware delivery of learning objects and managing the learning progress.

P211 proposes a client-server architecture, called ALICE (Architecture for Location-Independent Computing Environments) to support mobility by providing a range of application level client/server protocols. P061 exploits the publish/subscribe paradigm to receive and redirect messages from sensors to sensor and device models.

4.3 RQ 2 – Dimensions of Context

As aforementioned, three main dimensions of context are widely used in the research community: *User*, *Environment* and *Platform*. The purpose of this research question is to discover how each dimension of context is addressed and taken into account in the different proposals.

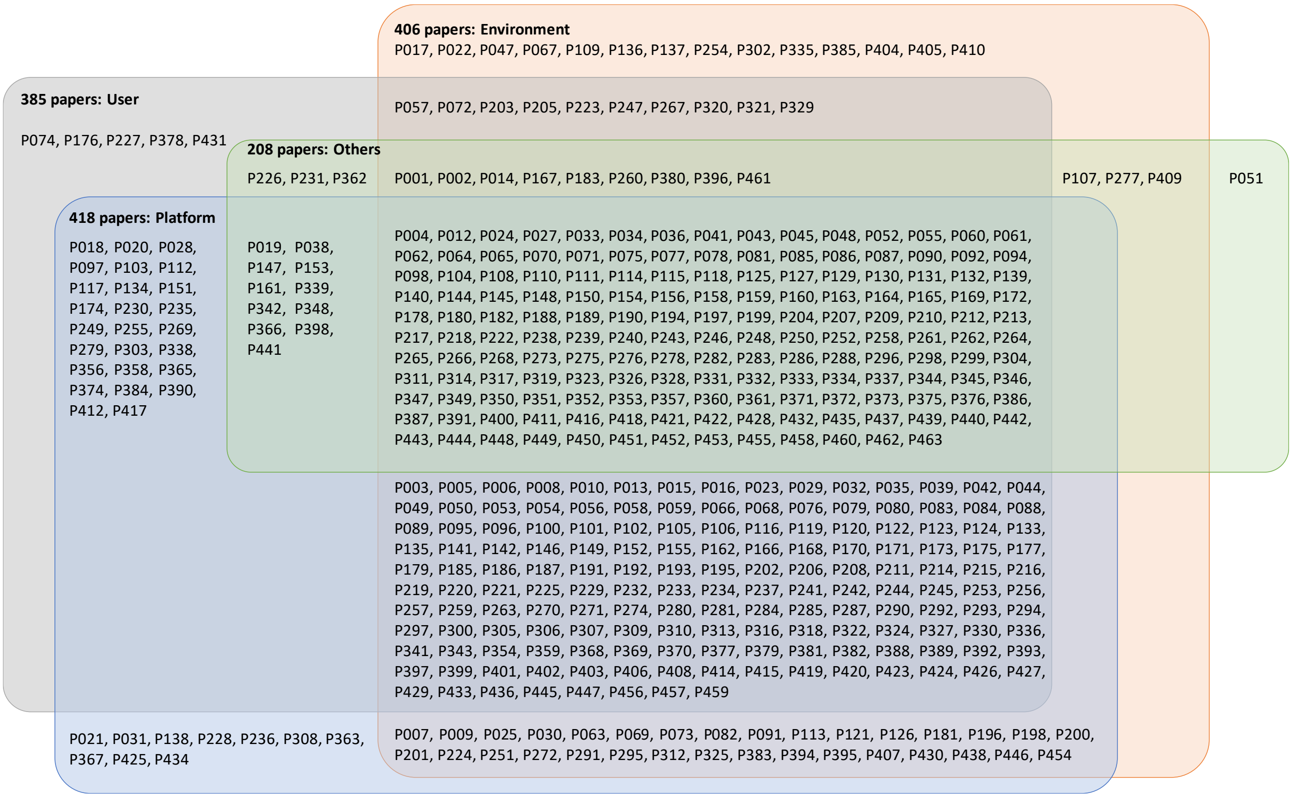

Fig. 10. Dimensions of context of the selected papers

Fig. 10 presents an overview of the different dimensions of context considered by each selected paper. Most of the selected papers (418 papers, i.e. 90,2%) consider the *Platform* in some way, followed by the *Environment* (406 papers, i.e. 87,7%), the *User* (385 papers, i.e. 83,1%) and, finally, *Other* dimensions of context (210 papers, i.e. 44,9%).

There are few papers that only consider one dimension of context, such as P074 and P176 (User), P109 (Environment), or P425 (Platform). Others treat two of them, such as P057 (User and Environment), P107 (Environment and Other dimensions), P374 (User and Platform), or P454 (Platform and Environment). On the other hand, some other papers deal with all the three main dimensions of context (User, Platform and Environment), such as P141 or P388, while others also consider extra dimensions of context in addition to the three usual ones, such as P218 or P373. Next, some examples of papers related to all these context dimensions are discussed.

There are many selected papers that deal with the three main dimensions of context, i.e. User, Environment and Platform. For example, P415 takes into account the user needs and preferences, the situation or the available resources, and also the presence and GPS location information for adapting services and applications. P211 revolves around mobile devices and their resources, such as memory, processing power, battery level or network features to adapt the system. It also takes into account the environment, the application characteristics and the user preferences at runtime for dynamic adaptation of services. P177 proposes a data gathering layer in its architecture for collecting and processing the profiles of the users (gender, age, job, hobby, etc.), or for managing data, such as time, location and temperature. By doing so, this proposal is able to predict the user preferences and provide personalized services or products based on those preferences.

Some papers address other dimensions of context in addition to the main ones. For instance, some papers, such as P148 and P347, take into account the *user activity* he/she is doing for guiding the adaptation. P108 considers location of an entity within the environment, current temperature, time, ambient light or noise level, as well as physiological factors of the user, and the activity the person is involved in, such as reading or talking, to carry out the adaptation. It also considers software components attributes, e.g. load of the CPU, state of the files in the file system, or state of the application. P213 in addition to location, time, network characteristics, user preferences, user profile, or system services, also considers the ongoing activities of the users. P416 treats as context for the adaptation the user activity, geo-location, speed and direction, battery level, time, available networks, favourite places, and means of transport. P331 considers many context information, e.g. location of a device, occurrence of an event, room temperature, number of people in a room, medical profile, blood glucose, blood pressure, heart rate or body temperature of a user. It also manages both daily activities of the user being monitored, e.g. eating, and abnormal activities, e.g. falling down, that should be detected in a reasonable time. P065 proposes the following context dimensions: user, device, network, activity, service, location, and resource. P060 presents a framework for improving recommender systems based on the user activity, his/her preferences and profile, information regarding the different devices used, and the location of the user, light, noise, temperature of the environment or time of the day, among others.

Other approaches pay attention to the *historical data* as another dimension of context, that is, past information related to the context of use, e.g. the interaction history of the user. For example, P362 exploits the learning history of the user for adapting his learning activities. P107 employs words used recently, user's previous conversations, current time, date, and user's location to select conversation topics, among others. P075 presents a system that takes into account location, temperature, light, noise or humidity level of the environment, behaviour and preferences of the user, battery level of the devices, among others, as well as the user activity and his historical information, represented as a data set generated using a variety of sensors. By analysing all this information, the system is able to learn user behaviours in an office environment in order to use the inferred rules to populate a user model and support appropriate proactive behaviour, e.g. turning on the fan under appropriate conditions.

Some papers exploit the user's *interaction task* for the adaptation process. For example, P333 presents a software that supports different sensor types, including location and user interaction sensors, to monitor the active application the user is involved in, among others. P107, in addition to historical data, uses the user' interaction task to support a word predictor to foresee which word a user is typing using the letters that have been typed so far. P169 proposes a context-aware system for museums that has the ability of monitoring the continuous changes of the user's interests during his interaction with the system. Finally, P183 presents an Affect and Belief Adaptive Interface System (ABAIS) that exploits a variety of user assessment methods (diagnostic tasks, physiological sensing, etc.) to determine which adaptation approach is the most appropriate.

4.3.1 RQ 2.1 – User dimension of context

We discovered a great variety of terms used for characterizing the *user* of a context-aware system. The terms that are used by at least 1% of the analysed papers are represented in Fig. 11, being among the top most frequently used terms: *profile* of the user including abilities, age, identity, etc.; *preferences*, such as interests; *physiological data*, e.g. heart rate, blood pressure, temperature; interaction considering aspects as user's behaviour or goals while interacting with the system; *health state* refers to any information related to the health conditions or medical data of the user such as his diseases; *emotional state* of the user as, for instance, bored. Note that we have grouped terms according to one of them, whenever they had less than 1%. For instance, in Fig. 11, physiological data is used to group several terms, such as breath rate and oxygen level, that have less than 1% of references. As can be observed, the terms most frequently used are *profile*, with a 41,03% of use and *preferences*, which appears in 31,74% of the selected papers.

