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Apports de la Notion de Contexte à Différents Systèmes

(*Context across the systems*)

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Context across the systems

Abstract

This document brings together several researches works carried out between 2002 and 2020, discussed in the habilitation entitled "*Apports de la Notion de Contexte à Différents Systèmes*". It synthetizes then the original document, written in French, presenting the problem statements tackled in the original document and summarizing the proposals that have been made, which are presented in more details thanks to the papers joined in annex. Thus, different contributions, crossing several Computer Science communities (CSCW, Ubiquitous Computing and Information Systems), are discussed here. All these contributions share a common guideline, the notion of context, which is applied all along these contributions on different kinds of system (notably Groupware Systems and Information Systems). All these contributions lead to a common perspective, a new generation of Information Systems called here Pervasive Information System, in which the notion of context plays a key role for adaptation purposes. Elements presented in this document intend then to synthetize all the different contributions leading to this vision.

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I Introduction

This document synthesizes an important part of my research work, which can be characterized by the application of the notion of context into different kinds of systems (Groupware systems, middleware systems or Information Systems). This research is the result of a career started in 2006, date of my PhD thesis defense, and that continues until today (2020), at the University Paris 1 Panthéon Sorbonne.

All along my career, I had the opportunity and the privilege to join several research teams, working in different areas of Computer Science. First of all, between October 2002 and September 2006, I prepared my PhD thesis at the University Joseph Fourier - Grenoble I, within the SIGMA team, a recognized team in the field of Information Systems, whose "multimedia" axis (currently known as STEAMER team) was specialized on the adaptation of Web-based systems. Within the "multimedia" axis, I could carry out my research on the adaptation of Groupware systems, and more particularly, on the adaptation of group awareness information, whose support is an outstanding characteristic of this kind of software application. It was during my PhD thesis that I have started working with the notion of context, notably through the proposal of a context model that considers both physical and organizational aspects.

After my PhD thesis, I could continue my research in the CSCW (Computer Supported Cooperative Work) community, from which come the notions of groupware and group awareness, by integrating the ECOO team (now COAST team) at LORIA in Nancy, during a one-year position (ATER from 2006 until 2007) at the IUT Nancy Charlemagne of the University Nancy 2.

On September 2007, I had the opportunity to join the prestigious K.U.Leuven for a postdoctoral position within the DistriNet laboratory, as part of the European project IST-MUSIC. During this period (2007-2008), I was confronted with a new environment, and a new team working on Distributed Systems. Working in the community of Ubiquitous Computing, I had to learn new concepts for me, such as peer-to-peer networks and the notion of service, in order to better adapt myself to this new environment and thus bring a real added value to my team and to the IST-MUSIC project.

Starting on September 2008, I joined the “Centre de Recherche en Informatique” of the University Paris 1 Panthéon Sorbonne, as Associate Professor. Once again, I had to adapt myself to a new team, particularly renowned on Information System, and notably for its skills in Requirements Engineering as well as in Service Engineering. In this new environment, I had to learn in new concepts for me, such as the notion of intention, which I have integrated to my own research, while bringing to the team my skills concerning the notion of context.

All along these years, I have the opportunity to integrate several teams belonging to different communities on Computer Science, by incorporating concepts from these communities into my research and by bringing my own contributions in return. The notion of context appears thus as a guiding thread for my research, since this notion has been applied in all the communities I have crossed during my career (CSCW, Ubiquitous Computing, Information Systems). Like a backbone, the notion of context has been applied in these different communities, with contributions for each one.

All these experiences and contributions converge today on the evolution of the Information Systems (IS), in what we call here Pervasive Information Systems (PIS). Indeed, the introduction of new technologies and trends in IS leads inevitably to their evolution towards a new generation of Information Systems, the Pervasive Information Systems. These new technologies primarily impact the infrastructures used by these systems, but their influence is not limited to this purely technical level. All levels of an Information System can be impacted. In a schematic vision, we may consider that these new technologies and the opportunities they bring are likely to influence not only the infrastructures, but also the services offered, the applications and business processes, and even the management of these systems (see Figure 1).

New technologies, such as IoT, Cloud and Fog Computing, are bringing more dynamism to Information Systems, and are enabling more flexible IT systems that are better able to adapt themselves to changes on their environment. The notion of context may contribute to achieve this flexibility, which has become necessary in order to take better account of the dynamic environment in which Information Systems are gradually moving towards. Context information can thus be captured and fed back up, level by level, like events, and contribute to the adaptation of each level and of the system as a whole.

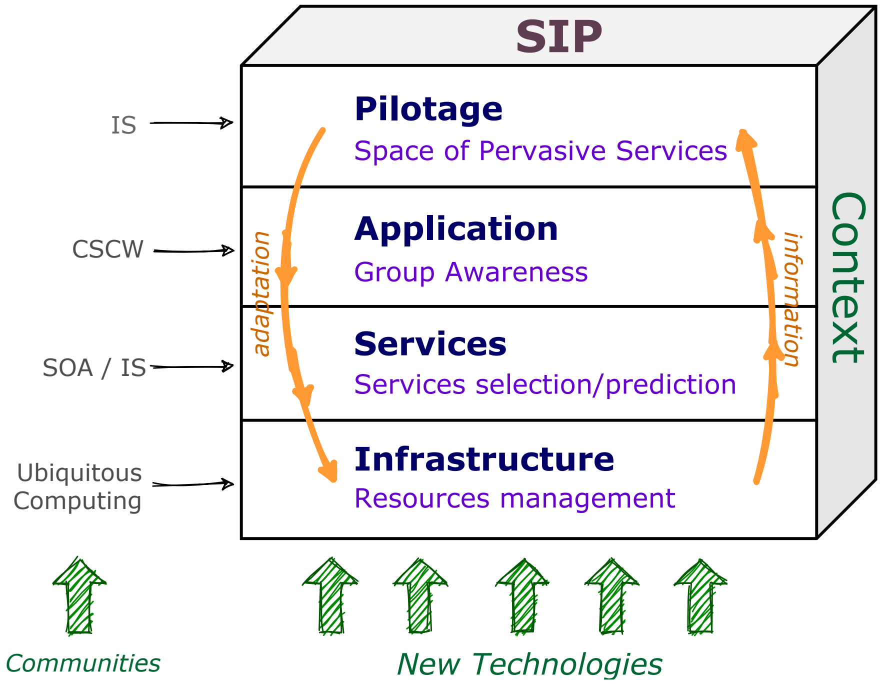

Figure 1. Contributions proposed in this document organized in a schematic view of a Pervasive Information System.

Over the years, the contributions I have made into these various communities find a direct application in this vision, illustrated in Figure 1. Each contribution presented in this document (noted in purple in Figure 1) is applicable to a different level of these systems. In each contribution, the notion of context appears as the key element allowing adaptation at a given level.

All the contributions presented in this document thus converges towards this new generation of IS. These contributions are presented thereafter, not in chronological order, but rather in a logical order (represented in Figure 2), organized according to the community in which these contributions were originally proposed. Besides, since the notion of context represents the common thread of this work, it is important to establish a common understanding of this concept and its characteristics. We therefore begin this document with a state of the art concerning the notion of context and its engineering. This "roadmap", originally proposed on [82], synthesizes my experience and my vision concerning the notion of context and its application (what we mean here by its engineering). This effort of popularization, initially intended for teaching, establishes the necessary bases for the understanding of this concept through a set of dimensions considered as necessary for its engineering. These dimensions find then their application in the various contributions presented in this document.

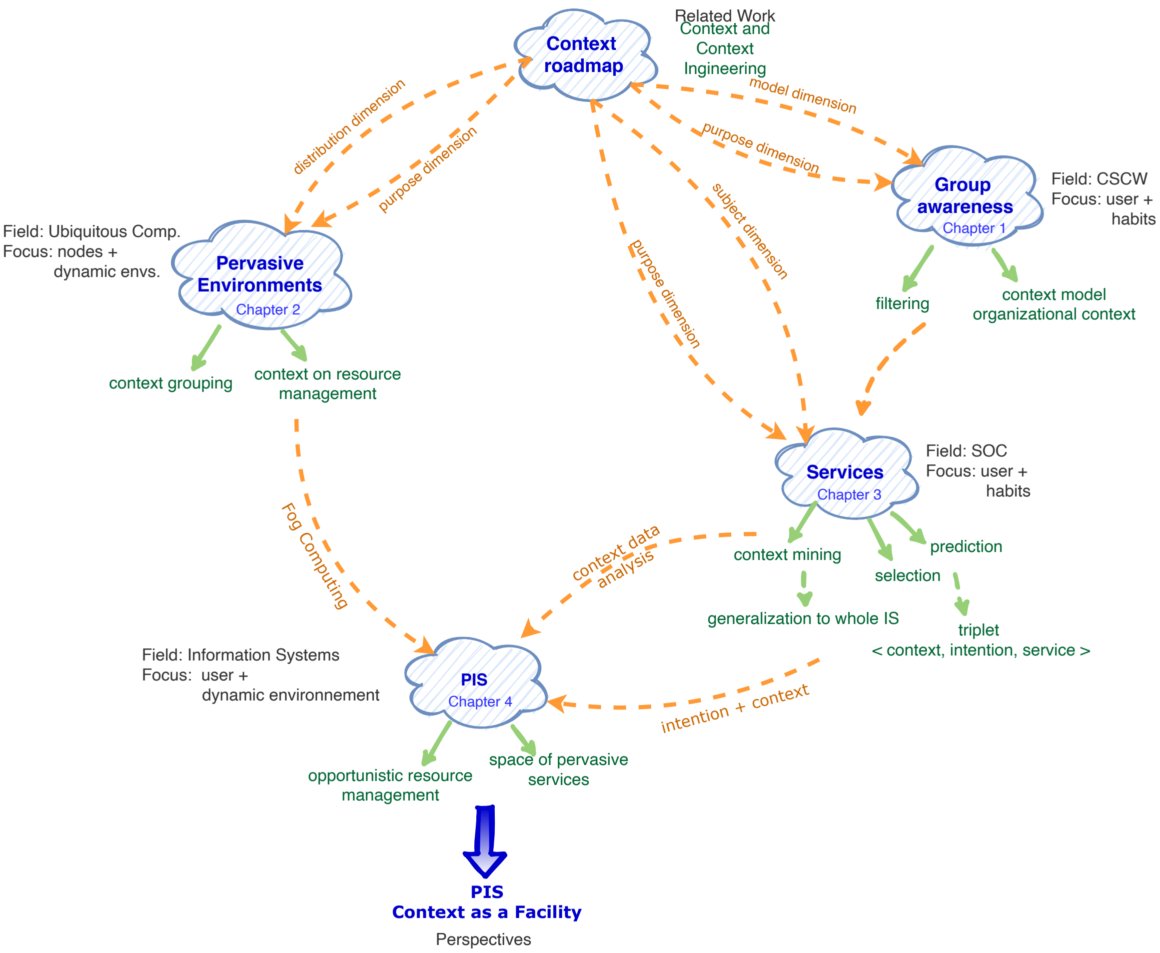

Figure 2. Cartography of the proposed contributions and their evolution.

The first of these contributions (Chapter 1) applies to the CSCW community. It concerns the work carried out mainly during my PhD thesis (2002-2006). This work aimed at adapting group awareness information, focusing particularly on end-users, organized in teams. This research raises the question of work practices and habits, proposing two major contributions: a context model including organizational aspects; and a filtering mechanism for group awareness information based on profiles representing users' habits.

These contributions, or rather their influence, can be found in my research work on the SOC (Service Oriented Computing) community. This work (chapter 3), carried out between 2008 and 2014, maintain this focus resolutely turned towards end-users and their work practices through three contributions on the selection and on the prediction of services, as well as a contribution on the analysis of contextual data, which we call here "*context mining*". This latter considers a major issue highlighted by the roadmap, the relevance of context information for a user, and *a fortiori*, for an application. This work also tackles the challenge of generalizing the context support to a whole Information System. Moreover, our researches on the selection and prediction of services introduces the triplet "*< intention, context, service >*" according to which a service is proposed in order to satisfy user's intentions in a certain context of use.

These contributions explored different dimensions present in the roadmap, including the "*model*" and "*subject*" dimensions. These contributions have been completed by more technical works, anchored in the Ubiquitous Computing community. These researches (chapter 2), carried out between 2008 and 2016, explore another dimension highlighted by the roadmap, the *distribution* of context data. They consider particularly the dynamic nature of pervasive environments. The focus is no longer on the user (at least not directly), but on the environment itself, which becomes more and more dynamic, and on the nodes that compose this environment. These contributions use context information for promoting a better use of the resources in such dynamic environment. They also introduce in my work a new community, the Fog Computing community, and the possibility of using proximity resources to perform various tasks as advocated by this community.

All of these contributions converge on the evolution of Information Systems towards Pervasive Information Systems (PIS). This new generation of systems is the subject of my latest research, carried out from 2016 onwards and presented in chapter 4. This research, anchored in the Information System community, no longer focuses only on user or only on the environment, but on both, together, notably through the definition of a conceptual framework for Pervasive Information Systems, called Space of Pervasive Services, as well as on the study of an opportunistic resource management adapted to this new generation of Information Systems.

Figure 2 proposes a cartography illustrating all these contributions and their reciprocal influences. The contributions illustrated in Figure 2 represent the most significant contributions of my career, those in which I have had a more significant impact on the community considered by the contribution. This work carried out in several different teams and communities, which illustrates my vision of what a research work in Computer Science should be: a collaborative work, of collective construction, built through the contribution of each one to the resolution of different research problems. When integrating each community, I had to assimilate several concepts and practices in order to understand the issues handled by each community and then bring my own added value back to the community. As this work were therefore carried out within different teams, the rest of this document is voluntarily written in the first-person plural (“we”), in order to underline what is perhaps the major characteristic of a Pervasive Information System, its pluridisciplinarity.

This document is thus organized as follows: we start with a state of the art on the notion of context (Part II), before introducing the contributions. Part III details the contributions. Chapter 1 introduces my contributions in groupware systems; Chapter 2 presents the contributions made around pervasive systems; while Chapter 3 presents my contributions in service-oriented systems. Finally, chapter 4 introduces my research around Pervasive Information Systems, before concluding (Part IV) with my perspectives and future works.

II State of art

The notion of context can be defined as any piece of information that characterizes the situation of an entity, whatever this entity could be a person, a place or another object (user, application, etc.), considered relevant for the interaction between the user and the application [37]. This notion has accompanied my research since my PhD thesis work. It has been applied to different research problems, and to various communities in Computer Science. It is important to understand this notion and its characteristics before being able to discuss the contributions I had proposed using it. Thus, this chapter presents a state of the art on the notion of context. Derived from [82], this state of the art synthesizes my experience and my perception of the notion of context and its engineering. Intended first of all for the popularization of the notion of context and its engineering among computer science students, this state of the art is presented in the form of a roadmap, presenting the different dimensions necessary to take into account this notion in software.

1 Context Roadmap

The notion of context is becoming more and more used today within applications that could be called “intelligent” (or “smart”), because they are able to observe the environment and to react accordingly. This phenomenon can already be observed with a growing number of applications capable of observing elements of the environment, such as the user’s location, her/his physical activity, etc. The observation of the environment is now possible thanks to different types of sensors and technologies. The development of sensors, actuators, nanocomputers and other low-cost technologies related to the Internet of Things (IoT) allows developers to easily propose applications that observe and interact with the physical environment. This kind of application is already part of our daily life but, in most cases, its development is still performed in an ad hoc manner, despite all the research that has been done on the notion of context and on context-aware applications (applications capable of adapting their behavior to the changes observed on its context of use [6,7]). Today, the main challenge no longer lies in the technologies themselves, but mainly in understanding the challenges and the issues that may raise when exploring this notion and all the possibilities offered by these new technologies. Indeed, in order to go further in the use of technology, it is necessary to better understand the notion of context and its issues, since this notion is central to the design and to the implementation of such new “smart” solutions.

Context-aware systems can be seen as applications capable of responding to these challenges. They are defined as applications capable of observing changes in their execution context and of adapting their behavior accordingly [6,7]. Compared to traditional applications, context-aware applications can be considered more complex because they have to cope with heterogeneous and dynamic environments. They must operate, often continuously, under changing conditions. They need to observe different elements located in their environment and to react to their changes, often using limited computing resources (*e.g*. nanocomputers or smartphones with battery and connectivity constraints). Such a dynamic and constrained execution environment has a significant impact on the architecture and on the development of such software applications, particularly in terms of modularity, integration, interoperability and a growing number of non-functional constraints (e.g. robustness and scalability). Under these conditions, the qualities traditionally expected from software applications, such as flexibility, modularity and extensibility, become more difficult to meet, especially with ad hoc development processes, which are often adopted when developing context-aware applications, as observed in [7, 8].

One aspect in particular makes the development of these applications more complex than "traditional" applications: the notion of context itself. This notion corresponds to a broad and ambiguous concept that has been studied and defined in several different ways, both in Computer Science and in other science fields [12,17,18,108]. Supporting this notion in a computer application raises several challenges ranging from the identification of relevant context information, its acquisition and modeling, to its interpretation and exploitation for different purposes [6,12,84,85]. It becomes quickly arduous for non-expert designers to design and to build new applications using this notion.

Understanding the notion of context and its support is a complex but necessary task. It is complex because the notion of context is itself a complex and ambiguous notion, whose integration within an application involves several technical issues. It is necessary because it is only by understanding this notion and the ways in which it can be integrated into an application that one can truly explore its full potential and all the opportunities it opens up. Only a better understanding of this notion will allow the establishment of a true context engineering process, allowing the development of new complex and extensible context-aware applications. More than ever, it becomes necessary to educate and to prepare a new generation of designers and developers capable of reasoning around context elements in the same way they are trained to handle concepts such as components and object-oriented programming.

It is therefore important to provide these young, non-expert designers with the necessary knowledge to reason about the challenges and issues related to context management and support. Through a literature review, we were able to identify a set of dimensions that can be considered as necessary for such support [84], and we could analyze the impact of the quality of context information on these dimensions [85]. These dimensions have been seen as guidelines in a requirement analysis process, helping non-expert designers to identify the possible issues around the support of the notion of context in context-aware applications. This review, detailed on [82], highlighted existing solutions and open questions related to context support and management. This study is intended to serve as a basis for the training of new "context engineers", capable of understanding and building new context-aware applications, especially for tomorrow's Information Systems.

Besides, this state of the art also considers the study of three application scenarios that illustrate possible uses cases that can take profit of context information, as well as the challenges for their implementation. These scenarios were used as examples to illustrate different issues raised by each dimension of the roadmap. Also, a study, carried out with a group of 50 master degree students, is discussed on [82]. The objective of this study is to better understand the perception that these young developers have of the notion of context. The roadmap and each of its dimensions are thus discussed, both in its functional aspects, but also in the consideration of qualitative aspects, which are particularly relevant when considering context information. The roadmap thus raises many questions that must be taken into consideration when designing context-aware applications. Several clues and elements of answer that are highlighted by the literature review were also discussed for each dimension.

The proposed roadmap was fully detailed in the journal paper indicated below [82]. It is presented in the Annex I.

- Kirsch-Pinheiro, M. & Souveyet, C. "Supporting context on software applications: a survey on context engineering" (« Le support applicatif à la notion de contexte : revue de la littérature en ingénierie de contexte »), *Modélisation et utilisation du contexte*, 2(1), **2018**, ISTE OpenScience. Available: https://www.openscience.fr/Le-support-applicatif-a-la-notion-de-contexte-revue-de-la-litterature-en/ (Last visit: Oct. 2020).

2 State of art: Final considerations

The notion of context has been widely explored in various ways through different applications. This use is likely to progress in the near future, notably thanks to the democratization of the IoT and its technologies, which allow easy observation of the physical environment using inexpensive devices. Nevertheless, the notion of context remains an obscure and ambiguous concept. The question of which information can be considered as part of context and which information is not, illustrates quite well this issue. Information such as the available memory, the battery level or the role of the user in an organization can be considered as a context element by some application [50, 127, 140], or as simple parameters by others [65, 142]. Some authors, including [26], have tried to distinguish between context data and application data. For these authors, context data correspond to a set of parameters, which are external to the application and which influence the behavior of the application. Despite efforts to clarify this distinction, the boundaries remain often blurred, as does the notion of context itself, which is often misunderstood by many young software designers.

This same ambiguity is also visible between context-aware applications and the so-called “self-adaptive” applications. The smart agriculture and GridStix scenarios proposed in the roadmap [82] illustrate these ambiguities. Both use context information to adapt their behavior, but the authors of the latter consider it as a self-adaptive application [142]. According to Khan [75], the concepts of context-awareness and self-adaptation are often confusing because self-adaptive applications use to adapt their behavior in response to stimuli from context information. It is therefore difficult to make a clear distinction between these two concepts. Both can be seen as adaptive systems which, according to Colman *et al.* [30], aim at achieving a certain goal by defining a form of loop in which the environment and/or system itself is monitored, the information collected is analyzed, a decision is made about necessary changes, and these changes are then implemented by the system. For these authors, "self-awareness" means that changes can often be processed automatically compared to conventional systems that require offline redesign, implementation or redeployment. This is also true for context-aware systems, since they adapt their own behavior, without human intervention, according to the changes observed in the context information. Although some authors have tried to make some distinction between these concepts [30,75], the most important question is not really these potential differences (if they really exist), but the support of context information in these systems. These two particularly complex concepts are based on context information, a very dynamic, heterogeneous and, moreover, uncertain kind of information. Context management thus raises several challenges that must be taken into consideration when developing a system that observes this notion.

Thus, the main question is how to manage and to exploit context information in a given system? As Coutaz *et al.* [32] pointed out, it is commonly accepted that context information concerns the evolution of a structured and shared information space, and that this space is designed to serve a particular purpose. Whatever information is considered as context depends profoundly on the system in question and on its objectives. Whatever this information is, it needs to be managed appropriately in order to realize its full potential. This requires an understanding on the challenges involved in using this notion and on its main characteristics, such as its heterogeneity, dynamism and uncertainty.

The main objective of the roadmap discussed in [82] is precisely to contribute to this understanding. This is particularly necessary in this document, since all along my career I have applied the notion of context into different systems, which often implied considering some of the issues highlighted by this roadmap. Without this understanding of the notion of context and its support, it is difficult to fully understand the research issues raised by each of the contributions presented in this document.

III Contributions

1 Context on Groupware Systems

1.1 Problem statement

This chapter presents the contributions resulting directly from my PhD thesis work (2002-2006) on the adaptation of group awareness information in groupware systems, especially those supporting a mobile use. The notion of group awareness designates a set of information through which the members of a group, while engaged in their individual activities, capture what other participants do (or do not) and may then adjust their own activities accordingly [55, 144]. Group awareness information can be defined as the knowledge a user has about the group, her/his colleagues and their activities, which provides a context for her/his own individual activities. This context is used to ensure that individual contributions are relevant to the group as a whole, and to evaluate individual actions in relation to the group's goals and progress [40]. This notion is indispensable for groupware systems, in which it heavily contributes to the team coordination in this kind of software exclusively dedicated to teamwork.

Group awareness information plays a very important role in coordinating team's activities notably when considering teams working in an asynchronous mode or in geographically remote way. Unfortunately, the sad reality of 2020 has put back in the spotlight this kind of software and the need for coordination on teams working in a distributed manner. Many employees who had to work at distant because of the pandemic situation (during lockdown and even afterwards) felt that they have lost contact with their colleagues and the activities performed by these colleagues during this period. The lack of adequate support for group awareness information was then cruelly felt.

Even before pandemic crisis, the need for an adequate group awareness information was already underlined by the literature, particularly when considering distributed and mobile teams. Indeed, as new technologies have freed up teams, working in mobile situations has become a reality, the adage "*anytime, anywhere*" being now applied to our daily professional life. Nevertheless, the risk of losing contact with other team members has also intensified with this new mobility, increasing the importance of adequate group awareness support.

When correctly observed, group awareness information can be abundant and the risk of cognitive overload becomes real: if the complete set of available group awareness information is proposed to the user, she/he risks being "overloaded" by all this information, preventing her/him from assimilating the relevant information. According to Bouthier [15], on the one hand, the information exchanged and presented can be very abundant, especially when the group is composed by a large number of active members or when many artifacts are manipulated. On the other hand, the user's mental resources, such as memory and attention, are limited. Yet, the user must interpret and integrate this information in order to coordinate her/his own actions on the group. The cognitive overload occurs when the user is faced with too much information to process. The user then experiences a stressful situation that can lead him or her to reject all of the proposed information. This stress can cause difficulties for a group member, which can lead to disruptions in the user's performance and on the information flow that may penalize the group as a whole.

The user in a situation of mobility is potentially confronted to a constrained environment (e.g. terminals with limited capacities, limited connectivity, inadequate environment, noisy, etc.), which improves the risk of cognitive overload. It is therefore imperative to adapt as much as possible group awareness information in order to reduce the risk of cognitive overload. In other words, the user must not spend more time becoming aware of what is happening in her/his team than she/he does performing the tasks assigned to her/him.

Hence, it is necessary to reduce the total volume of information presented to the user, in order to proposed her/him only the most relevant one, offering her/him the “right information” at the “right moment”. As this user is mobile and potentially equipped with a terminal with restricted capacities, it becomes important to consider the context in which this user is accessing group awareness information. Group awareness information should then be adapted to the user’s context, but also to the user’s particular interests regarding this kind of information. Indeed, the relevance of group awareness information may vary, for the same user, depending on the context in which he or she accesses the information. Users in groupware system tend to develop some work habits and practices, forming a kind of routine (e.g. consulting their messages in certain places or from certain devices, using certain terminals in particular for the performance of certain tasks, etc.). This routine may have an influence on the user’s preferences concerning the group awareness information.

Two sub-problems then arise from the issue of adapting group awareness information to the user's context: firstly, the question of the relevance of group awareness information, and secondly, the question of the representation of the notion of context within a groupware system. On the one hand, there is the question of the expression of the user's preferences and the adaptation process itself, which should take these variable preferences into account. On the other hand, a groupware being a collaborative application, it is important to consider the user not only as an individual, but also as a team member. The notion of physical context, commonly considered at this time (2002-2006) by context-aware applications, proved to be too narrow for a groupware system. It was necessary to enlarge the concepts considered by the notion of context and its support thanks to an appropriate model that takes into account also collaborative aspects of groupware systems.

To sum up, two main issues were tackled by this research work: the adaptation of group awareness information through a context-aware filtering mechanism, as well as an object-oriented context model that takes into account the physical and organizational aspects that characterize users on a groupware system. The proposed filtering mechanism filters group awareness information based on a set of user’s profiles representing her/his preferences for this kind of information in a given context. Each profile is then associated with a context description representing a situation in which these preferences are valid. Such description uses a context model, which includes both information about the user’s physical environment and about her/his organizational environment. Such “organizational context” allows considering the user not only individually, but also as part of a group (or an organization), which is particularly important for groupware systems. During the filtering process, the context description associated with the user’s profiles and the current user’s context are compared using similarity measures, defined based on the proposed context model, taking profit of the class and associations defined in this object-oriented model.

The proposed context model was originally introduced in [89]. This paper is reproduced in the Annex II.

- **CRIWG 2004** [89] **:** M. Kirsch-Pinheiro, Jérôme Gensel, Hervé Martin, “Representing Context for an Adaptative Awareness Mechanism”. In: Gert-Jan de Vreede, Luis A. Guerrero, Gabriela Marín Raventós (eds.), 10th International Workshop Groupware: Design, Implementation and Use, **CRIWG 2004**, LNCS 3198, 339-348 (**2004**)

1.2 Bibliometrics

This research on groupware systems has produced several publications, mainly between 2003 and 2008, including a PhD thesis in 2006. Out of a total of 17 publications, 11 of which were published during the thesis (2002-2006), and the remaining ones after 2006. Nine of those, listed below, can be highlighted by the number of citations or by their content. These publications have been analyzed, using scholar.google.com and www.researchgate.net in relation to their number of citations, as an indicator of their impact. These citations were ranked according to their publication date in three periods: before 2008, between 2008 and 2013, and after 2013. Self-citations have also been accounted for. Table 1 details the data obtained, illustrated in Figure 3.

- **COMIND 2003** [78]**:** M. Kirsch-Pinheiro, José Valdeni de Lima, Marcos R. S. Borges, "A framework for awareness support in groupware systems". **Computers in Industry**, 52(1): 47-57 (**2003**)
- **CRIWG 2004** [89]**:** M. Kirsch-Pinheiro, Jérôme Gensel, Hervé Martin, "Representing Context for an Adaptative Awareness Mechanism". In: Gert-Jan de Vreede, Luis A. Guerrero, Gabriela Marín Raventós (eds.), 10th International Workshop Groupware: Design, Implementation and Use, **CRIWG 2004**, LNCS 3198, 339-348 (**2004**)
- **MATA 2004** [90]**:** M. Kirsch-Pinheiro, Jérôme Gensel, Hervé Martin, "Awareness on Mobile Groupware Systems". In: Ahmed Karmouch, Larry Korba, Edmundo Roberto Mauro Madeira (eds.), First International Workshop on Mobility Aware Technologies and Applications, **MATA 2004**, LNCS 3284, 78-87 (**2004**)
- **SAC 2005** [91]**:** M. Kirsch-Pinheiro, Marlène Villanova-Oliver, Jérôme Gensel, Hervé Martin, "Context-aware filtering for collaborative web systems: adapting the awareness information to the user's context". In: Hisham Haddad, Lorie M. Liebrock, Andrea Omicini, Roger L. Wainwright (eds.), Proceedings of the 2005 ACM Symposium on Applied Computing (**SAC 2005**), 1668-1673 (**2005**)
- **CSCWD 2005** [92]**:** M. Kirsch-Pinheiro, Marlène Villanova-Oliver, Jérôme Gensel, Hervé Martin, "BW-M: a framework for awareness support in Web-based groupware systems". In: Weiming Shen, Anne E. James, Kuo-Ming Chao, Muhammad Younas, Zongkai Lin, Jean-Paul A. Barthès (eds.), Proceedings of the Ninth International Conference on Computer Supported Cooperative Work in Design, **CSCWD 2005**, Volume 1, 240-246 (**2005**)
- **PhD thesis** [77]**:** M. Kirsch-Pinheiro, « Adaptation Contextuelle et Personnalisée de l'Information de Conscience de Groupe au sein des Systèmes d'Information Coopératifs », **PhD Thesis**, Université Joseph Fourier - Grenoble I, Grenoble, France (**2006**)
- **CAISE 06 Workshop** [93]: M. Kirsch-Pinheiro, Marlène Villanova-Oliver, Jérôme Gensel, Hervé Martin, "A Personalized and Context-Aware Adaptation Process for Web-Based Groupware Systems". Proceedings of the **CAISE 06, Workshop** on Ubiquitous Mobile Information and Collaboration Systems, **UMICS 2006** (**2006**)
- **Ubicomm 2008** [94]**:** M. Kirsch Pinheiro, Marlène Villanova-Oliver, Jérôme Gensel, Yolande Berbers, Hervé Martin, "Personalizing Web-Based Information Systems through Context-Aware User Profiles", *International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies, **Ubicomm 2008**,* (**2008**)
- **EGC 2008** [51]**:** Jérôme Gensel, Marlène Villanova-Oliver, M. Kirsch-Pinheiro, « Modèles de contexte pour l'adaptation à l'utilisateur dans des Systèmes d'Information Web collaboratifs », *8èmes Journées Francophones d'Extraction et Gestion des Connaissances (**EGC'08**), Atelier sur la Modélisation Utilisateur et Personnalisation d'Interfaces Web,* 5-15 (**2008**)

Table 1. Bibliometric analysis of selected publications.