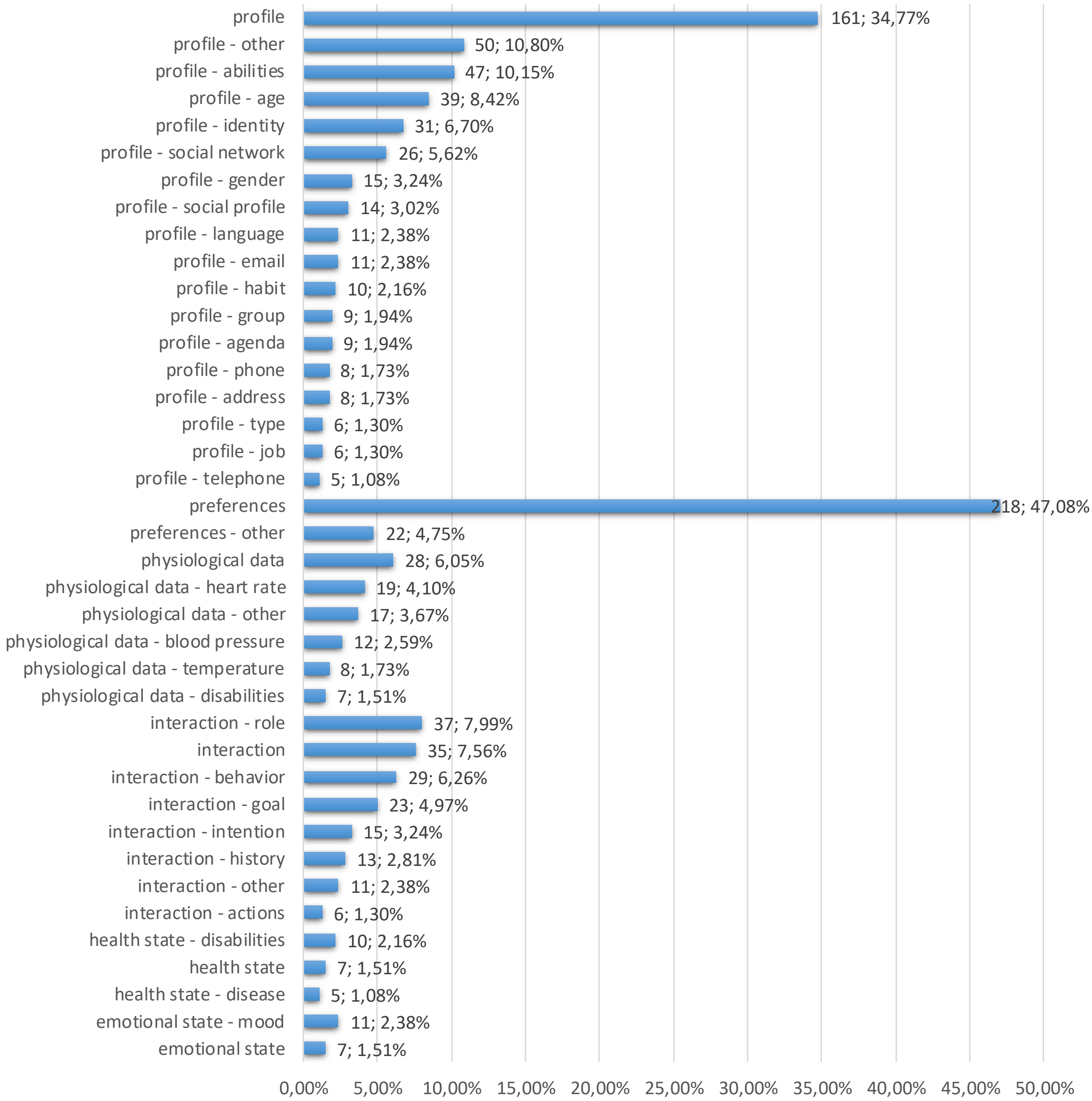

Fig. 11. Terms for characterize thing User dimension of context

4.3.2 RQ 2.2 – Platform dimension of context

While characterizing the platform of context-aware systems, we have also detected a great heterogeneity among the terms used in the selected papers. Fig. 12 the top terms that have been used by at least 1% of the analysed papers as well as how many times they have been used. However, there is some information related to the platform more widely used, as Fig. 12 shows: *devices* is the most frequently used; *sensors* considering either software and hardware elements in charge of collecting data from the context is the second most frequently used; *network* and its relevant information, e.g. speed, bandwidth or connectivity; *services* offered by the system, e.g. weather services or traffic information services; *content* offered to the user; *hardware* considered as other elements of the devices, being battery the most frequently used for considering aspects regarding the energy consumption; *storage* to be effectively managed by the system; *screen* and its related features resolution, size and color; *software* considering different elements such as applications developed, resources the system uses, etc.; *UI* offered to the user and different features regarding its interaction modality and format; *actuators*¸ both software and hardware, that apply changes to the context-aware system; and finally *CPU* being and *cost*.

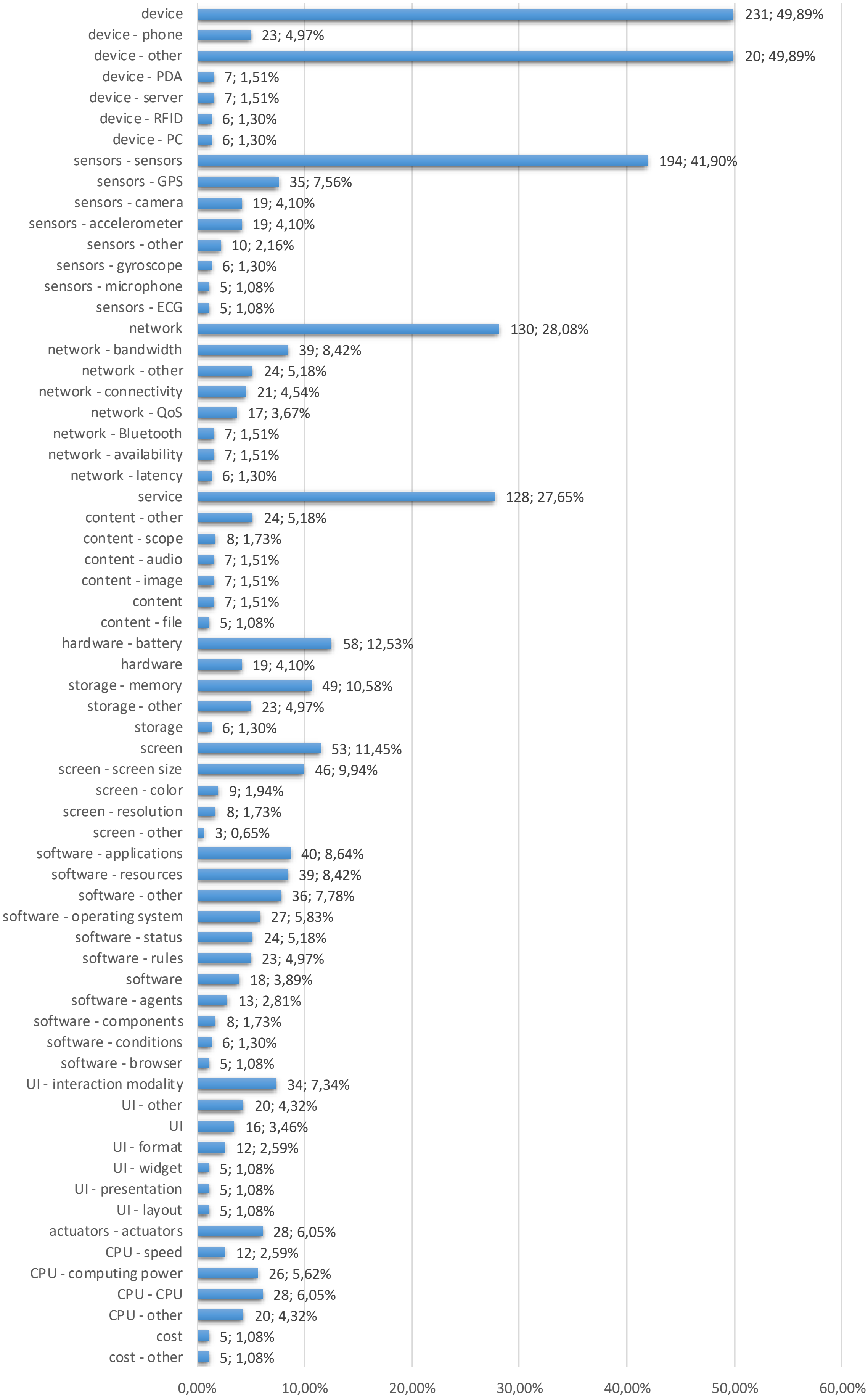

Fig. 12. Terms for characterizing the Platform dimension of context

4.3.3 RQ 2.3 – Environment dimension of context

Fig. 13 the most frequently used terms for characterizing the environment that have been used by at least by 1% of the analysed papers. Similar to the previous dimensions, we have identified many terms related to the environment. Nevertheless, there are also some of them that are very recurring. First, as identified by the feature *user in the environment*, there are many references that exploits user's information regarding the environment such as users' location regarding the environment, his movement, his orientation, etc. Next, we observed, it is very frequently used information about the *environmental conditions*, such as temperature, light, noise, etc. where the interaction is taking. *Events* happening in the environment is followed by all the terms used to describe the *physical environment* such nearby people, or nearby devices. As can be observed, the term most frequently used is by far the *location*, being used by 82,51% of the selected papers, followed by the *temperature* 19,22%, and *light* 17,71%.

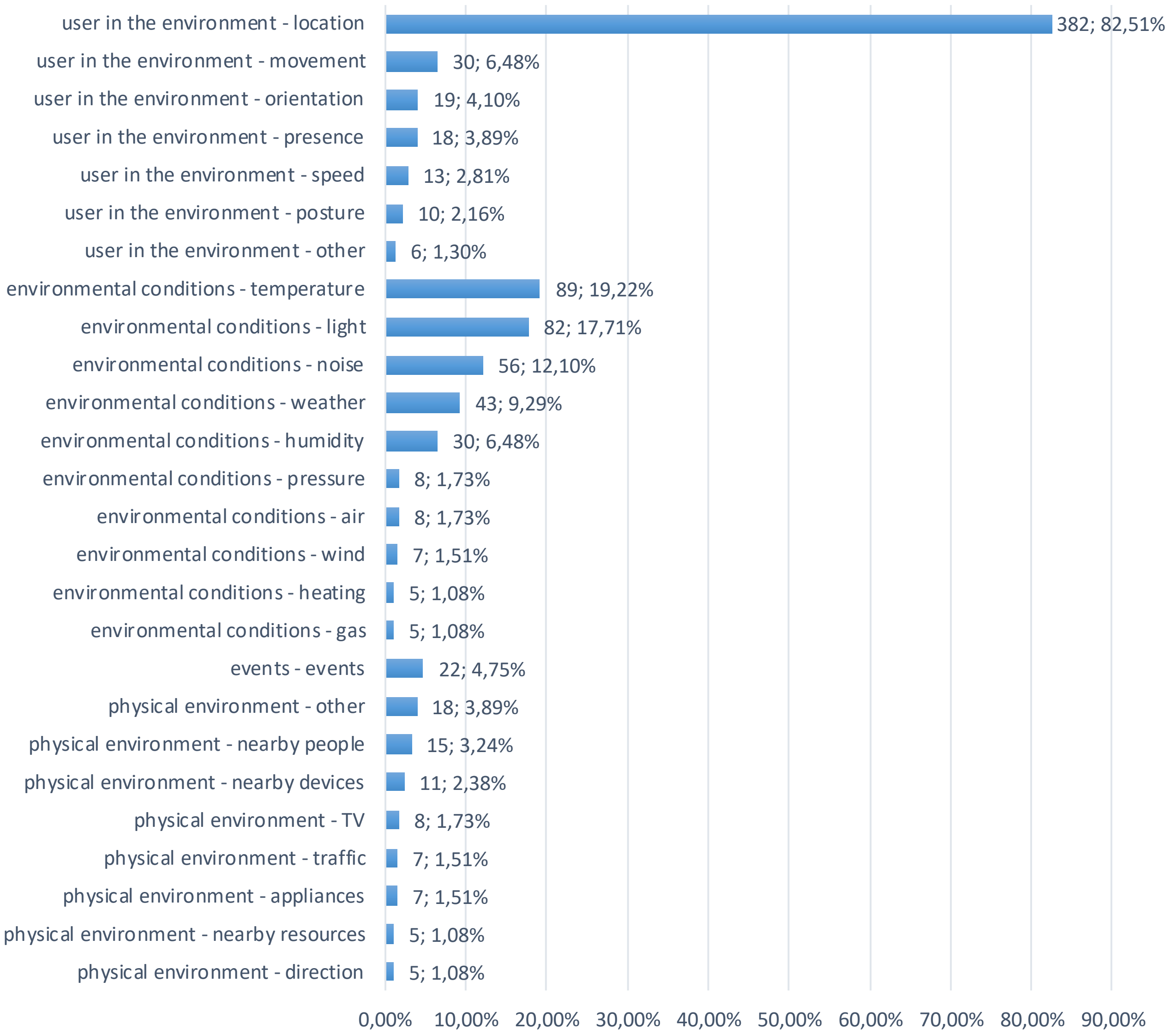

Fig. 13. Terms for characterizing the Environment dimension of context

4.3.4 Other dimensions of context

As aforementioned, we also wanted to determine if some proposals make use of other dimensions of context, in addition to User, Platform or Environment. In this sense, we have identified the following three dimensions of context: Historical data, User activity or Interaction task (see Section 2.4 for more details). Table 10 presents the number of papers that use these additional dimensions. Namely, the *interaction task* the user is doing with the system is used in 22,25% of the selected papers, the *user activity* the user is performing (e.g. walking, sleeping, shopping, cooking, etc.) in 16,41%, and the *historical data* in 11,45%.