Reference	Year	Total	≤ 2008	> 2008 & ≤ 2013	> 2013	Self-citation
COMIND 2003	2003	90	49	20	10	11
CRIWG 2004	2004	71	13	21	13	24
MATA 2004	2004	11	4	4	1	2
ACM SAC 2005	2005	45	16	22	4	2
CSCWD 2005	2005	8	2	3	2	1
PhD thesis	2006	8	4	2	1	1
CAiSE 06 Workshop	2006	13	0	7	4	2
Ubicomm 2008	2008	7	0	4	3	0
EGC 2008	2008	18	2	6	7	3
Total / %		271	33,95 %	32,84 %	16,61 %	16,61 %

Several elements can emerge from the analysis of this information (Figure 3 and Table 1). The most frequently cited article is the one published in the journal COMIND, which deals with mechanisms used to support group awareness. Although this is not technically part of these contributions, it provided the basis on which these contributions were built. One can also observe the important number of self-citations for the CRIWG 2004 article. This can be explained by the founding aspect of this article in relation to later work. It introduces the proposed context model, thus constituting the reference point for the continuation of this work.

It is also worth noting a change in the community focused by these publications during this period. These contributions have targeted both communities, Pervasive Computing as well as CSCW (Computer Support for Cooperative Work) community. The first works (COMIND 2003, CRIWG 2004, CSCWD 2004) have particularly targeted CSCW community, while the publications that followed (MATA 2004, SAC 2005, CAISE 06 Workshop, Ubicomm 2008) have mainly targeted Pervasive Computing community, which is also target by the contributions discussed in the next chapter.

Besides, the period in which this work had more influence (quantified by the number of citations) is the period up to 2013, corresponding to a period in which researches on context-aware systems were also numerous.

Finally, it is also important to underline the impact of this work on later contributions: the operations used in the proposed filtering mechanism have influenced my researches on services selection, as well as the context model has influenced my work on Information Systems, to which we may add the collaborations carried out since 2008 [21, 76] made possible thanks to this work.

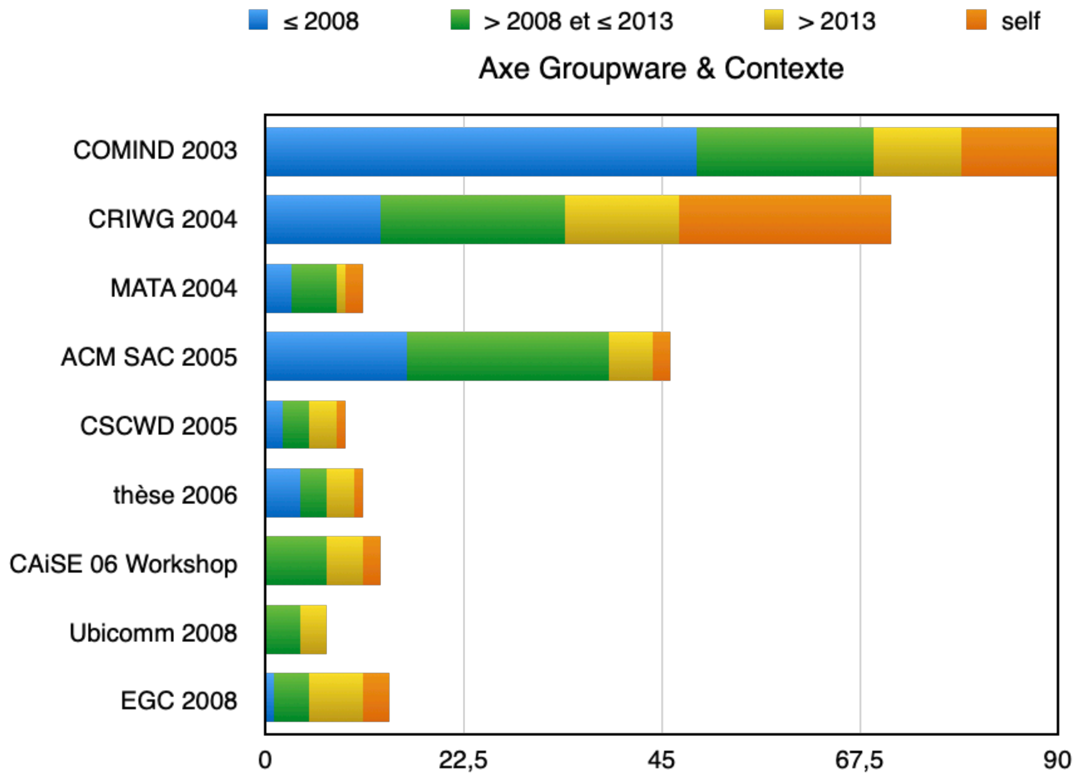

Figure 3. Evolution of citations over time.

As discussed above, among all papers resulting from this research work, the one published at CRIWG 2004 appears as the most relevant one, defining the basis of this work. It was then chosen as the most illustrative one, being consequently attached to this document in the Annex II.

2 Context on Pervasive Environments

Research works presented in this chapter have target particularly the community of Pervasive Computing, which can be defined as the transparent integration of IT and its devices into our daily life [6]. Also known as Ubiquitous Computing, this term represents, according to Moran & Dourish [104], a trend towards environments enriched by numerous computing devices, often mobile or embedded in the environment, connected by fixed or wireless networks. Originally proposed by Weiser [171], this vision of computing that has become invisible to our eyes is gradually becoming a reality, since, as Bell & Dourish [10] point out, we continually use computing resources without necessarily perceiving them as computers.

The challenges raised in this research domain are multiple and quite often related to the heterogeneity and dynamic nature of these so-called pervasive environments. Indeed, these environments are characterized by their heterogeneity, including devices as varied as network equipment (router, switch, etc.), "traditional" personal computers (fixed or portable), smartphones and tablets, and even devices used for IoT (*e.g.* RaspberryPI, Arduino). These environments are also often very dynamic, integrating devices that can easily join the network or leave it, by a simple disconnection or being switched off for different reasons. New devices can easily appear in the perimeter, while others can disappear depending on their use, on their mobility (or that of their owners), on their battery or power level, and so on. The notion of context becomes thus a key element here, promising to better take into consideration these environments. Observing the context in which these resources are executed represents a particularly relevant information for applications and platforms that desire to take advantage of these environments and of all the possibilities of interaction, storage and even computing capacities that can be found in these environments.

In this chapter, we are particularly interested in these pervasive environments, focusing on two distinct problems: firstly, we focus on how to make context information available in these environments (Section 2.1); secondly, how, based on the context information, could we rationalize the use of computing resources in these environments, particularly for the execution of "Big Data" applications (Section 2.2).

2.1 Context grouping

2.1.1 Problem statement

Context-aware applications are often presented as distributed applications. They may entail different nodes that can cooperate to achieve application goals or simply to provide a better user experience. Different scenarios can illustrate this trend, such as, for example, scenarios involving multi-scale systems [139], the adaptation of an application to the available resources (hardware and software) [34], or the possibility to propose an opportunistic composition of services to the user [35]. In any case, the distributed nature of these applications and services may also require the distribution of context information across the different nodes present in the environment.

Indeed, in order to take full advantage of the pervasive environment that surrounds them, some applications must rely on the exchange of information concerning the surrounding resources and their execution context. For example, a communication application may take advantage of the presence of a nearby node with a better display or a better connection capacity and then try to use these resources by deploying certain tasks on neighboring nodes. This scenario, considered for example in [33], requires that neighboring nodes share their execution context. Similarly, scenarios involving sharing resources in a smart building, as considered by [49], would also require sharing context information concerning available resources in order to exploit the full potential offered by these environments.

However, since pervasive environments are characterized by their dynamism, sharing context information about the resources that are available in the environment raises different challenges. First of all, context information concerning these resources will evolve over the time. The composition of the environment itself will also change, with new resources entering or leaving the environment or simply becoming unavailable. In addition, not all applications are necessarily interested in all the context information that can be available, without mentioning the obvious security and privacy issues that raise when considering sharing context information among available nodes.

Thus, in this contribution, carried out essentially between 2008 and 2009, partially within the European project named IST-MUSIC, we focused on the question of how to share context information in a pervasive environment. Without going into security and privacy issues, this research work focuses on the dynamism of context information itself and on the dynamism of the environment. Context information must be updated on a regular basis, according to changes observed in the surrounding environment, whose composition is fluctuating. We propose in this research work a peer-to-peer mechanism for distributing context information in a dynamic environment whose composition and nature varies over time.

In the proposed context distribution mechanism, the nodes that are available in the environment are dynamically organized into groups, according to a common context shared by the nodes participating of each group. The use of context information is twofold: it is used to organize the groups and is also shared among the nodes belonging to these groups. The nodes, which represent the resources available in the environment, are organized into groups according to a common context defined, at the application level, by a criteria set. For example, a group can be defined for resources that are co-located (*e.g.* located in the same room), have the same network connection, or belong to users sharing the same role in the organization. Within these groups, context information concerning the nodes is distributed among the other group members, who can thus become aware of the current situation of the other resources belonging to the same group. For example, in a group defined on a common location (*i.e.* co-located resources), it is possible to share information about available memory and display capabilities among the members. Such an information about neighborhood nodes would be useful, for example, in a communication application such as the one considered in [33].

This context distribution mechanism was originally published at DOA 2008 [86] conference and has, after that, been improved using notably the Formal Concept Analysis [131, 173], a data analysis technique, for discovering possible groups in the environment. The original paper can be consulted in the Annex III.

- **DOA 2008 [86]** : Kirsch-Pinheiro, M.; Vanrompay, Y.; Victor, K.; Berbers, Y.; Valla, M.; Fra, C.; Mamelli, A.; Barone, P.; Hu, X.; Devlic, A.; Panagiotou, G., “Context Grouping Mechanism for Context Distribution in Ubiquitous Environments”, In: Robert Meersman, Zahir Tari et al.(eds.), *10th International Symposium on Distributed Objects, Middleware, and Applications (DOA'08), OTM 2008 Conferences, Lecture Notes in Computer Science*, 5331, **2008**, 571-588.

2.1.2 Bibliometric

The research work described in this chapter was carried out between 2008 and 2009, with the publication of a paper at the DOA (Distributed Objects, Middleware and Applications) conference [86]. After, on 2012, this research work has improved, resulting in a new publication in 2013 [164]. Additionally, this research work has allowed the development of other collaborations concerning context distribution topic, in particular within the IST-MUSIC project. Each of these collaborations resulted in a publication. A first collaboration has concerned the definition of a P2P architecture allowing context distribution on the IST-MUSIC project [63], and a second one has tacked the privacy issues on context distribution thanks to the use of user-specific policies (as opposed to application-specific policies, as in our case) [36]. All the publications related to context distribution is then summarized in the list below.

- **DOA 2008 [86]**: Kirsch-Pinheiro, M.; Vanrompay, Y.; Victor, K.; Berbers, Y.; Valla, M.; Frà, C.; Mamelli, A.; Barone, P.; Hu, X.; Devlic, A.; Panagiotou, G., "Context Grouping Mechanism for Context Distribution in Ubiquitous Environments", In: Robert Meersman, Zahir Tari et al.(eds.), *10th International Symposium on Distributed Objects, Middleware, and Applications (DOA'08), OTM 2008 Conferences, Lecture Notes in Computer Science*, 5331, **2008**, 571-588.
- **ChapCtxGrp 2013 [164]**: Vanrompay, Y.; Kirsch Pinheiro, M.; Ben Mustapha, N.; Aufaure, M.-A., "Context-Based Grouping and Recommendation in MANETs", In : Kolomvatsos, K., Anagnostopoulos, C., Hadjiefthymiades, S. (Eds.), *Intelligent Technologies and Techniques for Pervasive Computing*, IGI Global, **2013**, 157-178.
- **ISD 2008 [63]**: Hu, X.; Ding, Y.; Paspallis, N.; Bratskas, P.; Papadopoulos, G.A.; Vanrompay, Y.; Kirsch Pinheiro, M.; Berbers, Y., "A Hybrid Peer-to-Peer Solution for Context Distribution in Mobile and Ubiquitous Environments", In: Papadopoulos G., Wojtkowski W., Wojtkowski G., Wrycza S., Zupancic J. (eds), *17th International Conference on Information Systems Development (ISD2008)*, *Information Systems Development: Towards a Service Provision Society*, **2008**, Springer, 501-510. DOI : 10.1007/b137171_52
- **CoMoRea 2009 [36]**: Devlic, A.; Reichle, R.; Wagner, M.; Kirsch Pinheiro, M.; Vanrompay, Y.; Berbers, Y.; Valla, M., "Context inference of users' social relationships and distributed policy management", *6th IEEE Workshop on Context Modeling and Reasoning (CoMoRea), 7th IEEE International Conference on Pervasive Computing and Communication (PerCom'09)*, Galveston, Texas, 13 March **2009**. DOI : 10.1109/PERCOM.2009.4912890

As for the previous chapter, these publications were analyzed in terms of number of citations. We used various sources for this, including scholar.google.com, www.researchgate.net and hal.archives-ouvertes.fr, as well as the publisher's site, when available. These citations were then organized into three categories: before 2013, which corresponds, approximately, to the first 5 years after the first publication; between 2013 and 2016; and after 2016. Self-citations were also accounted for and distinguished from other citations. Table 2 details the data obtained, illustrated in Figure 3.

Table 2. Citations concerning context grouping publications.

Reference	Year	Total	≤ 2013	> 2013 & ≤ 2016	> 2016	Self-citation
DOA 2008	2008	13	7	2		4
ChapCtxGrp 2013	2013	6	1			3
ISD 2008	2008	6	5			1
CoMoRea 2009	2009	22	12	6	3	
Total / %		47	53,19 %	17,02 %	6,38 %	23,4 %

As one might expect, citations for these articles are mainly concentrated on the first 5 years following their publication (between 2008 and 2013). This corresponds to a very intense period for research on context-aware computing. This work was therefore adopted by other authors from this community during this period, but, since it was not continued, this work has gradually ceded its place to more recent approaches on context distribution.

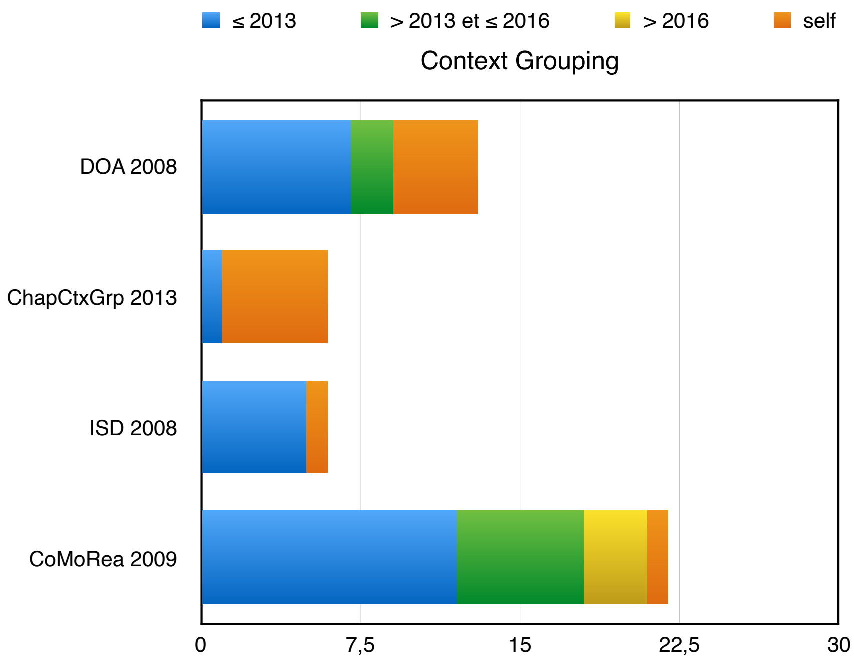

Figure 4. Citations evolution over different periods of time.

2.2 PER-MARE project

2.2.1 Problem statement

Unlike what one might expect, pervasive environments can offer computing capacities distributed among all the units (nodes) available on it. These different units can, in theory, collaborate for collecting and processing data from sensors in order to autonomously perform certain tasks. This scenario, which is envisaged, among others, by Ausiello [5], illustrates the interest of using resources integrated in pervasive environments for the execution of certain computing tasks, and particularly in the case of Big Data applications.

However, the heterogeneity that characterize pervasive environments represents an important challenge when considering using resources on these environments for task execution. With resources than can be very varied, even diametrically opposed, ranging from high-performance servers (HPC) to nanocomputers (Raspberry PI, Arduino, etc.), the use of such resources for computational purposes represents a challenge, notably concerning the placement of computational tasks on these very heterogeneous resources. As pointed out by Breitbach *et al.* [16], the placement of computing tasks in a heterogeneous environment is more complex than the one performed on a Cloud environment or on computing grids. Indeed, it is particularly difficult to distribute computing tasks and to guarantee their execution on resources that do not behave in the same way and whose performances can be very varied and variable. This heterogeneity can have a significant impact on the execution of these tasks and on their performance. The dynamism of these environments, with particularly volatile nodes that can disappear or join the network during the execution, will also have an impact on performance. Under these conditions, it is difficult to anticipate the execution performance of a set of tasks in such an environment. This is particularly true for Big Data type applications, which must combine their needs of computing capabilities with the management and the transfer of large amounts of data.

The PER-MARE project was born from this observation. Running from 2013 to 2014, this project is an international cooperation CAPES/MAEEA/ANII STIC-AmSud (project number 13STIC07) involving the University of Reims Champagne-Ardennes and the University Paris 1 Panthéon Sorbonne in France, as well as the Universidade Federal de Santa Maria (UFSM) in Brazil and the Universidad de la República in Uruguay. The main objective of the PER-MARE project was to provide a support for the execution of MapReduce applications in a pervasive environment. MapReduce is a programming model for data-intensive applications in which the processing is organized in two phases: the map, in which the data is divided into several blocks and processed to form a set of "key, value" peers; and the reduce, in which the results of the first phase are aggregated to produce a final result [172]. The data divided into several blocks are thus distributed among the cluster nodes and processed in the map phase, resulting in a set of "<key, value >" peers, which are then grouped again into several blocks according to the key values found, to be finally consolidated in the reduce phase (see Figure 5). Because of its easily distributed nature, the MapReduce principle has been widely used on Big Data platforms, including Apache Hadoop, which was the main Big Data platform at the time the PER-MARE project started.

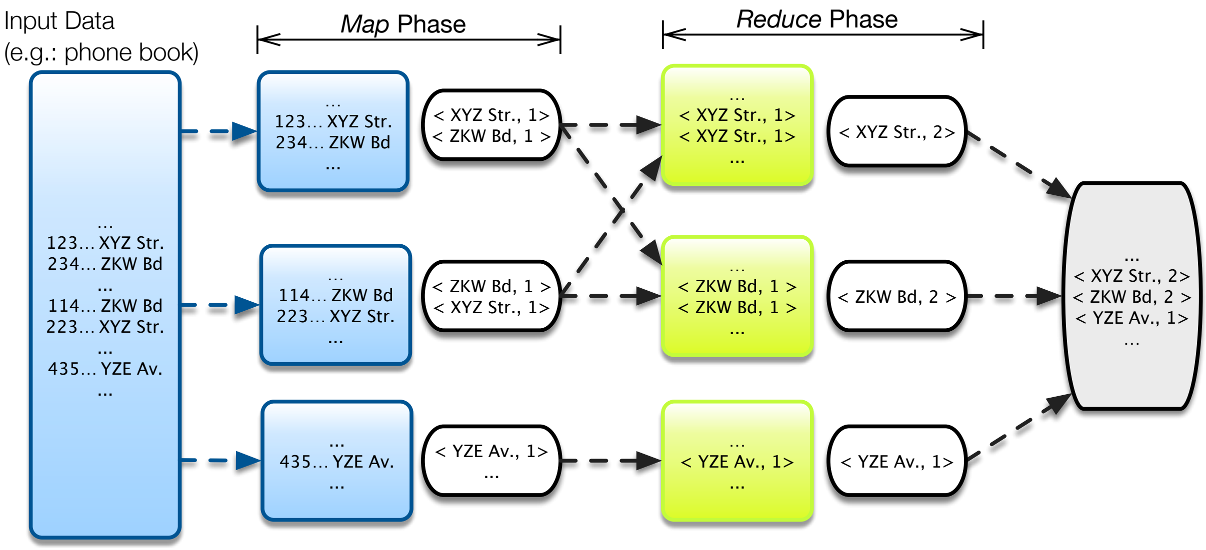

Figure 5. illustration of the MapReduce programming model considering a telephone directory, in which the number of telephones ("123…") by addresses ("XYZ Str…") is counted.

The execution of MapReduce applications in a pervasive environment requires a rationalized use of the resources present in these environments, in order to obtain a good distribution of data and processing tasks according to the capacities of the available devices. In the PER-MARE project, we have considered the use of pervasive grids [126], whose goal is to dynamically and opportunistically build computing grids from nearby available resources. According to Parshar & Pierson [126], pervasive grids represent the extreme generalization of the notion of computing grid, in which resources are pervasive. These grids can thus integrate both sensor or actuator-type devices and conventional high-performance terminals. Desktop grids, grids composed of desktop PCs made available by voluntary users, would thus be a particular case of pervasive grids, very heterogeneous by definition [153].

Pervasive grids can be assimilated to Fog or Edge Computing platforms [29, 122]. Fog / Edge Computing can be seen as a new trend complementary to Cloud Computing. It is an alternative to the "all-cloud" model in which all processing is done exclusively in the cloud. The aim would then be to use of nearby devices to carry out some processing tasks (data aggregation, pre-processing, anonymization, simple calculations, etc.), instead of systematically transferring all data processing for remote processing on cloud platforms or datacenters. This model is particularly interesting for minimizing problems related to network latency or to the transfer of large amounts of data to the cloud, as well as to problems related to data privacy or security [60, 143], since data remain as close as possible to its production environment. By minimizing or even avoiding data transfers to remote platforms and taking advantage of nearby resources, this model not only reduces these problems but also makes better use of available (and often underutilized) resources at the "edge" of the network or close to the user.

Thus, the main goal of the PER-MARE project was to explore the use of heterogeneous resources for Big Data processing. Two complementary approaches have been explored during this project: (i) to consider the execution context within the Hadoop platform; and (ii) the use of available resources within a Fog/Edge computing platform. In both cases, the problem remains the use of heterogeneous resources for Big Data in an opportunistic way. Each approach has given rise to its own contributions.

In the first approach, the Apache Hadoop has been modified in order to support heterogeneous clusters. Indeed, Apache Hadoop [172] was especially designed for the execution and the deployment of MapReduce applications on homogeneous computing clusters, *i.e.* homogeneous computing environments with a stable number of available homogeneous resources. The platform was not originally designed to run on heterogeneous and dynamic environments (*i.e.* environments whose composition and state may vary over time), such as pervasive grids. According to Hagras [56], the dynamic and ad-hoc nature of pervasive environments requires adapting to changing operating conditions and variations in user's preferences and behavior in order to promote more efficient and effective operation, while preventing system failures. Unfortunately, the Hadoop platform, in its original configuration, was unable to dynamically adapt its operation to a variable environment, in which resources are heterogeneous in their nature and can enter or exit the environment at any time. These variations lead to a degraded performance of the Hadoop platform is such environments.

In order to overcome this problem, we have proposed, within the PER-MARE project, to adapt the Hadoop platform in order to consider such heterogeneous environments. We have modified the *ResourceManager* and the *NodeManager*, elements in charge of the resource management in Hadoop, in such way they could capture context information of the executing nodes (number of available cores, available memory, etc.), and use this information instead of the static configuration of the node. To do this, we have integrated a *ContextCollector* into the *NodeManager*. This *ContextCollector* has been inspired by our previous work on context modeling [89] (see Chapter 1), as well as those carried out in the framework of the IST-MUSIC project [170]. It combines an object-oriented approach with an ontology approach, allowing a semantic description of context elements, while keeping the advantages of an object-oriented implementation, and mainly the lightness of this implementation, which is particularly important for high-performance applications.

This approach was the subject of different publications (see section 2.2.2), among those a journal paper published at JAIHC in 2016 [24], which presents latest results obtained by the project. This paper is available at the Annex IV.

- **JAIHC 2016** [24] : Cassales, G.W.; Charão, A.S.; Kirsch-Pinheiro, M.; Souveyet, C. & Steffenel, L.-A. "Improving the performance of Apache Hadoop on pervasive environments through context-aware scheduling", *Journal of Ambient Intelligence and Humanized Computing*, 7(3), **2016**, 333-345.

The second approach adopted by the PER-MARE project consists in proposing an alternative to Hadoop clusters through an independent Fog Computing platform. The CloudFIT platform [151], developed by the University of Reims Champagne Ardennes, was proposed in this sense. This platform aims at using the resources available on the environment for the execution of Big Data applications, without having to use a heavy platform such as the Hadoop platform. CloudFIT platform considers heterogeneous and volatile resources, such as the resources of a pervasive grid. According to Coronato & De Pietro [31], pervasive grids must be able to self-adapt and self-configure in order to accommodate mobile devices.

In these environments, the challenge is thus not limited to the heterogeneity of the available devices, but also to the volatility of these devices. As these devices are not dedicated to the computing tasks, they can easily connect and disconnect from the network according to their movements (or those of their owners), the availability of the network, or the state of their power supply.

The CloudFIT platform [151] was designed during the PER-MARE project to allow the execution of Java applications, including Big Data applications, targeted by the project, using resources available at the edge of the network. For this, the platform relies on a peer-to-peer (P2P) network in which participating devices (also called nodes) share tasks and data. Managing the volatility of these devices is done through both the use of the P2P network (and more precisely a P2P network overlay), and through the distributed nature of the task management, in which tasks are shared among the available nodes. Each new node wishing to participate in the computing effort can then request to join the community. It can make this request to any other node belonging to the community. As soon as it joins it, it receives from the other nodes the list of tasks to be performed and becomes a candidate to store data (data it produces itself or replicas of data present on the other nodes). Each node decides by its own which task it will execute according its own execution context and the availability of the data necessary for the task execution.

During the development of the CloudFIT platform, various experiments have been performed, whose results have been published in several articles, including CLIoT 2015 [153], which first details the CloudFIT platform, and which is available at the Annex V:

- **CLIoT 2015** [151] : Steffenel, L. & Kirsch-Pinheiro, M. "CloudFIT, a PaaS platform for IoT applications over Pervasive Networks", In: Celesti A., Leitner P. (eds). *3rd Workshop on CLoud for IoT (CLIoT 2015)*. Advances in Service-Oriented and Cloud Computing (ESOCC 2015). Communications in Computer and Information Science, vol. 567, **2015**, 20-32.

2.2.2 Bibliometric

The research works on the PER-MARE project have resulted in several publications, from 2013 to 2016, going well beyond the official duration of the project (2013-2014). In this section, we try to analyze the impact of these publications, listed below, in terms of citations. As in the previous chapter, we have considered the citations visible from the scholar.google.fr platform, which condenses information from the many other sources (IEEEExplore, SpringerLink, ScienceDirect, Arxiv, etc.), but also from the www.researchgate.net and www.semanticscholar.org platforms, as well as from the publisher's website where applicable. The citations are organized in two categories: those up to 2017 (dating from the first 5 years from the beginning of the project); and those from 2018 onwards. To these categories are added the self-citations, which have been accounted for separately. Table 9 presents the figures obtained from this analysis, while Figure 6 illustrates the proportion of these citations.

- **3PGCIC 2013** [153]**:** Steffenel, L. A.; Flauzac, O.; Charao, A. S.; Barcelos, P. P.; Stein, B.; Nesmachnow, S.; Kirsch Pinheiro, M. & Diaz, D., "PER-MARE: Adaptive Deployment of MapReduce over Pervasive Grids", *8th International Conference on P2P, Parallel, Grid, Cloud and Internet Computing (3PGCIC'13)*, **2013**, 17-24.
- **UBICOMM 2014** [23]: Cassales, G.W.; Charão, A.S.; Kirsch-Pinheiro, M.; Souveyet, C. & Steffenel, L.A. « Bringing Context to Apache Hadoop », In: Jaime Lloret Mauri, Christoph Steup, Sönke Knoch (Eds.),*8th International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (UBICOMM 2014)*, August 24 - 28, **2014,** Rome, Italy, ISBN: 978-1-61208-353-7, IARIA, 252-258.