Table 10. Other dimensions of context

Dimension	*No. of papers*	*% of papers*
Interaction task	103	22,25%
User activity	76	16,41%
Historical data	53	11,45%
Facts	2	0,43%

4.4 RQ 3 – Evaluations of Context-Aware Adaptations

Results presented in this section focus on proposals that apply context-aware adaptations and that provide some mechanism to evaluate these context-aware adaptations, that is, to determine their quality. Therefore, we want to find out to what extent the evaluation of context-aware adaptations in context-aware systems is covered in the literature to estimate its maturity. Fig. 14 shows the different types of evaluation identified to assess the adaptations in context-aware systems: *Automated evaluation, Design space, Satisfaction evaluation, Survey, Ubiquitous Computing Acceptance Model, Usefulness evaluation, User feedback, User-centred Evaluation (UCE), Visual and formal validation with a GUI*. Note that there are quite a few papers, i.e. only the 7,99% of the selected papers that deal with some kind of adaptation evaluation out of the selected papers. This lack will be further discussed in Section 5.

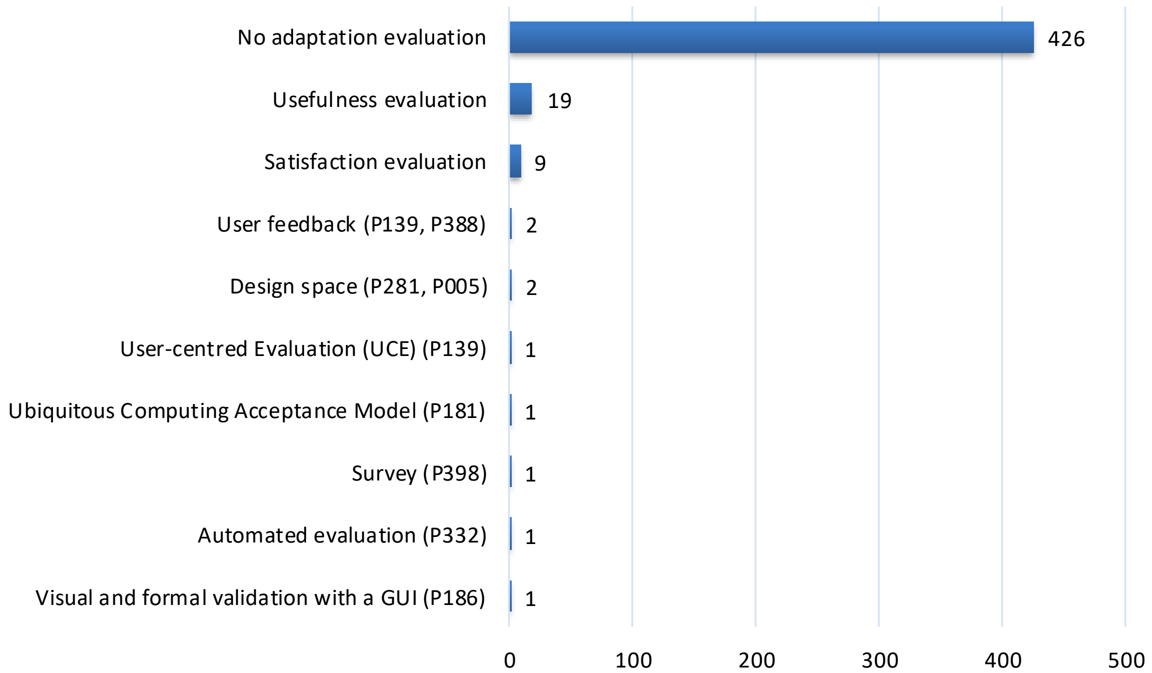

Fig. 14. Adaptation evaluations found in selected papers

P281 presents a framework that consists of, among others, a *design space* for evaluating the adaptation coverage in a reliable way. This design space is used to assess and compare the adaptation levels of different applications based on common criteria. However, other papers focus on evaluating the adaptation process by means of its *usefulness*, such as P139. This paper suggests a user-centred evaluation to verify the usefulness of the adaptations applied.

We have found other types of evaluation that assess the adaptation by means of a Graphical User Interface (GUI) or wizard that shows the user how the adaptation will change the system, so he/she can accept or reject it in a visual manner. We have called this type of evaluation *visual validation*. For example, P186 presents a tool for the generation of context-aware adaptive software system implementations that supports a visual validation of the context-aware adaptive behaviour of the system through a GUI. The user can press the button *Adapt to the Context Information Changes* to see how the context changes impact the system. This evaluation feature enables the detection of missing and incorrect adaptation behaviours in a visual manner. P186 proposes a visual validation of the adaptation too. Its proposal is able to recognize the actual policy rule that caused an incorrect behaviour of the system in order to assist the user when he/she corrects the adaptation behaviour by means of a wizard. Finally, P388 proposes a widget to support the user while expressing his/her opinion about the current presentation topic. This is carried out by means of two buttons: the *Wow* button that reflects the user feelings whenever he/she is positively impressed by a specific presentation and the *Basta!* button, which is used whenever the user is not interested in the current topic, thus stopping the current presentation.

We have also detected that other articles evaluate the adaptation by using the user *satisfaction*, usually through some type of survey or questionnaire. For instance, P012 evaluates the user's satisfaction regarding the offered context-based recommendations. P181 measures the user's satisfaction exploiting the perceived ease of use or perceived control, among others. P390 estimates the satisfaction degree between the adapted media selected by its proposed Content Adaptation Process and the media requested by the learner. Finally, P398 proposes the evaluation of the user's satisfaction regarding functionality and adaptability by means of a survey.

Lastly, automated adaptation is a possible solution to address evaluation of adaptation in many situations, when the target users are not available, time constraints make impossible making a regular evaluation or there are so many possible adaptations that regular evaluations are not a plausible option. P332 apply as input to the system under evaluation a programmed user model to simulate the behaviour of the user in the long-term more easily and thus draw useful conclusions about the quality of the adaptations relying on some underlying models such as a task model.

4.5 RQ 4 – Evaluations of Software Architecture Concepts

Finally, we wanted to find out what evaluations have been carried out up to now to validate the software architecture concepts proposed for context-aware systems. By doing so, we will be able to discover the degree of *maturity* of the different software architecture concepts. Therefore, we have categorized the different software architecture concepts found in the selected papers according to the type of evaluation presented by using the taxonomy of Wohlin et al. [54] for classifying *Empirical strategies*. We have also added the category *Example* for papers that do not present a formal empirical evaluation (see Section 2.4 for more details about this categorization).

Fig. 15 shows the results from the point of view of the evaluation type presented in each selected paper. The majority of the papers only include an *Example* (135 papers, i.e. 29,15%), followed by *Case Studies* (104 papers, i.e. 22,46%), *Experiments* (50 papers, i.e. 10,80%) and finally *Surveys* (20 papers, i.e. 4,3%). Thus, there are 161 papers among the selected ones (34,7%) that do not have any type of evaluation, validation or example, neither formal nor informal one, for assessing the SA concept proposed. Note that we have found neither formal nor informal evaluation for assessing *aspect-oriented architectures*.