- **JCS 2014** [152]: Steffenel, L. A., Flauzac, O., Charao, A. S., P. Barcelos, P., Stein, B., Cassales, G., Nesmachnow, S., Rey, J., Cogorno, M., Kirsch-Pinheiro, M. & Souveyet, C., "Mapreduce challenges on pervasive grids", *Journal of Computer Science*, 10(11), July **2014**, 2194-2210.
- **CLIoT 2015** [151]: Steffenel, L. & Kirsch-Pinheiro, M. "CloudFIT, a PaaS platform for IoT applications over Pervasive Networks", In: Celesti A., Leitner P. (eds). *3rd Workshop on CLoud for IoT (CLIoT 2015)*. Advances in Service-Oriented and Cloud Computing (ESOCC 2015). Communications in Computer and Information Science, vol 567, **2015**, 20-32.
- **CN4IoT 2015** [154]: Steffenel, L.A. & Kirsch Pinheiro, M. "When the cloud goes pervasive: approaches for IoT PaaS on a mobiquitous world". In: Mandler B. et al. (eds), *EAI International Conference on Cloud, Networking for IoT systems (CN4IoT 2015), Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering (LNICST)*, 169, **2015**, 347–356.
- **JAIHC 2016** [24]: Cassales, G.W.; Charão, A.S.; Kirsch-Pinheiro, M.; Souveyet, C. & Steffenel, L.-A. "Improving the performance of Apache Hadoop on pervasive environments through context-aware scheduling", *Journal of Ambient Intelligence and Humanized Computing*, 7(3), **2016**, 333-345.
- **Big2DM 2015** [155]: Steffenel, L.A. & Kirsch-Pinheiro, M., "Leveraging Data Intensive Applications on a Pervasive Computing Platform: the case of MapReduce", *1st Workshop on Big Data and Data Mining Challenges on IoT and Pervasive (Big2DM)* , London, UK, June 2 - 5, 2015. *Procedia Computer Science*, vol. 52, Jun 2015, Elsevier, 1034–1039. doi: 10.1016/j.procs.2015.05.102.
- **ANT 2015** [22]: Cassales, G.W., Charao, A., Kirsch-Pinheiro, M., Souveyet, C. & Steffenel, L.A., "Context-Aware Scheduling for Apache Hadoop over Pervasive Environments", *The 6th International Conference on Ambient Systems, Networks and Technologies (ANT 2015)*, London, UK, June 2 - 5, 2015. *Procedia Computer Science*, vol. 52, Jun **2015**, Elsevier, 202–209. doi: 10.1016/j.procs.2015.05.058.

In addition to these articles, which are directly related to the themes addressed by the PER-MARE project, the project has also enabled other collaborations between the project members around the topic of the use of heterogeneous resources. These collaborations, which can be called satellites, have also given rise to some publications, listed below:

- **ANT 2014** [45]: Engel, T.A., Charao, A., Kirsch-Pinheiro, M., Steffenel, L.A. "Performance Improvement of Data Mining in Weka through GPU Acceleration", *5th International Conference on Ambient Systems, Networks and Technologies (ANT 2014)*, Hasselt, Belgium, June 2 - 5, 2014. *Procedia Computer Science*, vol. 32, **2014**, Elsevier, pp. 93–100.
- **JAIHC 2015** [44]: Engel, T.A., Charao, A., Kirsch-Pinheiro, M., Steffenel, L.A. "Performance Improvement of Data Mining in Weka through Multi-core and GPU Acceleration: opportunities and pitfalls", *Journal of Ambient Intelligence and Humanized Computing*, Springer, June **2015**. doi:10.1007/s12652-015-0292-9.

As the PER-MARE project has been built up over the years, the number of self-citations on certain publications is naturally high, notably on those establishing the working bases [152, 153] and detailing the CloudFIT platform [154]. Nevertheless, it worth noting that the number of citations for some works (notably [23, 24, 44]) has been increasing since 2017. This is mainly due to a certain democratization of Big Data and data analysis applications (subject treated by the last two publications).

Finally, there is a deliberate willingness in the PER-MARE project to give priority to publications on an "open access" mode. Among the publications presented above, half are open access, being both free and peer-reviewed. These contribute to 48.83% of the citations (excluding self-citations).

Table 3. Synthesis of citations concerning PER-MARE project papers, organized by publication year.

Reference	Year	Total	≤ 2017	> 2017	Self-citations
3PGCIC 2013	2013	11	4	0	7
JCS 2014	2014	7	2	1	4
Ubicomm 2014	2014	3	0	1	2
CN4IoT 2015	2015	7	0	2	7
CLIoT 2015	2015	6	3	1	2
Big2DM 2015	2015	4	1	1	2
ANT 2015	2015	9	4	3	2
JAIHC 2016	2016	9	1	6	2
ANT 2014	2014	9	2	6	1
JAIHC 2015	2015	6	1	4	1
Total / %		**73**	**24,66 %**	**34,25 %**	**41,10 %**

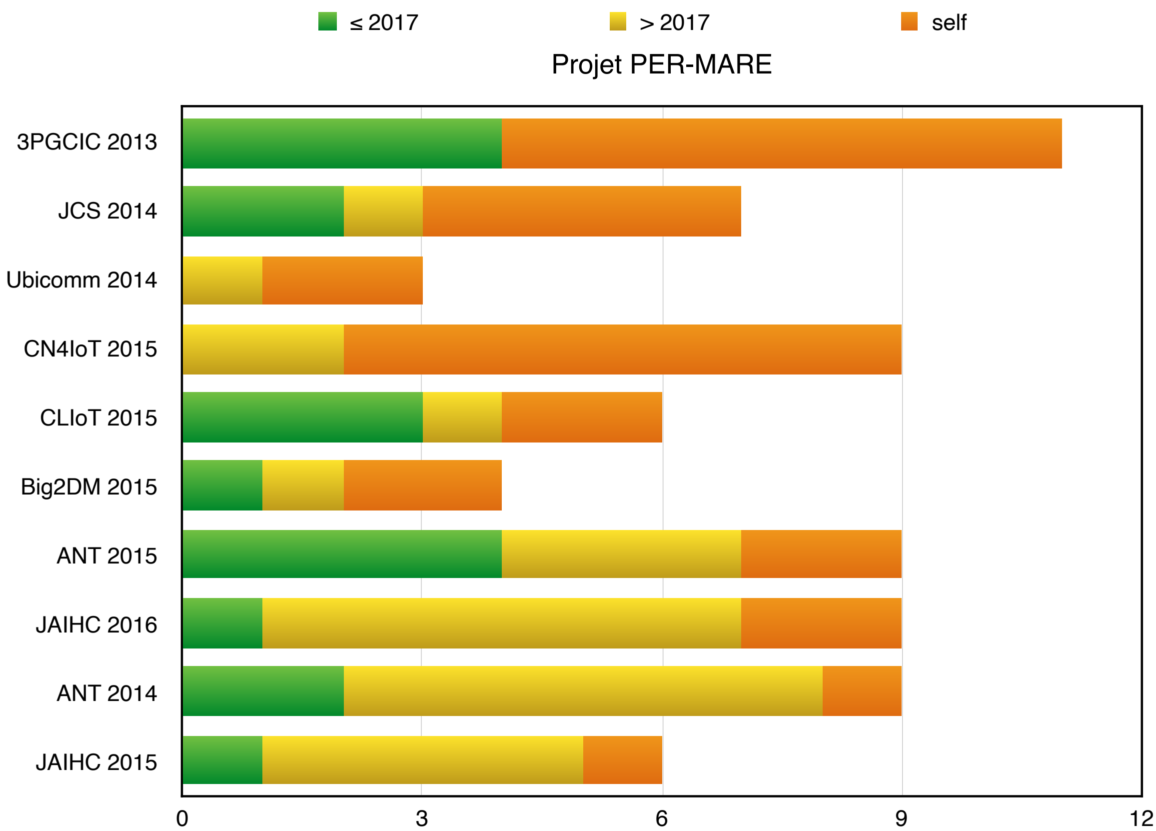

Figure 6. Illustration of the evolution of PER-MARE citations over the time.

2.3 Chapter Summary

In this chapter, we have discussed research works taking place from 2008 to 2010 (context grouping) and from 2013 to 2015 (PER-MARE project) and considering two distinct projects: IST-MUSIC for the first (cf. section 2.1), and PER-MARE for the second (cf. section 2.2).

The main concern of these works is the pervasive environments. Contrary to the work presented in Chapter 1, in which the human element (the user) was at the center of the analysis, here the focus was on these environments. Particular attention was given to the heterogeneity and the dynamicity of such environments. These characteristics raise several questions, including the opportunistic use of available resources for computational tasks, for which considering the context information during execution can represent a determining factor, illustrating hence the relevance of work such as ours on the distribution of context information within these environments.

Considering the pervasive environments and the resources these environments may offer represents a growing trend with the development of Fog/Edge Computing platforms and other related concepts [16, 28, 43, 64, 122, 168, 169]. All these concepts share the same vision: they aim at using resources with a certain computing capacity that would be available (or potentially under-exploited) in the environment around the user or the data. This proximity computing model is particularly interesting when associated with the IoT. The data and/or the treatments from/related to the IoT can thus be handled by devices close to the objects at the origin of these data or treatments. This would allow, for example, to significantly reduce the volume of data transmitted over the network, which represents a significant advantage in a Big Data context, or to reduce the reaction time following a decision.

The PER-MARE project (2013-2014) has focused on Big Data application, which represented, at the time of the project proposal, a rapidly growing field. The project's central proposal of using pervasive grids to execute these applications was very innovative at this moment, since at this specific period the use of dedicated platforms (cluster or cloud) was still largely dominant, as illustrated by the 2012 Gartner's Hype Cycle shown in Figure 7. It is important to note that the terms Fog/Edge Computing were still mostly unknown. These terms appeared around 2012 [14, 29, 48, 122] and have gained more attention more recently, as a complement to Cloud Computing, especially in the context of IoT and data analysis applications.

The current development of Fog Computing [28, 43, 66, 122, 161, 168] highlights the relevance of the PER-MARE project's proposals, especially as they remain innovative compared with the literature. Indeed, the predominant vision remains of fog platforms as an intermediary stage before data is sent to Cloud platforms. This dependency is underlined by Alrawais *et al.* [3], for whom the goal of Fog Computing is to reduce the volume and the traffic of data to cloud servers, thus reducing latency and increasing quality of service. In the PER-MARE project, this constraint was removed, since we did not consider the constant presence (or rather availability) of a dedicated platform, whether a cluster or a cloud, for running applications at one time or another. The objective has always been an opportunistic use of whatever resources are available. By freeing ourselves from this constraint, we have been able to consider the use of any resource at hand, be it resources from the IoT (such as the RaspberryPIs used in our experiments), laptops or even clusters or resources on the cloud.

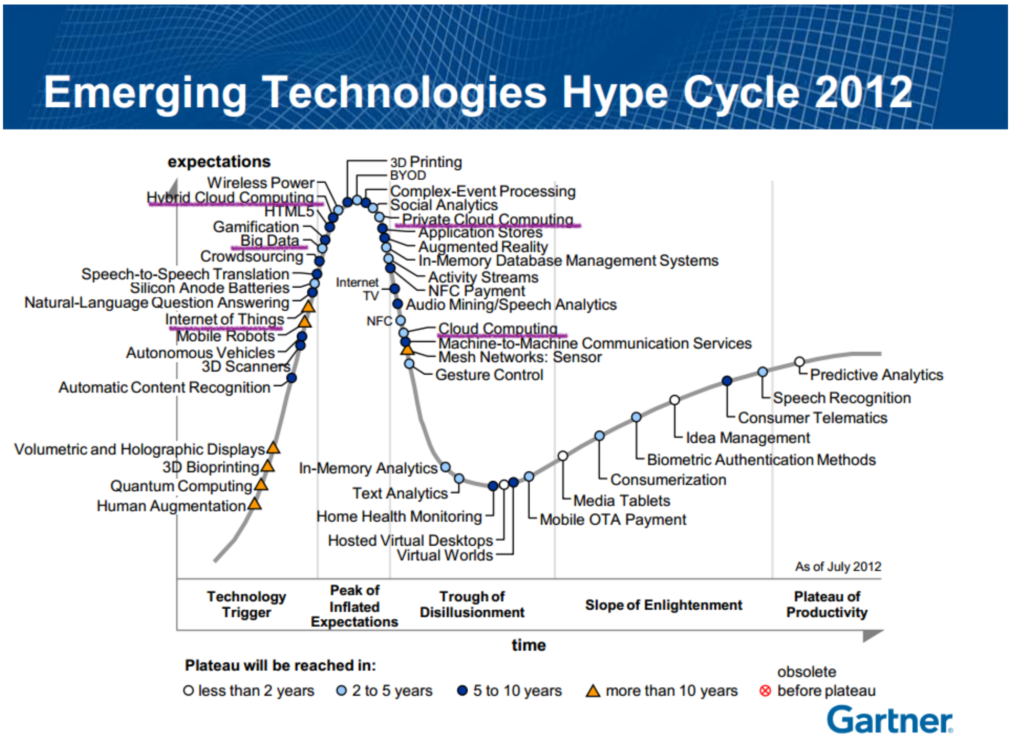

Figure 7. Gartner's emerging technology hype cycle de technologies for 2012[1].

Besides, today's availability of an unprecedented mass of data, including data from the IoT, combined with the available computing offer (whether on Cloud or Fog Computing platforms) opens up new application perspectives, especially in terms of data analysis. We are talking here about what some people call "Edge AI" or the use of Fog Computing platforms, in association with Cloud platforms, for the application of Artificial Intelligence techniques, and in particular Deep Learning, on data mostly from the IoT. The entry of this term into the 2019 Gartner Hype Cycle (see Figure 8) illustrates the industry's growing interest for this kind of solution. The PER-MARE project can be seen as a precursor, proposing since 2013 the use of local resources for processing data, whether or not it comes from the IoT. The "Edge AI" represents a new field of application for resources already available in an Information Systems, which could benefit a wide range of sectors: Industry 4.0, logistics, but also Human Resources (HRIS), financial, and so on. Whatever the field of application is envisaged, in order to become a reality these scenarios ought to observe the execution context. Context information must be taken into account appropriately, so that the heterogeneity of these environments could be considered. Context-awareness becomes then essential, as highlighted by the results we obtained within the PER-MARE project, and consequently context distribution mechanisms, as the one presented in section 2.1, will become more and more necessary in order to allow the growing development of such applications.