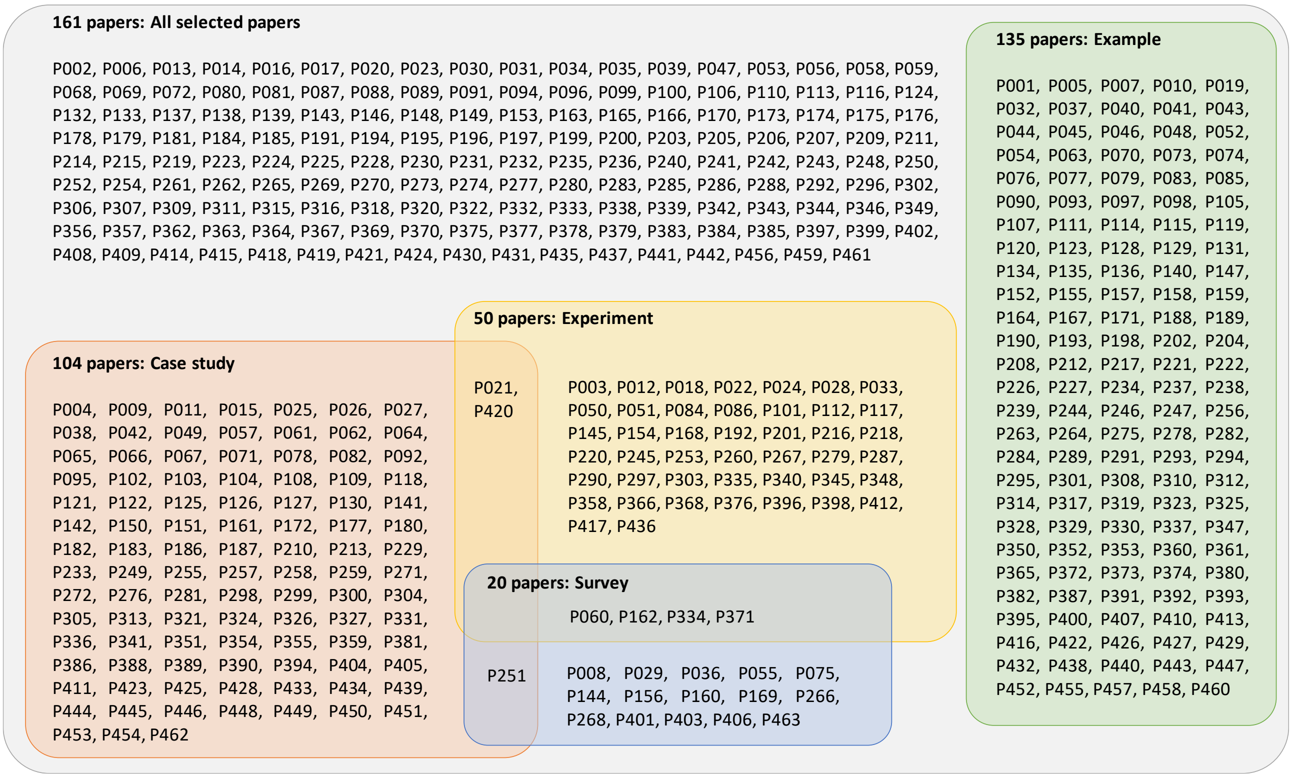

Fig. 15. Type of evaluation presented in each selected paper

With regard to the *Example* category, most of the software architecture concepts use examples to illustrate and validate the proposals in an informal way regarding the following SA concepts: *client-server architecture* (P070 or P128), *component-based architecture* (P019, P054 or P373), *middleware architecture* (P382 or P391), *distributed architecture* (P347 and P413), *model-driven architecture* (P090 or P120), *multi-layered architecture* (P295 or P393), *event-triggered architecture* (P440), *micro-architecture* (P129), *service-oriented architecture* (P007 or P171), *multi-agent system* (P111 or P263), *publish/subscribe architecture* (P115), and *peer-to-peer architecture* (P005 or P284).

We have identified some *Surveys* for assessing the following software architecture concepts: *client-server architecture* (P266), *component-based architecture* (P156 or P160), *distributed architecture* (P251), *model-driven architecture* (P162), *multi-layered architecture* (P401 or P463), *event-triggered architecture* (P036), *service-oriented architecture* (P055 or P144), and *multi-agent system* (P029 and P268).

Some *Case studies* have been also carried out for evaluating the following software architecture concepts: *client-server architecture* (P150 or P454), *blackboard architecture* (P210), *component-based architecture* (P009, P161 or P172), *middleware architecture* (P042 or P102), *distributed architecture* (P251), *model-driven architecture* (P064 or P066), *multi-layered architecture* (P078, P249 or P446), *event-triggered architecture* (P272), *service-oriented architecture* (P065, P151 or P331), *multi-agent system* (P062, P082 or P299), *publish/subscribe architecture* (P061 or P122), *peer-to-peer architecture* (P331), *pipe-and-filter architecture* (P351), and *plug-and-play architecture* (P127).

Finally, we have found a few *Experiments* for the validation of the following software architecture concepts: *component-based architecture* (P112 and P334), *model-driven architecture* (P162), *multi-layered architecture* (P012, P033, P218, P253, P297, P340, P376), *service-oriented architecture* (P371), and *multi-agent system* (P033, P145, P348, P398).

Next, some of the most referenced selected papers are highlighted to provide some insights about the evaluation strategy applied to validate their software architecture proposals.

P416 uses just an *example* to demonstrate and validate its *multi-layered* architecture. It presents a typical use of the infrastructure in a mobile healthcare application scenario. On the other hand, P036 presents a *survey* for assessing the maturity of the *event-triggered* and *multi-layered* architecture proposed. It is the only paper that has applied and evaluated the proposal in a real industrial scenario. Therefore, it has been categorized as *Evaluation research*. First, the system was deployed in a hospital and it went into pilot use. Afterwards, a survey focusing on users' experience while using the system was handed out to the doctors, and over 40 responses were collected.

Other papers have validated their proposals by means of *case studies*. P065 proposes a *service-oriented architecture* which has been evaluated by a case study applied in a medical system scenario and using concrete adaptation rules. P108 also provides a *service-oriented architecture* assessed by a case study. Authors show how the toolkit proposed can be used to design and build context-aware applications and how it supports reusability of components, evolution of applications, and acquisition of complex context. P177 suggests a framework based on the *multi-agent* and *multi-layered* approaches. This framework has been validated by using a case study to show its feasibility. P213 presents a *multi-agent system*. Authors designed and implemented a prototype as a case study to test the applicability, scalability and context effectiveness in everyday activities. Finally, P331 makes use of several paradigms, such as *peer-to-peer*, *multi-layered* and *service-oriented architecture*. To validate the proposal, authors used a case study by deploying a prototype in their research laboratory and using different real scenarios, such as a smart home, an office or a shop.

To conclude, P340 proposes a context-aware system supported by a *multi-layered* infrastructure. Its effectiveness has been proved by conducting *experiments* with a complete implementation of the system with some available sensors and an Android-based handheld device that acted as the host for the main activity recognition module.

5 Discussion

In this section, an analysis of the results described in the previous section regarding the Research Questions is presented, in order to foresee future directions in this research field (Section 5.1). Afterwards, some implications for researchers and practitioners are discussed (Section 5.2).

5.1 Analysis and Synthesis of Results

This section presents an analysis and synthesis of the results described in the previous section.

5.1.1 Publication venues, years and countries

As shown in Table 9, only around 17,71% of the selected papers were published in the top ten publication venues. The rest of the papers were published in a great variety of venues. One of the reasons for this issue is the heterogeneity and number of terms we have considered while performing the automated search. This great amount and variety of words implies a wide number of results, from venues focused on ubiquitous and pervasive computing, to others related to mobile and wireless communications. We detected a high number of venues related to ubiquitous and pervasive computing; context modelling, especially user modelling; smart environments and ambient intelligence; adaptive systems; and HCI in general. These topics are directly related to context-aware so it is obvious that many papers were published in this type of venues. There were also other venues that revolved around other topics not related to context-aware, but to software architectures. Evidently, the results depended on basically the words used for defining the search string and, as aforementioned, this search string included many terms associated to software architectures, context-aware and context dimensions (see Section 3.2.3).

As Fig. 3 illustrates, a clear evidence has been found regarding the growing interest of the research community in context-aware systems and their supporting architecture. It can be seen that, although this topic emerged many years ago (seminal papers were published in 1999), it has been since 2007, approximately, when the interest has increased significantly until nowadays. One of the main reasons for that interest on context-aware systems is the enormous benefit they provide and the wide availability of sensors at a reduced cost. Context-aware systems are usually implemented in smart environments where users interact through an interface transparent for them. This ubiquitous and transparent way of interaction is becoming a very attractive paradigm, especially when dealing with older or impaired people. Furthermore, there is an increasing attention on healthcare since the worldwide population is aging progressively, among other issues. In this way, context-aware systems have emerged as an appropriate solution for assisting, especially, older people in their daily life. This fact is confirmed as one of the main application domains for context-aware systems is healthcare (see Section 5.1.2).

It can be observed in Fig. 4 that Asian countries China and South Korea lead the ranking of countries more interested in context-aware systems, followed by Germany, Spain and Italy. However, as aforementioned, the advantages of context-aware systems are recognized worldwide so papers about this topic are published all over the world. In conclusion, observing the tendency, context-aware systems will remain one of the main research fields in future years, involving more and more countries worldwide and possibly more and more publication venues.

5.1.2 Research topics, applications domains and research types

The research topics most frequently used, as Fig. 5 depicts, are: *context inference*, *context management*, *context modelling* and *context gathering*. These results highlight that most of the selected papers focus on handling the context of use in some way, as well as on developing context-aware applications. This has positive implications. For example, most architectural proposals take care of context in some way, one of the main aims of this study.

Furthermore, we also aimed at identifying the most frequent application domains of context-aware systems (see Fig. 6) that were: *smart environment* and *healthcare*. The vast majority of these systems focus on building smart spaces to assist people in their daily life. In this line, we detected that many papers whose proposals were developed to assist people while they are at home, in a hospital or in a city, even one paper was found regarding smart kitchens. Next, healthcare is the second more important application domain for context-aware systems.

Fig. 16 depicts how many papers are dealing with the five most frequent topics (x axis) and the five most frequent application domains (y axis). When considering both aspects, research topics and application domains, we can notice that all the frequent topic related to smart environment are the most frequent one, followed by that related to healthcare. Context management is the main interest when dealing with applications for smart environments where there are usually a wide variety of sources of context information so that there is a clear need for solving conflicts among such sources. On the other hand, one of the main focus of the research has been related to context inference in applications for smart environment, healthcare and older people. This result is consistent as most of these applications exploit some kind of reasoning mechanisms to infer which kind of activity is carrying out the user using context information in order to provide him with the best assistance. Finally, it can be noticed that less attention has been paid to the definition of proposals for context-aware applications development, that is, on the description of whole frameworks for developing applications of these domains as most of the analysed papers emphasis on an specific aspect, such as context inference or context gathering.

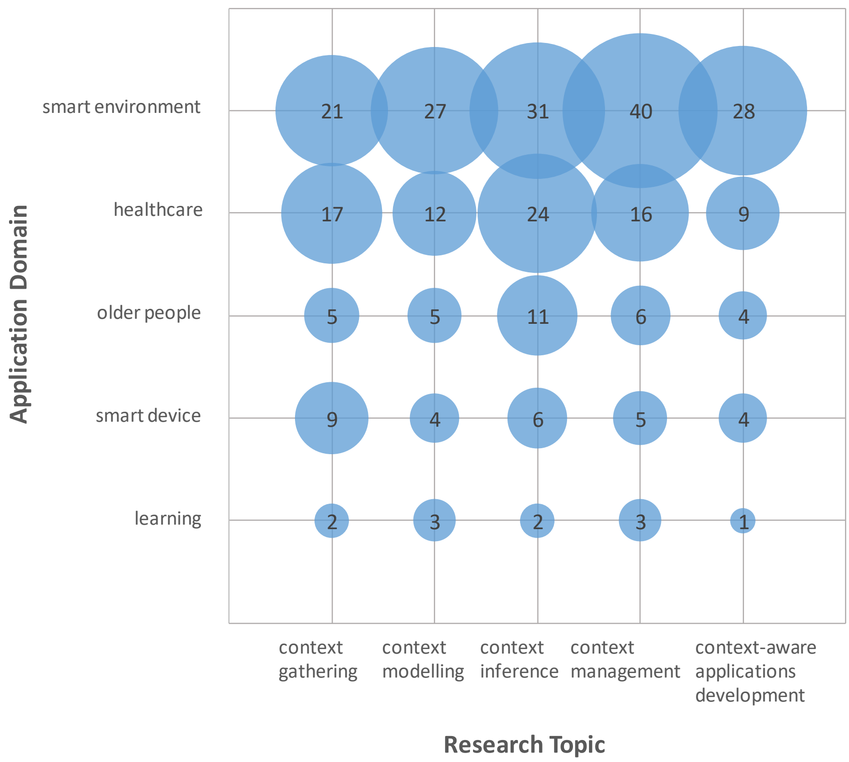

Fig. 16. Relationship between research topics and applications domains

Regarding the research types of the selected papers, they were classified according to Wieringa et al. [52] taxonomy (see Fig. 7). Most of the selected papers were categorized as *Solution proposals* (91,58%), followed by *Validation research* (25,48%), *Experience paper* (2,16%), *Evaluation research* (0,64%), *Philosophical paper* (0,21%) and *opinion paper* (0,21%). These results are quite disturbing as many selected papers were only solution proposals, without any type of validation or evaluation, neither formal nor informal. Only 25,48% of the selected papers offered some kind of laboratory validation which means that the context-aware systems were developed, but not deployed nor evaluated in a more real and industrial setting. P036 was the only one classified as Solution proposal and Evaluation research, since its proposal was developed and evaluated in a real and industrial scenario. First, the system was deployed in a hospital and it went into pilot use. Afterwards, a survey focusing on users' experience while using the system was handed out to the doctors, and over 40 responses were collected.