[1] Source : https://res.infoq.com/news/2012/08/Gartner-Hype-Cycle-2012/fr/resources/hype1.png

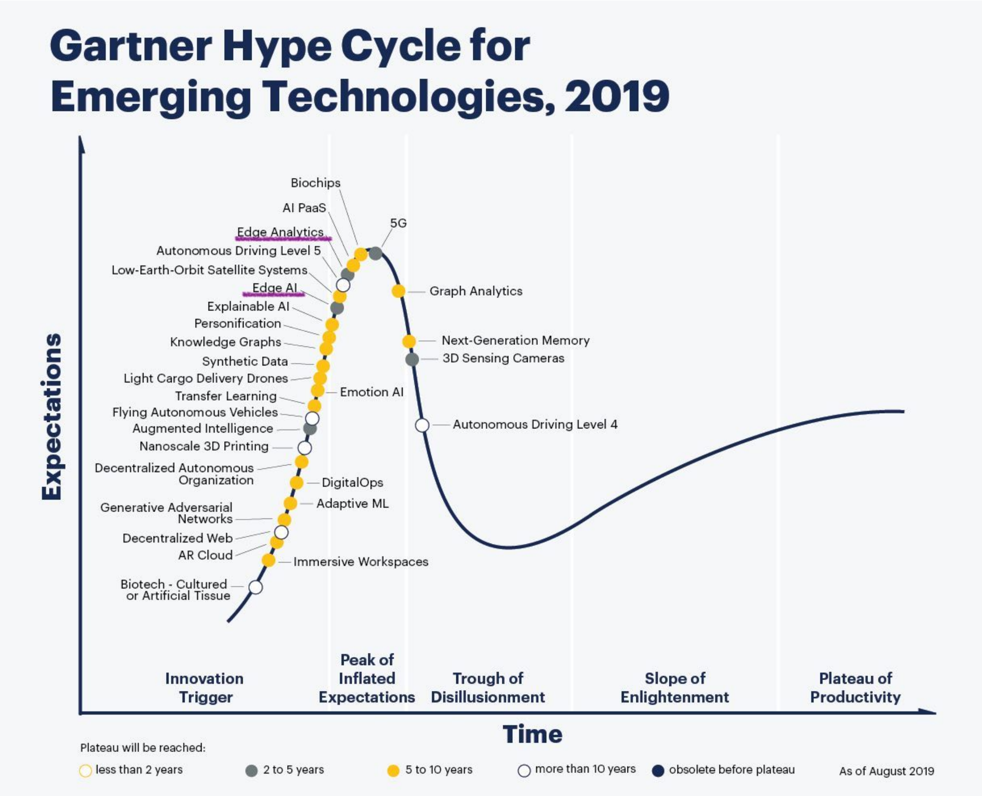

Figure 8. Gartner's emerging technologies hype cycle for 2019[2].

[2] Source : https://www.gartner.com/smarterwithgartner/5-trends-appear-on-the-gartner-hype-cycle-for-emerging-technologies-2019/

3 Context on the Service Orientation

Among the questions raised by Pervasive Computing, we may cite the context management, but also the management of the interoperability, considering the heterogeneity that characterize pervasive environments. In this context, service orientation has emerged as a viable approach for dealing with these issues, providing interesting solutions to the problems at hand, but also benefiting from context awareness. Service Oriented Computing (SOC) can be seen as a computing paradigm relying on the notion of service as a basic unit for faster, more reliable and cheaper design and development of distributed applications over heterogeneous environments [123,124,125]. A service can be defined as an independent entity with well-defined interfaces that can be invoked in a standard way, without requiring any knowledge from the customer about how the service actually performs its tasks [67]. They are self-described software elements, independent of the platform and accessible through a standard interface [2]. Customers and service providers are thus independent, communicating only through the interface of these services. Services can thus be exposed, published, discovered, composed and negotiated at the request of a customer and invoked by other applications [125].

Service orientation can thus be characterized by its loose coupling, technological independence and scalability [67]. It is this loose coupling that makes the notion of service particularly attractive for pervasive environments, since these environments are characterized by the volatility of their elements [166]. Indeed, service orientation, through its loose coupling and the self-describing nature of services, allows, on the one hand, to better manage the volatility of pervasive environments and to better isolate applications from the different technologies involved. On the other hand, by observing context information made possible the emergence of services that can better adapt their own behavior to their execution context and therefore to these highly dynamic environments.

Since 2007, the notion of services in the field of Pervasive Computing has been an important part of my research. Different research issues have been treated over the years: (i) the identification of relevant context elements for a service (or an application); (ii) the selection of the most appropriate service (or implementation) according to the execution context; (iii) the integration of the user and her/his business goals in the definition of these services; and (iv) the forecasting of user’s goals for a more proactive behavior. These different issues have led to several contributions presented in the following sections. The common element of these proposals, beyond the notion of context and the main community in which they were made (Pervasive Computing), is the notion of service itself: in each of these contributions, we find the vision of a system as a set of services proposed to the user, and whose adaptation according to the context proves to be necessary. The following sections summarize the proposed contributions and their impact.

3.1 Context mining

3.1.1 Problem statement

A particularly important challenge for the development of context-aware applications is the identification of the context elements that will be observed by the application [7,37,53,54]. Indeed, since context information is a key element for controlling the behavior of these applications, the identification of the relevant elements for these applications becomes a crucial task in their development, forcing the designers of these applications to anticipate their combinations and their relevant characteristics before implementation [7]. The same applies to context-aware services, whose behavior must be adapted to the execution context.

Even if this delicate question remains, until now, without a satisfactory answer, it raises a second related question: would it be possible to characterize the use of a service (or an application) by observing its execution context? In other words, by observing the context in which a service is executed, would it be possible to determine recurring context elements capable of characterizing the use of this service (or application) by an ordinary user?

This research work on "context mining" derives from this question. This work aims at using data mining techniques on context data, in order to identify relevant context elements that could characterize the use of a service (or a simple application).

In this work, carried out mainly between 2012 and 2014, first during Ali Jaffal's master thesis [72], then during the beginning of his PhD thesis [71], a methodology has been proposed allowing to associate the use of a service to characteristic situations, recognized thanks to the observed context elements. This methodology allows identifying, from data concerning application usage, context elements that characterize the use of a given application. Through the applications, it is the notion of service that is focused. The objective is to recognize the influence of one (or several) context element(s) in the choice of a service (represented here by an application) by a user. In order to do this, this methodology proposes the application of Formal Concepts Analysis (FCA) [131, 173], which allows services to be organized into several clusters according to the context elements observed during their use.

The choice of the FCA is a particularly innovative element in this work. Most works on context mining [133, 147] use statistical methods, such as Bayesian Networks [133] or Markov chains [102, 175]. The use of the FCA was then quite original at this time (2012-2014). Moreover, most of these works [133, 147, 102] use data mining techniques for the recognition of the user's activities (*e.g.* running, walking, sleeping, etc.), and not for the analysis of the relevance of a context element as here. In this case, we may cite [132, 133] as a similar approach, since these authors seek to learn, from the data, associations between contextual elements and the actions to be taken by the system (the actions taking the place of services here). Besides, the adoption of the FCA brings an interesting feature to this work: a "multi-class" classification. Indeed, unlike many statistical clustering methods, the FCA allows the overlapping of the different "classes" identified from the data. In other words, the same service can be simultaneously placed in different formal concepts (which represent the "classes"), thus identifying several situations, recognized thanks to a set of context elements, in which a given service has been invoked.

However, the most interesting impact of this work does not necessarily lay on its results, but rather on the limitations it has highlighted. Indeed, the heterogeneity of the context data appears to be a major obstacle for a generalized and fully automated analysis of these data. Very often, data mining methods are applied to certain "categories" of data. For example, the FFT (Fast Fourrier Transformation) used in [133] is particularly adapted to numerical data, whereas the FCA applied is more adapted to symbolic data (*i.e.* labels). The localization data demonstrate this issue particularly well. A pre-processing was necessary in order to translate the localization data, extracted during a first experiment we have performed using an Android tablet, into "labels" (localization_1, localization_2, etc.) that could be more easily exploited by the FCA. During this experiment, a "spy" application has observed several context elements, including GPS coordinates and services executed in the tablet. The GPS coordinate data had to be classified, during a pre-processing phase, into several geographic regions, to which labels were assigned. It is these labels that were used during FCA analysis. Without this transformation, the application of FCA was unviable. Therefore, given the heterogeneity that characterizes context data, it is difficult to imagine the application of a single technique for data analysis regardless of the context element considered, and at the same time, it is difficult not to consider the risk of losing information on the possible links between the different context elements by splitting the data set according to their nature.

It seems clear that current data mining techniques are not sufficiently adapted to manage the heterogeneity of context data without a significant pre-processing or training phase. Based on this observation, we wanted to analyze to what extent the difficulties we encountered with the application of FCA could also occur when using other Machine Learning methods. Thus, in 2019-2020, a collaborative project [11] was launched to study the use of Machine Learning (ML) techniques with context data. We analyzed how ML approaches are used for context mining and the conditions necessary for this analysis considering the specificities of context information. These limitations, which we have observed during the application of the FCA, suggest an issue when considering the possible generalization of ML techniques for context mining on a large scale, *i.e.* on the scale of an entire Information System (IS). Indeed, in [11], we introduce a vision of a "context mining facility", in other words, context mining functionalities proposed as a service offered by an IS for all its applications. Such "context mining facility" would open up new application perspectives within IS (adaptation to the context, recommendation of services or content, prediction/anticipation of user's needs or actions, decision-making, etc.). We may thus envisage the generalization of these behaviors, which could be described as "smart" or "intelligent", by offering an appropriate support for context mining as a service specific to an IS.

Last but not least, these difficulties encountered in the analysis of context data have led to a change of focus in Ali Jaffal's PhD thesis [71], in which part of this work has been carried out. These difficulties have demonstrated the limitations of FCA when applied to heterogeneous data such as context information, but also the difficulties in the application of this technique for non-expert analysists. The focus of this PhD thesis has then changed to this method of analysis and the possibility of making the application of this later better handling and easier for non-expert users. Pervasive Computing thus became a case study for the PhD thesis, and not its main subject, especially considering the limitations for an automatic application of this method to context-aware systems.

The paper published at CoMoRea 2020 [11] represents the latest published result mentioned in this document. It opens up several interesting perspectives, mainly considering the vision of a "context facility" and its challenges. For this reason, this paper has been chosen to represent this work. It can be found in the Annex VI.

- **CoMoRea 2020** [11] : Ben Rabah, N.; Kirsch Pinheiro, M.; Le Grand, B.; Jaffal, A. & Souveyet, C., "Machine Learning for a Context Mining Facility", *16th Workshop on Context and Activity Modeling and Recognition, 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, **2020**, pp.678-684.

3.1.2 Bibliometric

This research work on context mining began in 2012, with Ali Jaffal's MSc. work, and continued until 2014 as part of his PhD thesis, under the supervision of Bénédicte Le Grand. Three papers directly resulting from this work can be cited here [117, 116, 120], to which it can be added our last article on the applicability of Machine Learning techniques to context information [23]. Moreover, this work has highlighted the potential use of FCA with context data, which has opened the door to several collaborations in other fields, notably BPM (Business Process Modeling). Several publications mentioned below (Adaptive 2013, BPMDS 2013, Chapter BPM 2014, CoMoRea 2020) are the result of these collaborations, which would not have taken place without this work on context mining. All these publications are listed below. As for the previous chapters, each publication has been analyzed, using the scholar.google.com website, concerning the number of citations. These citations have been organized into two categories, according to their publication date: before 2016 (up to 3 years after the first publication) or after 2016. Self-citations were also included. Table 9 details the data obtained, illustrated in Figure 9.

- **ANT 2015** [69]: Jaffal, A. ; Grand, B. L. ; Kirsch-Pinheiro, M., "Refinement Strategies for Correlating Context and User Behavior in Pervasive Information Systems", *1st Workshop on Big Data and Data Mining Challenges on IoT and Pervasive (Big2DM), 6th International Conference on Ambient Systems, Networks and Technologies (ANT-2015)*, Procedia Computer Science, vol. 52, Jun **2015**, pp.1040-1046. DOI : http://dx.doi.org/10.1016/j.procs.2015.05.103
- **Ubicomm 2014** [70]: Jaffal, A. ; Kirsch-Pinheiro, M. & Le Grand, B., "Unified and Conceptual Context Analysis in Ubiquitous Environments", In : Jaime Lloret Mauri, Christoph Steup, Sönke Knoch (Eds.), *8th International Conference on Mobile Ubiquitous Computing, Systems, Services and Technologies (UBICOMM 2014)*, August 24 - 28, **2014**, ISBN 978-1-61208-353-7, IARIA, pp. 48-55.
- **EGC 2016** [73]: Jaffal, A.; Grand, B. L. & Kirsch-Pinheiro, M., « Extraction de connaissances dans les Systèmes d'Information Pervasifs par l'Analyse Formelle de Concepts », Extraction et Gestion des Connaissances (EGC 2016), Revue des Nouvelles Technologies de l'Information, RNTI-E-30, 2016, pp. 291-296
- **AdaptiveCM 2013** [88]: Kirsch-Pinheiro, M. & Rychkova, I., "Dynamic Context Modeling for Agile Case Management", In : Y.T. Demey and H. Panetto (Eds.), *2nd International Workshop on Adaptive Case Management and other non-workflow approaches to BPM (AdaptiveCM 2013), OnTheMove Federated Workshop (OTM 2013 Workshops)*, LNCS 8186, Graz, Austria, 9-13 September **2013**, Springer, pp. 144–154, 2013.
- **BPMDS 2013** [134]: Rychkova, I. ; Kirsch Pinheiro M. & Le Grand B., "Context-Aware Agile Business Process Engine: Foundations and Architecture", In : Nurcan, S., Proper, H., Soffer, P., Krogstie, J., Schmidt, R., Halpin, T. & Bider, I. (Eds.), *Enterprise, Business-Process and Information Systems Modeling, Proceedings of the 14th Working Conference on Business Process Modeling, Development, and Support (BPMDS 2013)*, Lecture Notes in Business Information Processing, vol. 146, Valence : Espagne, **2013**, pp. 32-47.
- **Chapitre BPM 2014** [135]: Rychkova I. ; Kirsch-Pinheiro M. & Le Grand B., "Automated Guidance for Case Management: Science or Fiction?", In : Ficher, L. (Ed.), *Empowering Knowledge Workers: New Ways to Leverage Case Management*, Series BPM and Workflow Handbook Series, Future Strategies Inc., **2014**, pp. 67-78. ISBN : 978-0-984976478
- **CoMoRea 2020** [11]: Ben Rabah, N.; Kirsch Pinheiro, M.; Le Grand, B.; Jaffal, A. & Souveyet, C., "Machine Learning for a Context Mining Facility", *16th Workshop on Context and Activity Modeling and Recognition, 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, **2020**, pp.678-684

As can be seen from Table 9, these articles still have a small number of citations, most of them concentrated in the early years of their appearance (see Figure 38). This behavior is not surprising since, on the one hand, context mining remains a relatively confidential and developing field, especially when aimed at identifying the relevance of contextual information. Few authors have addressed this issue, with most works focusing on identifying a user's activities. On the other hand, the use of the notion of context in BPM is not yet generalized, even if this use is developing more and more (*e.g.* [129,140]), which explains the higher number of citations for publications in this field. From this information, it seems evident that, for the moment, the main impact of this work cannot be measured in terms of citations. Instead, it must be evaluated in terms of the opportunities it has opened up and in terms of the collaborations it has allowed to develop. In addition to the publications mentioned above (Adaptive 2013, BPMDS 2013, Chapter BPM 2014, CoMoRea 2020), born of exchanges with other researchers, the exchanges around context mining also led to an invitation to Arun Ramakrishnan's PhD thesis jury [133], at the K.U. Leuven university, as an external member of the jury.

Table 4. Bibliometric analysis concerning papers on context mining.

	Year	Total	≤ 2016	> 2016	Self-citation
ANT 2015	2015	2	1		1
Ubicomm2014	2014	7	1	1	5
EGC 2016	2016				
AdaptiveCM 2013	2013	5	2	2	1
BPMDS 2013	2013	10	4	5	1
Chapitre BPM 2014	2014	2	1	1	
CoMoRea 2020	2020				
Total / %		**21**	**42,86 %**	**28,57 %**	**28,57 %**

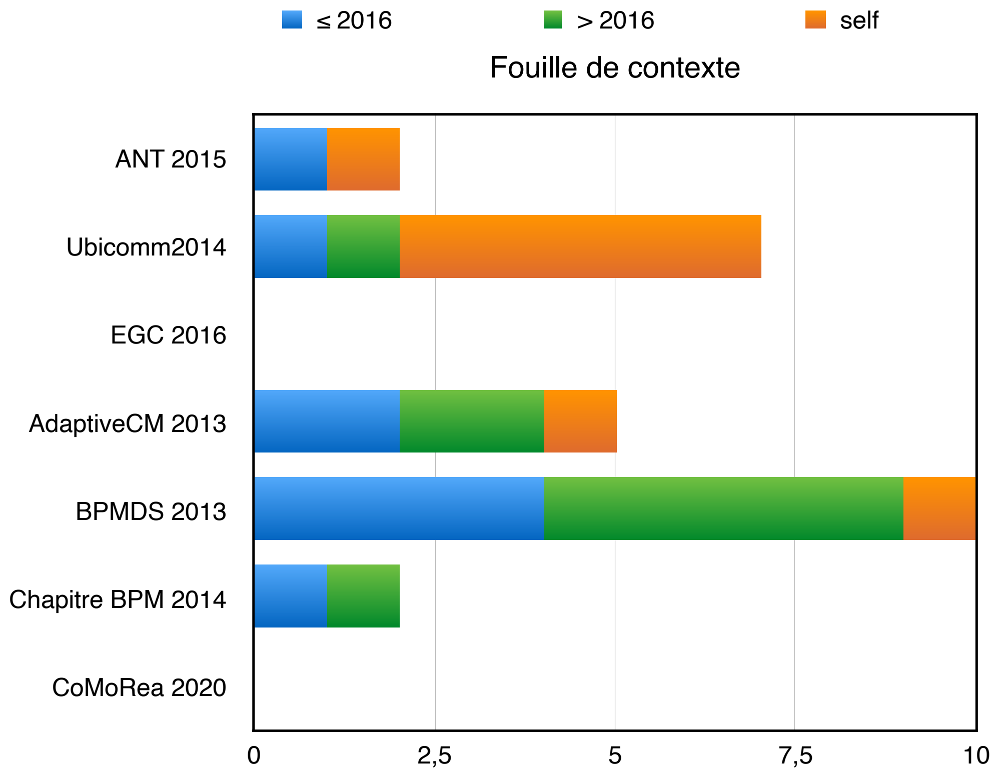

Figure 9. Citations evolution for context mining works over different periods of time.

3.2 Service selection using graphs

3.2.1 Problem statement

In a pervasive environment, characterized by its dynamism and its heterogeneity, the same service can have several distinct implementations. Indeed, a service offers an interface allowing a customer to invoke it without knowing how it is implemented. This principle of an invokable unit through a "standard" interface makes service orientation an interesting paradigm for managing interoperability. Under this interface, it is possible to imagine different implementations (for example, proposed by different vendors or offering different qualities). As pervasive environments are particularly heterogeneous, proposing alternative implementations for the same interface become interesting, even desirable, in order to better support variability on these environments.

Such variability raises the question of choosing the implementation that adapts the best to the execution circumstances. These circumstances can be assimilated to the execution context of a service (or its client). However, since the context information is uncertain and often incomplete, the lack of information can significantly impact the selection mechanism. In this case, a second question arises: how to choose the implementation of a service that is best adapted to the execution context, knowing that this information may be incomplete? The work described here addresses precisely this question.

Carried out between 2008 and 2009 as part of the European project IST-MUSIC, this research work proposes a context-aware service selection mechanism based on graph comparison, inspired by the similarity measures proposed for groupware systems (chapter 1). From a first selection, in which only the functional aspects are considered, this mechanism seeks to identify the implementation (already meeting the functional demand) that best suits the current context of use. The mechanism considers that each implementation is designed to target specific situations (*e.g.* a service aimed particularly at customers in a particular geographical area or requiring specific resources). These situations are described by a “required” context associated with the OWL-S description of the service. This context is then compared to the customer's execution context. These two descriptions (the required context and the client context) are interpreted as graphs, in which the context elements are seen as nodes and their relationships as arcs connecting them. The two graphs are compared using different similarity measures: first so-called “local” measures, which compare the nodes individually, and then “global” measures, which look at both graphs as a whole. Finally, the results obtained by these measures are used to rank the implementations responding to the functional aspects, thus making it possible to select the one that is the most favorable to the execution context on the client side.

In this mechanism, context information is then considered as a non-functional requirement associated with each implementation of a service. The objective is to sort out the different implementations that can satisfy the customer's request and select the one that seems to better match the context of use.

Besides, the present work has influenced in its turn other following works, such as Salma Najar’s PhD thesis [107] (whose contribution is discussed in the following sections), in which we adopt the same idea of a required context in the description of services presented in this work. The implementation also follows the same inspiration, with a “context” element added to the service description pointing to an external XML description, which can be updated more easily.

This service selection mechanism was first published in NFPSLA-SOC 2008 workshop [87]. This paper detailing the proposed mechanism is presented in the Annex VII.

- **NFPSLA-SOC 2008** [87] : Kirsch-Pinheiro, M.; Vanrompay, Y. & Berbers, Y., « Context-aware service selection using graph matching ». In: Paoli, F. D.; Toma, I.; Maurino, A.; Tilly, M. & Dobson, G. (Eds.), *2nd Non Functional Properties and Service Level Agreements in Service Oriented Computing Workshop (NFPSLA-SOC'08), at ECOWS 2008*, CEUR Workshop proceedings, vol. 411, **2008**.

3.2.2 Bibliometric

The research work described here has led to three publications, including a book chapter. It has also allowed the production of a fourth publication (Chapter IGI 2009), in which different concerns of context-aware applications are analyzed. These publications are listed below. Data concerning citations of these papers have been obtained, as for previous chapters, from Web site scholar.google.com. These citations have been organized in groups (see Table 4), according to the date of their publication (before 2013, between 2013 and 2016, and after 2016), in addition to self-citations. Figure 10 illustrates these results.

- **NFPSLA-SOC 2008** [87] : Kirsch-Pinheiro, M.; Vanrompay, Y. & Berbers, Y., « Context-aware service selection using graph matching ». In: Paoli, F. D.; Toma, I.; Maurino, A.; Tilly, M. & Dobson, G. (Eds.), *2nd Non Functional Properties and Service Level Agreements in Service Oriented Computing Workshop (NFPSLA-SOC'08), at ECOWS 2008*, CEUR Workshop proceedings, vol. 411, **2008**.
- **CAMPUS 2009** [165] : Vanrompay, Y.; Kirsch-Pinheiro, M. & Berbers, Y., "Context-Aware Service Selection with Uncertain Context Information", *Context-Aware Adaptation Mechanism for Pervasive and Ubiquitous Services 2009 (CAMPUS 2009), Electronic Communications of the EASST, vol. 19*, **2009**.
- **Chapitre IGI 2011** [166] **:** Vanrompay, Y.; Kirsch-Pinheiro, M. & Berbers, Y., "Service Selection with Uncertain Context Information", In: Stephan Reiff-Marganiec and Marcel Tilly (Eds.), *Handbook of Research on Service-Oriented Systems and Non-Functional Properties: Future Directions*, IGI Global, pp. 192-215, **2011**.
- **Chapitre IGI 2009** [130] **:** Preuveneers, D.; Victor, K.; Vanrompay, Y.; Rigole, P.; Kirsch Pinheiro, M. & Berbers, Y. « Context-Aware Adaptation in an Ecology of Applications ». In: Dragan Stojanovic (Ed.), *Context-Aware Mobile and Ubiquitous Computing for Enhanced Usability: Adaptive Technologies and Applications*, IGI Global, **2009**.

The first of these publications (NFPSLA-ECOWS 2008 [87]) describes the principles of this mechanism, while the subsequent publications (CAMPUS 2009 [165] and Chapter IGI 2011 [166]) have further improved it by adding quality consideration through metadata and transformation functions. The last of these publications (Chapter IGI 2011 [166]) is the one with the most self-citations, since it summarizes, in a rather complete way, the contributions of the previous publications. It has thus been used as a reference for the works following this one.

Table 5. Bibliometric analysis of publications concerning graph service selection research works.

Reference	Year	Total	≤ 2013	> 2013 & ≤ 2016	> 2016	Self-citation
NFPSLA-ECOWS 2008	2008	43	22	11	3	7
CAMPUS 2009	2009	9	1	4	4	0
Chapitre IGI 2009	2009	19	7	6	0	6
Chapitre IGI 2011	2011	11	0	3	0	8
Total / %		**78**	**28,21 %**	**41,03 %**	**3,85 %**	**26,92 %**

Among these publications, the one with the most citations remains the first, presenting the mechanism's founding principles. These citations are spread over the first 8 years following its publication (from 2008 to 2016) and fade after this date. This period (2008 to 2016) corresponds to a period in which service orientation has been widely discussed in Pervasive Computing. Today, the notion of service, as described in the SOA community, is gradually being replaced by the notion of micro-service. Even though conceptually these two notions are fundamentally similar, the micro-service approach is now perceived as more advantageous because it is more suitable for implementation in a virtualization and Cloud Computing context. In any case, the proposals from this research work remain valid and could, if necessary, be adapted to the micro-service concept.

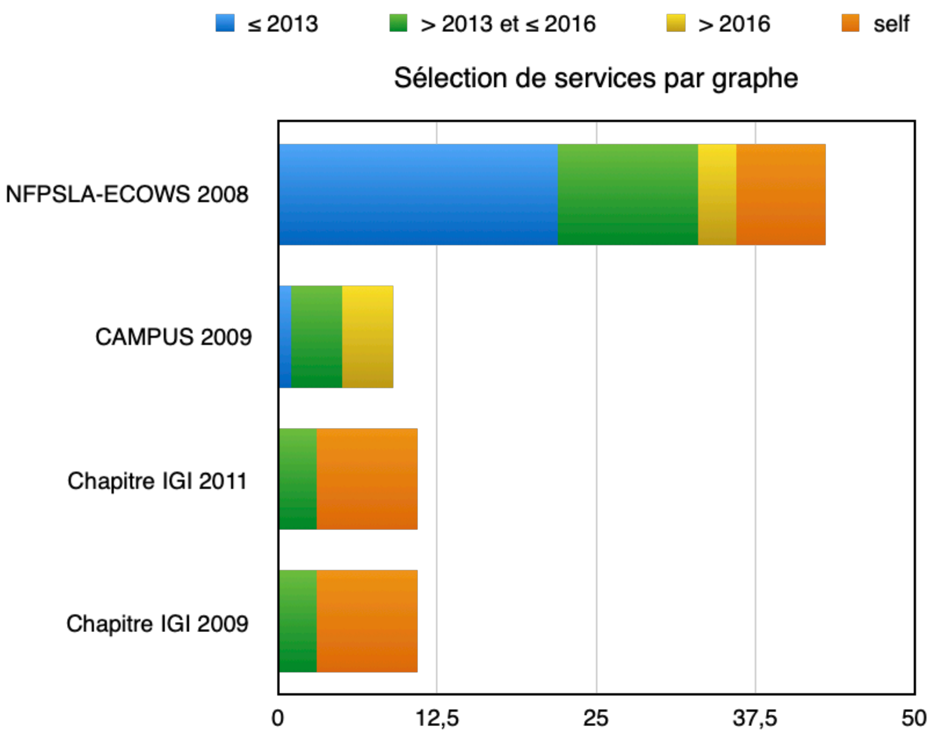

Figure 10. Distribution of the papers citations all along the time.

3.3 Service selection by the user's intention and context

3.3.1 Problem statement

The introduction of new technologies (such as smartphones, IoT, Big Data) brings profound changes in organizations and in their Information Systems (IS), as they are now facing a pervasive environment. These systems and their users are thus confronted with a growing heterogeneity that must be managed. Since these systems are transforming and becoming more and more complex with the arrival of new technologies, it becomes crucial to hide the heterogeneity of these systems and the services in such way users may focus more on the objectives to be achieved rather than on these technologies. More than ever, systems need to evolve towards the vision Ubiquitous Computing given by Weiser [171] in which technology becomes invisible to the user. These new systems, which can be called Pervasive IS (which will be discussed in chapter 4), have an increasing need for transparency. Therefore, this research work aims at improving the transparency of Information Systems by hiding the technical details concerning the services, by taking into account the notion of context and the user's business goals, represented by the notion of intention.

Carried out between 2009 and 2012 along with Salma Najar's Ph.D. thesis [107], this work proposes a service selection mechanism that takes into account both the user's context and her/his intention. The notion of intention corresponds to a widely recognized notion in the field of Requirements Engineering [174, 68, 163, 136]. It is used to represent the user's business goals and has already been associated with the notion of service in the past [46, 74, 103, 137, 141].

The use of the notion of intention denotes the user-centered focus adopted by the present work, which distinguishes it from previous works on service selection (cf. section 3.2). Although previous work considers the context in which a service is requested, it considers mainly the context of a client application requesting the execution of a service. In the present works, the user is directly considered, with her/his needs and context of use. The main focus when analyzing the notion of context is, therefore, the user herself/himself. This user-centered approach can also be found in our research works on Pervasive Information Systems, which will be discussed later (see Chapter 4).

Besides, this work is based on the hypothesis that an intention emerges in a particular context, which in turn influences the choice of an implementation. In other words, users would invoke a service because they have a particular intention (*i.e*. a goal to achieve) that arises in a particular context, which in its turn will determine the choice of the service implementation to be executed. This work was among the first ones (in 2009) connecting the user's intentions, her/his context of use, and the services invoked. We may cite [141, 46] as examples of works combining the notion of intention with the notion of context. However, it is worth noting that, unlike those works, ours propose a detailed semantic description of both the notions of intention and context, which is not necessarily the case in other works in the literature such as [141, 46], who focus more on one or another of these aspects.