Thus, we have found that there are many proposals attending to develop context-aware systems for solving a concrete problem. However, we have detected a lack of maturity as many of these works are not validated at all. In this sense, future directions in context-aware computing should go on performing more evaluations on such systems in order to implement them in a real environment and provide additional feedback about the effectiveness, usefulness, etc. these systems can offer.

5.1.3 Context dimensions covered by software architecture concepts

As Fig. 17 illustrates, the three main dimensions of context (User, Platform and Environment) are covered by different software architecture concepts. With respect to other dimensions of context, such as historical data, user activity or interaction task, all the analysed architectural approaches cover some of them, except for the aspect-oriented architecture.

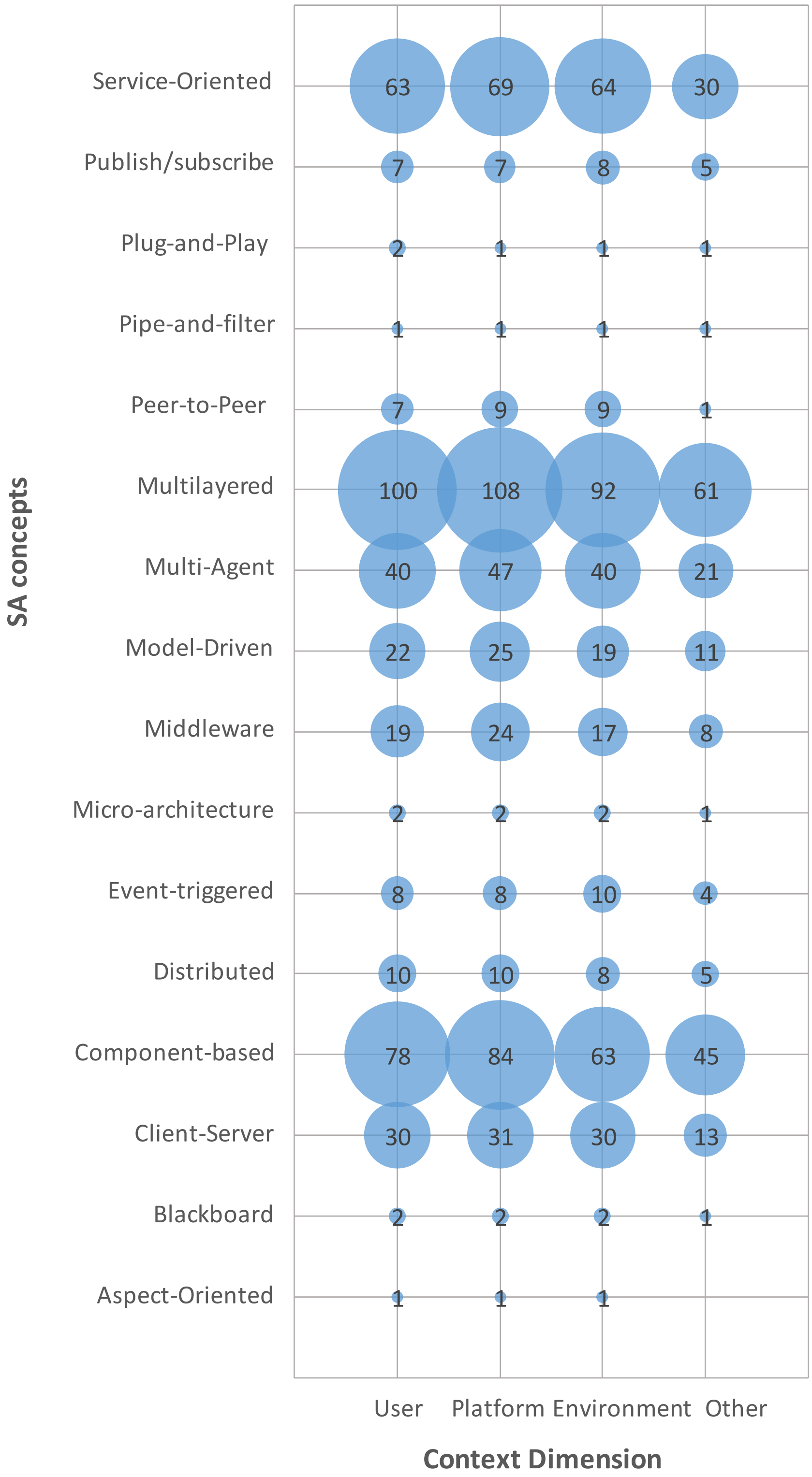

Fig. 17. Relationship between context dimensions and SA concepts

Therefore, it can be claimed that architectural concepts used for developing context-aware systems take into account the context of use in some way. Hence, context is not addressed as an isolated issue, but it is included as a key part of the software architecture. It has been observed that the main purpose was to reflect that some actions would be executed in the system, depending on the current context. Furthermore, it was also detected that most of the systems analysed react to context changes using rules defined following an Event-Condition-Action (ECA) format. Hence, systems perceive a context change by means of an event, then systems check whether the condition related to such event was satisfied in order to react using the corresponding action. For example, in a smart home scenario, an ECA rule could be defined so that, if the system detects that a person is falling down (event), and such subject is an old person (condition), an alarm call is made to the emergency centre, the caregivers and the family of the person (action). Usually, the necessary infrastructure to exploit the ECA approach, and the process to obtain valuable and high-level context information of data collected from different sensors (e.g. that the user is laying on the floor because of a falling) are usually considered during the design of the software architecture of the context-aware system. This is done by adding one or more architectural components that are specifically in charge of this treatment of the surrounding context.

Regarding the software architecture concepts used to develop context-aware systems, most of the proposals employ, as Fig. 17 depicts, *multi-layered* architectures, *component-based* architectures, *SOAs* and *MASs* since they appeared as the most suitable ones for context-aware systems. The main reason for the popularity of these software architecture concepts is their simplicity, ease of use, and that they provide useful and effective mechanisms to facilitate the adaptation of the system to context conditions. For instance, as seen in Section 4.1.4, many context-aware systems are focused on adapting the services offered to the user so that most of them employ a SOA approach since its main foundation is the support of services. Moreover, the less popular software architecture concepts are aspect-oriented, blackboard, distributed, micro-architecture, pipe-and-filter, and plug-and-play.

It is interesting to highlight that, generally, all these architectural approaches deal with all the dimensions of context, but with some particularities. In general, the platform dimension is the most widely dealt with for adapting the system, followed by the environment, the user and other dimensions. Even though the environment dimension was identified as the second one, there is no significant difference regarding the number of papers between this and the user dimension. Therefore, despite these little differences, we confirm that all context dimensions, including other ones, are more or less considered in a similar way by every software architecture concept.

In conclusion, most of the selected papers, independently of the architecture schema adopted, when they say they take into consideration the current context for adapting the system, such context is referred most of the time to the user, the platform and the environment, and least often to other dimensions of context.

5.1.4 What is adapted?

After analysing all the selected papers, we noticed that they were focused on adapting specific elements of the system so we looked for those elements that are adapted since we considered this information very useful and a cornerstone when designing and developing context-aware applications. As seen in Fig. 8, *services* are overwhelmingly the component of context-aware systems most frequently adapted, followed by the user interface, as well as the *content* of these UIs.

The main reason for this is that many of the context-aware systems analysed were designed following a service-oriented approach. It is interesting to highlight that they provide services as assorted as calendar, weather, location, time, news or traffic information ones. Moreover, since many selected works were focused on the healthcare domain, *alarm calls* appeared here too as a relevant element to be adapted in context-aware systems. An alarm call referred to any type of message delivered to caregivers, doctors or patient’s family when an emergency situation was detected. Patient was usually an old person and/or an impaired one who still wants to live alone, but needs to be monitored to prevent them from getting severe injuries.

It is not surprising that UI presentation and navigation are also commonly adapted, since content, presentation and navigation have been traditionally the three aspects considered for adaptive hypermedia, where adaptation has been a key topic for several decades. Some aspects adapted are related to the increasing ubiquity and intelligence of context-aware systems. For instance, recommendations (4,1%) are used in different domain, but it’s probably in e-commerce where they probe more useful nowadays. Because of ubiquity, adapting the way people makes an activity (4,97%) has gained also importance in context-aware systems so that these activities actually fit the current context of use.

From these results, we can claim that not many context-aware systems were interested in adapting or reconfiguring the software architecture (1,3%), its components (3,24%) or its configuration (5,18%), compared to other aspects adapted previously discussed. As mentioned before, there is no doubt that context-aware systems should pay attention to its architecture and the way it is designed. In this sense, they could take advantage of the support provided for architectural changes to offer adaptation to the context of use. Therefore, this significant gap in context-aware computing should be covered in future research, requiring more effort in order to align the adaptation at *architectural level* (changes in the configuration of architectural components) and at *HCI level* (changes in the interaction modality or the user interface).

5.1.5 RQ 1 – Software architecture concepts

RQ1 focuses on identifying which architectural concepts were used in existing context-aware systems in order to provide an overview of primary studies aiming at defining and/or exploiting those software architecture concepts. Fig. 9 summarizes the results that answer this research question. One of the problems faced to answer this RQ was that not all the selected papers describe clearly the architecture patterns applied. Sometimes, such software architecture concepts had to be identified from the context of the paper, while sometimes, there was no way to detect a well-defined architecture approach. In this last case, 55 papers, which represents 11,87% of the total of selected ones, did not describe a software architecture concept. Most of these papers were published in HCI and ubiquitous computing venues, and others were related to mobile networks and wireless communications, but not in venues related to Software Engineering or Software Architecture. These findings demonstrate our first intuition about the existing gap between HCI and SA. Most of the papers focused on context-aware adaptations, but do not consider the software architecture at all since they neglect partially or completely any possible change in the system architecture during the adaptation process.

As illustrated in Fig. 9, *multi-layered* architectures, *component-based* architectures, *SOAs* and *MASs* were the most widely used for context-aware systems. On the contrary, the software architecture concepts less popular were *plug-and-play*, *micro-architecture*, *blackboard*, *pipe-and-filter* and *aspect-oriented* architectures. It is worth noting that many works use at the same time several software architecture concepts for structuring their architectural elements. We found many different combinations, but there were three quite repeated (see Table 11), which involved the most popular ones: multi-layered architecture and MAS; multi-layered architecture and SOA; and, finally, multi-layered and component-based architecture.

Table 11. Top three combinations of software architecture concepts

Combination of software architecture concepts	*No. of selected papers*
Multi-layered architecture + MAS	12
Multi-layered architecture + SOA	10
Multi-layered + component-based architecture	10

It is worth noting that the application of multi-layered architectures was considerably extended in context-aware systems. The main benefit of using a multi-layered architecture here is the separation of concerns since it enables the creation of different layers, organized hierarchically, where each one is in charge of providing a different functionality of the context-aware system. In this sense, the most popular elements for representing this functionality in the different layers were agents (MAS), services (SOA) and components (component-based architecture), as observed in Table 11.

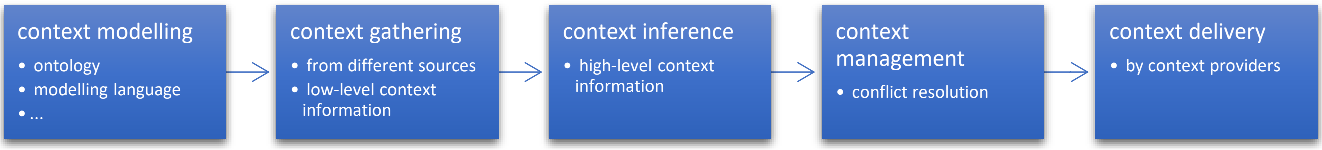

Fig. 18. Context treatment in context-aware systems

After analysing the selected papers, we found that some of these elements in the architecture of context-aware systems were commonly used to provide specific context-aware functionality. For example, we found elements for adapting the UI, namely for adapting the content information of the UI, and others for handling services associated to the context of use or any other relevant aspect of/for the system.

We found a common schema, illustrated in Fig. 18, for dealing with context in context-aware systems. Some of the steps that make up this process are often turned into components, services or agents in the software architecture responsible for such context handling. *Context modelling* is the first step and consists in stablishing what the representation of context information will be, e.g. by means of an ontology or a modelling language such as OWL or RDF. Second stage corresponds to *context gathering*, i.e. obtaining context data when required or subscribing to event notifications from multiple sources, usually demanded by services and applications (adapted from [38]). All these context data should be modelled as previously established at the first stage (adapted from [45]). Third, some context information cannot be obtained directly, but by processing low-level context information. This task is performed by the *context inference* part of the system, usually by applying some reasoning mechanism, as mentioned before. For example, to know whether a person is travelling and which means of transport he is using, a reasoning must be carried out using other context information, such as Wi-Fi access points or calendar information (adapted from [47]). Here, it is interesting to highlight that some context-aware systems present a single component/service/agent in charge of both context gathering and inference, usually called *context discovery*. Once the context inference is executed, and the system has all the necessary context information, then *context management* is performed for solving conflicts among contradictory sources of context information, processing the context information previously gathered (adapted from [8]). Finally, the last step is *context delivery*, i.e. when an event occurs and matches any rule previously specified, then some context information is provided to the application or service that requires it, or simply when such application or service requires it (adapted from [14]). It is worth noting that some of this context information can be stored in, e.g. a database, for future context requests. This information stored refers to the historical context of the system.

However, not all the selected papers supported all these stages of the context treatment process, so its software architecture normally reflected only those steps they were focused on. More details about the software architecture concepts and terms related to context treatment are provided in [42], respectively.

5.1.6 RQ 2 – Dimensions of context

This research question revolves around discovering how software architecture concepts proposed for context-aware systems considered the three main dimensions of context (User, Platform and Environment) to support adaptation. We have also included in our study the context dimension *other* since we noticed many authors exploit other information, e.g. historical context, user activity or interaction task. Fig. 10 presents an overview of the different dimensions of context considered in the selected papers. Most of them (90,2%) considered the Platform in some way, followed by the Environment (87,7%), the User (83,1%), and, finally, Other dimensions of context (44,9%). This confirms that the three main dimensions of context are more or less equally dealt with by context-aware systems. This is highly important, since the more dimensions and terms related to context are considered by the system, the more appropriate and correct the adaptations provided will be, because, although context-aware systems will become more complex, they will be able to react to much more events and changes in the surrounding context, avoiding that users refuse to use the system.

The majority of the selected papers lack a description of terms and dimensions of context, and neither presented nor described context concepts with enough clarity those context concepts by using, for instance, a table, a figure or just an enumeration. On the contrary, we notice that these context terms were hidden through the text and distributed all over the paper among the different sections. Another important finding is the heterogeneity of the different context terms. Every author uses his/her own words to refer to the different context terms and dimensions, thus hindering the classification of context dimensions. This led us to define a glossary with different context terms and synonyms that is presented in [42].

We only found some works that concisely presented and modelled such context dimensions. For example, P088 proposed a *Context Dimension Model* for defining at design time the possible contexts of use of a given domain of interest by using a hierarchical structure. This structure is made up of *context variables*, e.g. time, location, current company; and the set of *values* for such context variables, e.g. evening, Spain, with friends. Context variables values perceived at runtime by means of sensors trigger the activation of a given context. P288 also proposed a context model for categorizing context entities using agents, devices, environment, location and time. Location and time were kept separated from other concepts to emphasize the spatial and temporal aspects of the ubiquitous environment. Finally, P127 distinguished the variety of context elements along with how such context information was exploited to adapt the application in the form of a table. For instance, it specified that "when the *battery level* is extremely low, the application terminates in a graceful way to avoid data loss. Also, the interaction with the user is adapted to his/her *preferences*, e.g. vibration on/off".

As seen in Section 4.3.1, we discovered a great variety of terms used for characterizing the *user* of a context-aware system. Fig. 11 presented those results. The *profile* of the user represented the most frequent element that context-aware systems used for the adaptation, along with the *preferences* and information related to the *health state* or *physiological data*, especially the heart rate, which determined the current state of the user. We believe that user preferences have become a key element for adapting the system, since they explicitly exhibit the likings of the user regarding many aspects, e.g. the language, colour, type of content, interaction modality, etc. Therefore, if the system is able to adapt its behaviour depending on such preferences, the success of the adaptation process is almost ensured, i.e. there is a strong likeliness that the user will not reject the adaptation proposed, improving, thus, the quality of adaptation desired for every context-aware system. It is also evident that handling at runtime any information about users' health conditions is quite valuable since healthcare appeared as one of the most important issues worldwide, as previously mentioned.

On the other hand, as seen in Section 4.3.2, we also detected a high heterogeneity of the terms used in the selected papers for characterizing the *platform* of a context-aware system. Fig. 12 showed those results. Nevertheless, *devices* and *sensors* were in the first positions of the ranking of most used concepts. In context-ware systems, devices in general, and sensors in particular, are very important elements. Sensors are essential as they are in charge of monitoring at runtime many context information, from location (hardware sensors) to system logs (software sensors). Furthermore, almost all the selected papers consider them in the design of their architecture, which demonstrates their importance in context-aware systems. But also, other types of devices, such as smartphones, computers, monitors, etc., were considered for adaptation purposes. Many context-aware systems adapt their behaviour attending to network bandwidth or connectivity, screen size, available memory, battery level, or interaction modalities supported by the devices.

Section 4.3.3 presented many features for determining the *environment* of a context-aware system. Fig. 13 depicted those results. Some of the top terms were *location*, *time*, *temperature*, *light* or *noise*. But especially, the location of the user/entity in the interaction place with the 83,38% of appearance rate was the most used one. Many papers include in their architectural designs components exclusively used to locate elements in the environment, such as GPS or GSM. Furthermore, the majority of those works do not talk about context-aware systems, but only about purely location-aware systems.

To conclude, as mentioned in Section 4.3.4, we also wanted to determine if some proposals use other dimensions of context, different from User, Platform or Environment. We distinguished other three dimensions of context widely used by the context-aware research community: *Historical data*, *User activity* and *Interaction task*. Table 10 presented those results. Namely, the *interaction task* the user was doing with the system was used in 22,25% of the selected papers, the *user activity* the user was performing (e.g. walking, sleeping, shopping, cooking, etc.) in 16,41%, and *historical data* in 11,45%. Therefore, it is interesting to highlight that more than 40% of all selected papers also paid attention to other dimensions of context for adapting the system, making them more rigorous and providing a higher quality of adaptation than others which do not considered these other dimensions at all. Moreover, in addition to detect a broad consensus regarding the main context dimensions (User, Platform and Environment), we also detected such consensus when considering other dimensions of context. In this way, we were able to classify context data related to Historical data, User activity and Interaction task, but defining them previously in a more formal way (see Section 2.4 for more details).

5.1.7 RQ 3 – Evaluations of context-aware adaptations

This research question focuses on discovering to what extent the evaluation of context-aware adaptations in context-aware systems was covered in the literature. The results of this research question are presented in Fig. 14Fig. 15. Surprisingly, there were only 37 papers with some kind of proposal for assessing the adaptation, i.e. only the 7,99% of the selected papers. After a deep analysis, we classified them into the following categories for assessing the adaptation:

- *Design space evaluation*. To assess and compare adaptation levels of different applications based on unified criteria.
- *Usefulness evaluation.* A user-centred evaluation to verify the usefulness of the adaptations applied.
- *Visual validation*. To assess the adaptation by showing how it will change the system, usually by means of a Graphical User Interface (GUI) or wizard.
- *Satisfaction evaluation*. Evaluation of the adaptation by taking into account the satisfaction of the user, usually through a survey or questionnaire.
- *User feedback*. The user provides some simple feedback, for instance a rating, for the adaptation.
- *User-centred evaluation*. The adaptation was assessed throughout the development of the context-aware system starting from prototypes to the final application, as usually done in user-centred methodologies.
- *Survey*. A survey not intended for user satisfaction assessment, but intended for other adaptation quality factors (performance, etc.).
- *Automated evaluation*. Adaptation evaluation by using some automated parts. For instance, automating user behaviour simulation as in [P332].
- *Visual and formal validation with a GUI*. Adaptation evaluation by using inspection methods to check heuristics or formal validation rules supported by a GUI (for instance, consistency checks between adaptations).

As aforementioned, every software artefact, such as a user interface or a software architecture, should guarantee a certain degree of quality when delivered in order to prevent the rejection of the final user. Therefore, more concretely, context-aware adaptations should also ensure a certain degree of quality when they are applied to the system at runtime. In this sense, those proposals that apply context-aware adaptations should provide some mechanisms to evaluate them. Nonetheless, we have seen that almost none of the selected papers, except 37 works, considered such evaluation of the quality of adaptation. So, we have confirmed that the maturity of the proposals for adaptation is negligible. Hence, there is a huge gap here to be covered during next years by the research community in order to provide quality context-aware systems.

5.1.8 RQ 4 – Evaluations of software architecture concepts

This RQ was defined to find out what evaluations had been carried out until now to validate the software architecture concepts proposed for context-aware systems. Fig. 15 and Fig. 19 summarize the results to answer this RQ. We categorized the different software architecture concepts found in the selected papers, depending on the type of evaluation presented by using the taxonomy of Wohlin et al. [54]. We also added the category *Example* for papers that did not present a formal empirical strategy but provide some example about the proposal.

As Fig. 19 depicts, *multi-layered architecture*, *component-based architecture*, *SOA* and *MAS* were the software architecture concepts having a higher level of maturity. These four architectural concepts were overwhelmingly the most broadly evaluated in the literature. They all were validated by means of examples, surveys, case studies and experiments, but not in the same number. For the multi-layered architecture, examples were the most widely user form of evaluation, followed by case studies, experiments and surveys in the last position. For component-based architecture, the situation was very similar. SOA was evaluated most of the time by means of case studies, followed by examples, surveys and only four experiments. Finally, MAS presented the same results as multi-layered architecture, being example the evaluation strategy more applied, followed by case study, experiment and survey. For these four architectural concepts, there is a good maturity, since we found many papers that used them in their proposals, along with a well-defined validation. Moreover, almost all the experiments identified were done to assess those four software architecture concepts.

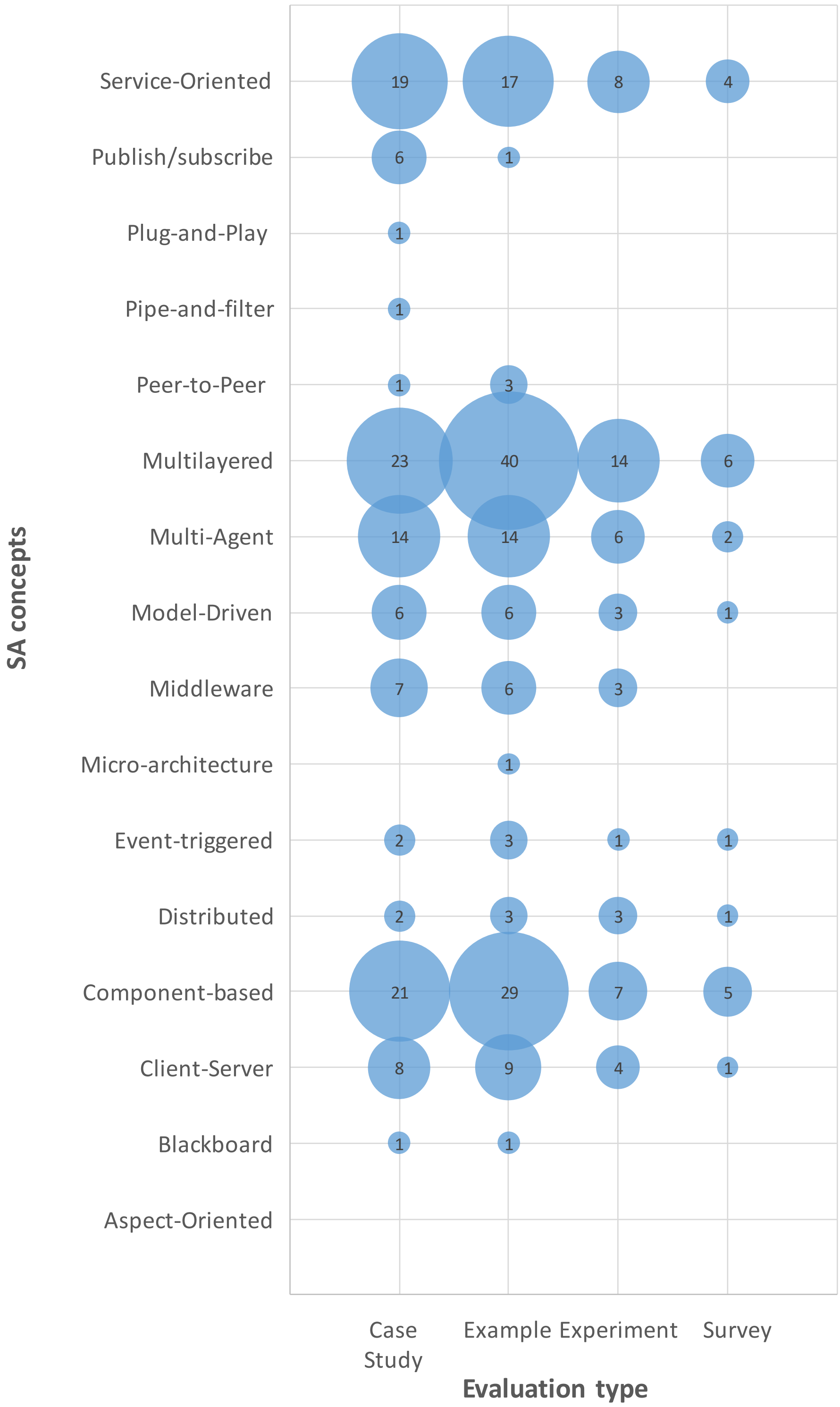

Fig. 19. Relationship between SA concepts and evaluation types

Moreover, Fig. 19 illustrates an important fact. For most of the software architecture concepts, there were four or less evaluations, namely for: distributed architecture, P002P, event-triggered architecture, blackboard architecture, micro-architecture, pipe-and-filter and plug-and-play. Aspect-oriented architecture has no evaluation. So, in these cases, we confirm that the maturity is marginal, because of the low number of evaluations and their type, less formal than for other approaches and without experiments at all.

Finally, we also discovered other software architecture concepts with a medium maturity level since they were not enough validated up to now, such as client-server architecture, MDA, middleware architecture and publish/subscribe architecture.

Fig. 15 presents another overview from the point of view of the evaluation type found in each selected paper. Most of the papers only presented an *Example* (29,15%), followed by *Case Study* (22,46%), *Experiment* (10,80%) and finally, *Survey* (4,3%). Thus, the 34,7% of the total of selected papers did not present any type of evaluation or example, neither formal nor informal, for assessing the SA concept proposed.

In conclusion, we have discovered another important gap related to the lack of maturity regarding software architecture concepts when used for developing context-aware systems. We encourage researchers and practitioners to perform more exhaustive and formal validations over these proposals, describing in more detail the participants involved, their number, etc. By doing so, the desired level of maturity will be reached.

5.1.9 Delimitation of context-aware systems from self-adaptive systems

One aspect in our findings that deserves attention is the delimitation of context-aware systems from self-adaptive systems, as the two areas have some overlaps. Context-aware systems are different from self-adaptive systems (and autonomic computing) in a number of respects. A self-adaptive system is a closed-loop system which is able to modify itself automatically at runtime in response to continuous changes of the system and its requirements [34]. Self-* or self-management properties such as self-configuration, self-healing, self-optimization and self-protection aim to reduce efforts to develop and deploy increasingly complex systems [31]. While a self-adaptive system may be able to function without any human intervention, guidance in the form of higher-level objectives is useful and realized in many systems [6]. In contrast to self-adaptive systems, research in context-aware systems is more concerned with how to model, process and manage the context information and less concerned with how a system adapts itself in response to changes in operational context and the adaptation in response to changes of requirements.

On the other hand, studies of context-aware systems and self-adaptive systems reveal common properties like the capability to adapt to changes in their environment [6,33,44]. While context-awareness is a foundational property of both fields, in self-adaptive systems, context-awareness means that the system is aware of its operational environment [31]. In self-adaptive systems, 'context' is more comprehensive and usually extends the set of information that can be used to characterize a situation of an entity. Especially human-centred design and development plays an important role in context-aware systems. Our study clearly indicates that context-aware systems research is predominantly concerned with context information stemming from users and their environment, resulting in systems and applications adapting user's context (e.g. location). The increasing interest in research of recommendation systems, adaptation of user interface or content adaptation emphasizes the differences to self-adaptive systems in general.

To gain an understanding of the differences (boundaries [31]), common features as well as synergies of context-aware systems and self-adaptive systems Hussein et al. [27] investigate context-aware adaptive systems, exemplified by a vehicle routing planning system. While the context information (e.g. vehicle speed) is modelled, processed and managed, to adapt the system to cope with context and requirement changes, the layered architecture also includes monitoring of system-context operational relationships, and a control loop to automatically adapt the system to unanticipated changes (e.g. if the system loses ability to acquire the traffic information).

5.2 Implications for Researchers and Practitioners

This mapping study has revealed that context-aware systems are a growing important research topic, both for HCI and Software Architecture fields. As can be seen in Fig. 3, the interest of the research community in context-aware systems and their architecture has been increasing since 1999 up to now, especially since 2007. We have found 17 relevant papers (as part of the QGS) that propose some kind of framework for context-aware systems (see Section 3.2.2). These important works have influenced others through the years since 1999 until the present day. They have provided a better understanding about context and context-awareness, as well as many advices and recommendations when dealing with context-aware systems in terms of context and user modelling, UI adaptation, and adaptive infrastructures.

This study has shown that there was a real need to analyse which research works highlighted the use of context and its relationship with the software architecture in existing context-aware systems. By doing so, we have provided an overview about the different approaches used in context-aware systems, attending to align the adaptation at both architectural and

HCI levels. In this sense, we have seen the effort invested in improving the use of context in context-aware systems and, especially, by means of their architecture. Moreover, we have also identified gaps existing up to now regarding the deficiencies and weaknesses of the systems when dealing with context and its different dimensions. Therefore, we have documented such effort and gaps by means of this mapping study so researchers and practitioners can make use of the 463 selected papers to improve their research and work. Namely, they can follow the guidelines proposed for modelling, retrieving and managing context and its different dimensions, as well as for knowing how to consider such context in the software architecture in order to provide a good adaptation experience to the final user. We have also offered a list of the most popular publication venues regarding context-aware systems, so researchers may use it for choosing an adequate venue to publish their work. As indicated below, there is a clear trend towards more diversity with regard to application domains and towards more advanced research topics. For practitioners searching for specific papers among our 463 selected papers for a particular problem, we recommend to first follow the requirements of the problem at hand in terms of required dimensions of context (i.e., the answers to RQ2.1-2.3) and if the resulting selection of studies is still too large, we recommend searching among those papers for similar application domains. Our study also indicates clear future trends for researchers coming both from the software architecture and HCI domains, explained in detail in the next section: While early years showed a lot of research on basic aspects of context-aware architectures, the trends are indicating a need for more specialized research into advanced topics and architectures, as well as more application-specific focus.

In this sense, as seen in Fig. 18, independently of the software architecture concepts used for structuring a context-aware system, we have found some important and common elements which should be included in such infrastructure for ensuring a correct context treatment within our system. These components are: *context modelling*, *context gathering*, *context inference*, *context management*, and *context delivery*. Thus, researchers should pay attention to these elements and describe their behaviours and mechanisms for adapting the system. Furthermore, the most advanced software architecture concepts for building context-aware systems are: *multi-layered architecture*, *component-based architecture*, *SOA* and *MAS*, and multiple combinations of them. Researchers have a guideline here too that will help them in the task of choosing the most convenient architectural patterns for developing their context-aware systems. As these architectures are more or less equivalent to the state-of-the-art distributed systems architectures in the years of our study, it seems obvious that context-aware systems researchers leverage state-of-the-art distributed systems architectures but do not require specific base-line architectures that are different to the main trends. Consistently in recent years, we see an ongoing trend towards cloud computing, IoT, microservices, etc. which will likely increase both in the distributed systems architectures in general and for context awareness.

With regard to the context of use, researchers here have an extensive analysis of many works which have evidenced the most common terms used for characterizing such context. In addition, we have presented the context dimensions these context terms belong to, such as *User*, *Platform* and *Environment*, as well as other dimensions quite recurrent used in context-aware systems, such as *Historical data*, *User activity* and *Interaction task*. Thus, researchers can take into account this information in order to model context in an appropriate way and to perform adaptations according to these context variables.

Another implication for researchers is the need of providing some quality during the adaptation process. We have detected that there are almost no proposals that focus on evaluating the adaptations applied. This generates strong negative consequences as users may reject the adaptations, and eventually reject the whole system. Hence, more effort should be made at this point by researchers interested in context-aware adaptations with a certain degree of quality.

Apart from evaluating the adaptation, there is still a need to make researchers aware of the task of validating the software architecture concepts they used when building context-aware systems. Especially, if they do not use the most mature ones, i.e. *multi-layered architecture*, *component-based architecture*, *SOA* and *MAS*, those validation becomes an indispensable need.

In addition to the above implications, there are other implications derived from this mapping study. For example, researchers and practitioners can pay attention to the application domains identified that make use of context-aware systems (see Section 4.1.3), or the elements most usually adapted by such systems (see Section 4.1.4). Therefore, we encourage both researchers and practitioners to follow the guidelines and the different tips presented here for building context-aware systems and adaptations with a more than acceptable degree of quality.

5.3 Trends

The results of this study indicate a growing interest in research of context-aware systems development, recommendation systems as well as content adaptation. As can be seen, for many sub-fields the four most recent years have more publications than have been published before; while basic topics like context management or service delivery, do rather shrink more advanced topics like decision support or context adaptation, as well as application-focused topics, are on the rise. We also notice that there is a continuous interest in various research topics like context inference and dynamic reconfiguration.

Regarding the application domain we see an ongoing trend in studies investigating mobile environments, context-aware systems research in the area of health-care and studies on smart homes. Smart environments in contrast became less interesting for researchers in recent years. The most interesting finding is a clear trend and growing interest in the domain of Internet-of-Things. Finally, we can also notice the rise of "Other" application domains, indicating the adoption of context-aware systems in various fields of applications and a broadening of the fields of studies in general - which is consistent with the trend towards more application-focused topics noted above.

According to the data, we can infer that an increasing number of studies include usefulness or satisfaction evaluation of context-aware adaptation. Although on a low level, in recent years 28 out of 163 papers published between 2013 and 2017 contributed empirical evidences. Another interesting finding is the shift from software architecture evaluation by surveys or by providing examples to more comprehensive experiments, while case studies remain a proven method to evaluate software architecture aspects of context-aware systems.

6 Validity Threats

This mapping study addresses these validity threats: internal, external, conclusion and construct. They are described in the following sections.

6.1 Internal Validity

Internal validity [50] refers to the use of statistical analysis in order to know how well the data supports the results of the mapping study. In our case, we have only applied basic statistical analysis in the form of bar charts, bubble plots and tag clouds, among others. Moreover, another limitation is related to the likely bias due to the fact that synthesizing the extracted data may be subjective. To mitigate this threat, we defined and revised a review protocol. Additionally, the completeness and performance of the automated search could be also another threat to the internal validity. For this aim, the quasi-sensitivity was calculated and, as shown in Section 3.2.5, the result was 82,4%, higher than the threshold recommended by Zhang et al. [56]. Therefore, we can state that the internal validity of the study is acceptable.

6.2 External Validity

External validity [50] refers to the strength of generalization claims of the study results. The results of this mapping study reflect the state of the art of software architectures for context-aware systems, involving both the HCI and Software Engineering research fields. We have identified 463 relevant papers under these research topics, after an exhaustive search process and after applying a well-defined selection criterion. Therefore, we believe that we have reached an acceptable external validity as our results can be enough generalized, always considering the selected period of time from 1999 to 2017.

6.3 Conclusion Validity

If other researchers replicate the mapping study, the same results would be obtained, that is *Conclusion validity* [50]. We have exhibited very clearly our selection criteria (see Section 3.1) for including or excluding papers in this mapping study. Therefore, we believe that the conclusions and results are valid, and they can be obtained again by using the same research questions. Furthermore, we have followed a systematic mapping study process, along with an exhaustive and well-defined search process based on the Quasi-Gold Standard (see Section 2). The data collection has been also explained in detail, showing all steps followed and the results obtained at every step (see Section 3). Finally, we have clearly described terms and their synonyms in [42].

6.4 Construct Validity

Construct validity [50] refers to the correct interpretation and measurement of the theoretical concepts. In our case, these theoretical concepts are software architecture, context-aware and context dimensions given that we wanted to identify the software architecture concepts used for the development of context-aware systems, and also which context dimensions were involved. We have spent quite a lot of time and effort in studying in detail each concept in order to prepare the most suitable search string for the automated search. We reviewed the literature to find the best words for each theoretical concept, and it was a very challenging task. We had to deal with works from two research fields really different: HCI and Software Architecture. With regard to the concept *software architecture*, we noticed that its name depended on the authors and of course on the research field. The architecture concepts identified ranged from a simple design with not many details to a more complex structure that detail clearly the architectural patterns and styles applied.

In this manner, we had to incorporate to our search string several terms for referring to the architecture of a system in order to cover as many relevant papers as possible.

Something similar happened with other theoretical concepts. For *context-aware* we found also many synonyms in the literature, since it is a popular and widely used concept nowadays, but with different interpretations. We encountered many words, such as adaptive, reactive, responsive and situated, used instead of context-aware, but they were too generic to use them in an isolated way. So that we had to accompany them with other words, like user interface, agent or application, to refine the search. Hence, we included in our search string the most frequently used terms for referring to context-aware.

Finally, regarding the *context dimensions*, we considered the three main ones, accepted by the research community: user, platform and environment. However, we also took into account other widely extended words for referring to context dimensions, such as human, device and task. By doing so, we covered the vast majority of context dimensions that we could find in the literature.

Therefore, we conclude that we have achieved construct validity as the final set of papers is complete thanks to the rigorousness while defining the search string (see Section 3.2.3). We have used not only the theoretical concepts for searching relevant papers, but also similar terms, which provides a high-level of confidence over the search process and its results. Moreover, we have performed the search process based on the Quasi-Gold Standard (see Section 3.2). In our case, we considered 17 papers, the most relevant and referenced ones regarding our research topic, for being part of the QGS. Finally, we verified our results from the automated search against this QGS, obtaining an acceptable quasi-sensitivity (see Section 3.2.5).

7 Conclusions

With this mapping study, we have achieved several goals. We have identified the different *software architecture concepts* proposed for designing and building context-aware systems with the aim of understanding the relationships between them. We have reviewed how *context-based adaptations* are taken into account in those software architecture concepts. Finally, we have also checked the *maturity* of both the existing methods for assessing the context-based adaptations, as well as the maturity of those software architecture concepts. To reach these objectives, we have answered some research questions with the aim of:

- Offering an overview to help researchers and practitioners to analyse which software architecture concepts are the most relevant and the most widely used in context-aware systems.
- Discovering how each dimension of context (User, Platform, Environment and others) is addressed and taken into account within the different architectural proposals to carry out the adaptations based on these dimensions of context.
- Discovering to what extent the evaluation of context-aware adaptations in context-aware systems is covered in the literature.
- Finding out what evaluations have been carried out until now to validate the software architecture concepts proposed for context-aware systems.

This mapping study has shown that there was a real need to analyse which research works highlighted the use of context and its relationship with the software architecture in existing context-aware systems. So, we have provided an overview about the different approaches used in context-aware systems, attending to align the adaptation at both architectural and HCI levels. We have found out the effort invested in improving the use of context in context-aware systems and, especially, within their architecture. Moreover, we have also identified the gaps encountered up to now regarding the deficiencies and weaknesses of systems when dealing with context and its different dimensions. In this sense, it is important to highlight that we have not detected a standard approach for architecting this type of systems. Different commonly used architectural styles are used but without providing guidance about which one should be used and when according to the characteristics of the system to be developed. This gap is highlighted because most of the existing proposals are not published in venues related to software architecture but to pervasive computing and HCI. Therefore, a clear gap exists that the software architecture community should deal with to provide this field with the expected maturity. This need of maturity is also emphasised for the lack of papers that present empirical evaluations that is also an important niche of research for the coming years.

Finally, researchers and practitioners can make use of the results of this mapping study to improve their research and work. They can follow the guidelines proposed for dealing with context and its different dimensions, as well as for knowing how to consider such context for the design of the software architecture. By doing so, they will provide a good adaptation experience to the final user and they will develop context-aware systems and adaptations with higher degree of quality of adaptation. Further studies could be conducted to complement this mapping with insight about the particularities of the process to design context-aware systems [51], which guide the development of such system.

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Appendix A. Selected Papers

The 463 selected papers included in this mapping study are listed below (ordered by author). Notice that the papers included in the QGS (see Section 3.2.2) are in bold, e.g. **[P002]**.

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