The selection mechanism itself is a two-step mechanism, taking advantage of both an ontology describing the notion of intention and an ontology modeling the notion of context. In the first step, the intention requested by the user and likely to be satisfied by a service is analyzed and related to those declared by the available services (through their descriptors). It is important to note that the service look up is made directly on the basis of its intention and no longer according to the functionalities offered by the service, as traditionally in the SOA approach. The functional description of a service (corresponding to the functionalities expected by the service, expressed through the operations it is capable of performing) remains hidden from the user, who looks for a service only through its intention (*i.e*. its business goals). In the second step, the mechanism compares, using the context ontology, the elements present in the context required by the service and those present in the user's current context, evaluating to which extension the conditions expressed in the required context are fulfilled by the elements in the user's context. The values present in the user's observed context (at user side) are thus confronted with these conditions in order to assess their level of satisfaction. The score obtained by each service over these two steps is then used to rank the available services. It is worth noting that, similar to our previous works (cf. section 3.2), a service can be proposed to a user even if its required context does not fully correspond to the user's current context.

This research work was the subject of multiple publications (see section 3.3.2), considering different aspects of this work, from the semantic descriptions proposed for it until the selection mechanism itself. Among these publications, the paper published at ICWS 2012 appears as the most complete one, detailing the proposed mechanism and some experiments we have performed in order to validate the mechanism. This paper is proposed on the Annex VIII.

- **ICWS 2012** [118] : Najar, S.; Kirsch-Pinheiro, M.; Souveyet, C. & Steffenel, L. A., "Service Discovery Mechanisms for an Intentional Pervasive Information System". *Proceedings of 19th IEEE International Conference on Web Services (ICWS 2012)*, Honolulu, Hawaii, 24-29 June **2012**, pp. 520-527.

3.3.2 Bibliometric

As with the works discussed previously, this research work also led to several publications (a total of 7), including a journal paper. This subject is also mentioned in two other publications, including our developments on service prediction (cf. section 3.4), which will be considered in the next section. Thus, similar to previous chapters, the publications cited below have been organized in different groups (see Table 6), according to their publication date (before 2013, between 2013 and 2016, and after 2016), in addition to self-citations. Figure 11 illustrates these results.

- **CIAO 2009** [108]: Najar, S.; Saidani, O.; Kirsch-Pinheiro, M.; Souveyet, C. & Nurcan, S., "Semantic representation of context models: a framework for analyzing and understanding". In: J. M. Gomez-Perez, P. Haase, M. Tilly, and P. Warren (Eds), *Proceedings of the 1st Workshop on Context, information and ontologies (CIAO 09), European Semantic Web Conference (ESWC'2009)*, Heraklion, Greece, June **2009**, ACM, pp. 1-10.
- **Service 2011** [110]: Najar, S.; Kirsch Pinheiro, M. & Souveyet, C., "Bringing context to intentional services". *3rd Int. Conference on Advanced Service Computing, Service Computation'11*, Rome, Italy, pp. 118-123, **2011**. Best Paper Awards.
- **REFS 2011** [109]: Najar, S.; Kirsch Pinheiro, M. & Souveyet, C., "The influence of context on intentional service". *5th Int. IEEE Workshop on Requirements Engineerings for Services (REFS'11), IEEE Conference on Computers, Software, and Applications (COMPSAC'11)*, Munich, Germany, pp. 470-475, **2011**.
- **WEWST 2011** [111]: Najar, S.; Kirsch Pinheiro, M. & Souveyet, C., "Towards Semantic Modeling of intentional pervaisve System", *6th International Workshop on Enhanced Web Service Technologies (WEWST'11), European Conference on Web Services (ECOWS'11)*, Lugano, Switzerland, **2011**, pp. 30-34.
- **IJAIS 2012** [106]: Najar, S. ; Kirsch-Pinheiro, M. & Souveyet, C., "Enriched Semantic Service Description for Service Discovery: Bringing Context to Intentional Services", *International Journal On Advances in Intelligent Systems*, volume 5, numbers 1 & 2, June **2012**, pp. 159-174, IARIA Journals / ThinkMind, ISSN: 1942-2679.
- **ICWS 2012** [118]: Najar, S.; Kirsch-Pinheiro, M.; Souveyet, C. & Steffenel, L. A., "Service Discovery Mechanisms for an Intentional Pervasive Information System". *Proceedings of 19th*

IEEE International Conference on Web Services (ICWS 2012), Honolulu, Hawaii, 24-29 June **2012**, pp. 520-527.

- **UbiMob 2012a** [119]: Najar, S. ; Kirsch-Pinheiro, M. ; Steffenel, L. A. & Souveyet, C., « Analyse des mécanismes de découverte de services avec prise en charge du contexte et de l'intention ». In : Philippe Roose & Nadine Rouillon-Couture (dir.), *8èmes Journées Francophones Mobilité et Ubiquité (Ubimob 2012)*, June 4-6, **2012**, Anglet, France. Cépaduès Editions, pp. 210-221. ISBN 978.2.36493.018.6.

Table 6. Citations concerning papers on context and intention service selection obtained from Google Scholar

Reference	Year	Total	≤ 2013	> 2013 & ≤ 2016	> 2016	Self-citation
CIAO 2009	2009	51	14	8	11	18
Service 2011	2011	6	2	2	0	2
REFS 2011	2011	13	1	2	2	8
WEWST 2011	2011	7	0	3	0	4
IJAIS 2012	2012	4	0	0	1	3
ICWS 2012	2012	18	4	4	3	7
UbiMob 2012a	2012	1	0	0	0	1
Total / %		**100**	**21,00 %**	**19,00 %**	**17,00 %**	**43,00 %**

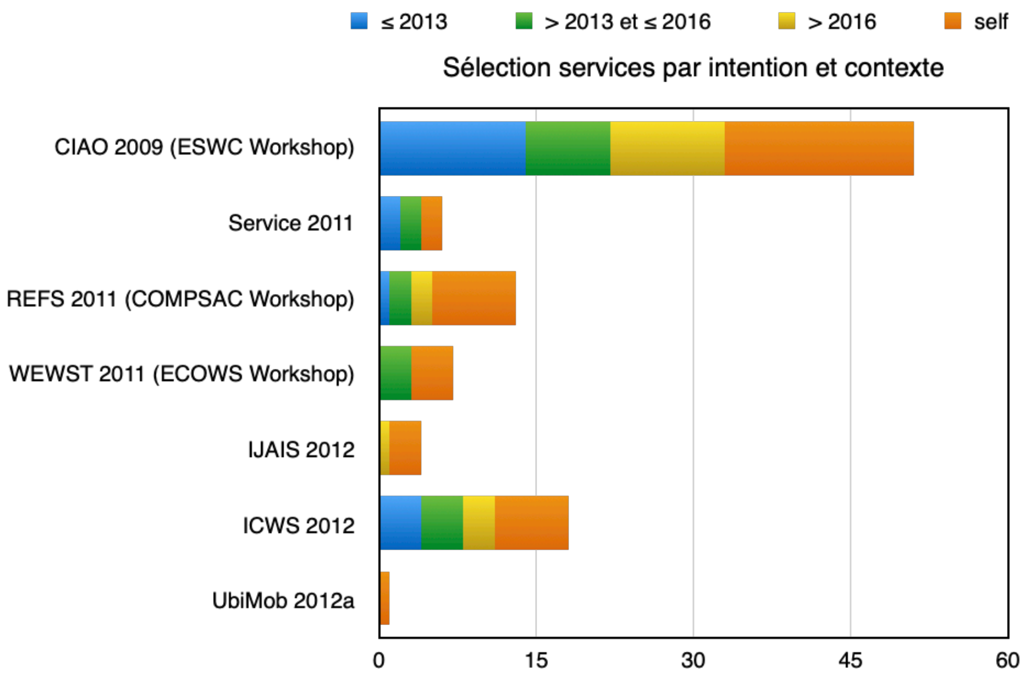

Figure 11. Graphic illustrating the evolution of papers citation over the time.

Among these publications, the one with the most citations (CIAO 2009 [108]) provides a framework for the analysis and the comparison of different context models. This framework has been widely used in our subsequent works for the analysis of the proposed context models. Focusing the analysis of context models in a general way may also explain the more significant impact of this article in terms of citations compared to other publications mentioned here. It should also be noted that the significant number of self-citations in these publications is justified by continuity of this work, many of which have served as a basis for further work.

Finally, one may also observe that most of the citations are concentrated in the first 4-6 years following the publications (from 2009 to 2016), which corresponds to a period when the selection of services reflected a popular research problem in the literature on Pervasive Computing.

3.4 Service prediction

3.4.1 Problem statement

When considering the evolution of Information Systems (IS) towards Pervasive IS, these new systems are characterized, among other things, by an increased need for transparency, as discussed earlier (see section 3.3). Hiding the technological complexity that now characterizes IS from end-users is essential, freeing users from technological constraints so that they could concentrate on tasks with an added value to the organization. To do this, proactivity becomes a necessity. Indeed, users expect an increasingly "intelligent" IS, capable of anticipating their needs and responding to them appropriately. According to Bauer & Dey [7], we can already witness a move towards increasingly sophisticated systems ("smart", "intelligent", "context-aware", "adaptive", etc.). Here, the notion of context is central as systems become aware of the context in which they are used and intelligently adapt their execution. We believe that the democratization of this kind of behavior that could be considered "intelligent" creates a certain expectation on the users: they now expect that a software and a system will be more intelligent, it will be able to recognize their situation, their behavior, and to adapt itself in a reactive way as well as in a proactive way. Thus, we advocate that Information Systems must be able to recognize user's habits and practices in order to be able to anticipate users' needs and proactively propose to these users the services that correspond the best to their needs.

Similar to the works presented in the previous section (cf. section 3.3), this research work on service prediction is also part of Salma Najar's PhD thesis [107]. In these works, carried out between 2012 and 2014, a service prediction mechanism is proposed. This mechanism allows, based on the user's history and her/his current context, to anticipate the user's future intentions and context of use, and thus to proactively provide her/him the next service that the user would probably request. The main objective here is to anticipate the user's next intentions and context of use from the her/his history and current context of use, and then be able to proactively provide her/him the next service that this user will most probably request.

The basic hypothesis of the one describing the user as someone with particular habits and work practices. During her/his professional activities, a user of an IS can acquire certain work habits related to her/his professional routine (for example, a salesman who solicits on her/his tablet data about a client when she/he arrives at this client's office). We assume that it is possible to characterize, and therefore automatically identify, these habits through the intentions behind these actions (the reason motivating the service request) and the context in which these intentions arise.

It is important to note that this research on service prediction work also considers the triplet "*< intention, context, service >*", similar to our works on intentional and contextual service selection, presented previously (cf. section 3.3). In addition, the traces resulting from this selection mechanism are considered here. Thus, from the traces of previous solicitations, by applying a clustering algorithm, the proposed prediction mechanism will first group similar situations already observed by comparing them using different similarity measures. Each situation is represented by the triplet "*< intention, context, service >*" from a previous user's request (and thus from a previous service selection process). These clusters are organized using a Markov chain model, which calculates, from the known data about these situations, the probability of moving from one cluster (*i.e.* from a "typical" situation) to another. Thanks to this model, and as soon as the current situation (*i.e.* the expressed intention, the current context, and the service selected to meet this demand) is sufficiently similar to an already identified cluster, it is possible to anticipate the next most probable situation (intention, context, and service).

Anticipating the triplet *"< intention, context, service >"* thus responds to the habit hypothesis stated above, but also to the founding hypothesis of Salma Najar's PhD work, already used in the previous works on service selection (see section 3.3). This hypothesis establishes that an intention emerges in a particular context, which influences the choice of which service implementation is most likely adapted to satisfy this intention. Thus, even if this mechanism leads to the prediction of the next service to be invoked on the user's behalf, it determines not only the next service but all the triplet "*< intention, context, service >*". Therefore, it is the intention and the context in which it emerges that are anticipated here. This behavior differs from other works on context prediction, such as [95, 102, 148, 167], which focus on predicting the next context of use or on missing elements in the observed context. Our work can also be distinguished from those, such as [62], which focus on predicting context-aware services. Generally speaking, service prediction can be compared to recommendation systems [1, 19, 128], whose objective is often to propose personalized content according to other users' traces, but also to works considering recommendation in business processes [20, 39, 59]. Here again, the notion of intention and context are not combined in an anticipation process, either of an activity or a service. To the best of our knowledge, our work remains one of the few to have combined these two elements (context and intention) in a prediction mechanism.

Finally, it should be emphasized that the clustering process used in our work is based on the similarity of concepts, which means that the user does not need to behave precisely as in a previous situation. This is particularly important, especially with regard to the dynamic nature of context information, which can vary between multiple observations. If these variations are not significant, it is still possible to classify a request, even if it is not exactly the same as those observed previously.

Similar to our previous works, this research work produced several publications, focusing on different aspects of the service prediction mechanism. Among these publications (see section 3.4.2), the paper published on ICWS 2014 [115] details the proposed mechanism and present some experimental results on it. This paper is proposed in the Annex IX.

- **ICWS 2014** [115]: Najar, S. ; Kirsch-Pinheiro, M. & Souveyet, C., "A context-aware intentional service prediction mechanism in PIS", In: David De Roure, Bhavani Thuraisingham & Jia Zhang (Eds.), *IEEE 21st International Conference on Web Services (ICWS 2014)*, 27 June - 2 July **2014**, Anchorage, Alaska, USA, IEEE CS, pp. 662-669. DOI : 10.1109/ICWS.2014.97

3.4.2 Bibliometric

This work on service prediction has resulted in 5 publications, cited below. As for previous works, we have studied the citations to these works, obtained from scholar.google.com Web site. According to their date of publication, these citations have been organized in two groups (pre-2016 and post-2016), covering the first years after the appearance of these publications and the last 4 years. Table 7 groups this information, illustrated in Figure 12.

- **UbiMob 2012b** [120] : Najar, S. ; Kirsch-Pinheiro, M. & Souveyet, C., « Mécanisme de prédiction dans un système d'information pervasif et intentionnel », In : Philippe Roose & Nadine Rouillon-Couture (dir.), *8èmes Journées Francophones Mobilité et Ubiquité (Ubimob 2012)*, June 4-6, **2012**, Anglet, France. Cépaduès Editions, pp. 146-157. ISBN: 978.2.36493.018.6
- **ICWS 2014** [115] : Najar, S. ; Kirsch-Pinheiro, M. & Souveyet, C., "A context-aware intentional service prediction mechanism in PIS", In: David De Roure, Bhavani Thuraisingham & Jia Zhang (Eds.), *IEEE 21st International Conference on Web Services (ICWS 2014)*, 27 June - 2 July **2014**, Anchorage, Alaska, USA, IEEE CS, pp. 662-669. DOI : 10.1109/ICWS.2014.97
- **ANT 2014** [116] : Najar, S. ; Kirsch-Pinheiro, M. & Souveyet, C., "A new approach for service discovery and prediction on Pervasive Information System", *5th International Conference on Ambient Systems, Networks and Technologies (ANT-2014), Procedia Computer Science*, vol. 32, **2014**, Elsevier, pp. 421–428. DOI : http://dx.doi.org/10.1016/j.procs.2014.05.443
- **Chapitre IGI 2013** [117] : Najar, S.; Kirsch Pinheiro, M.; Vanrompay, Y.; Steffenel, L.A. & Souveyet, C., "Intention Prediction Mechanism in an Intentional Pervasive Information System", In : Kolomvatsos, K., Anagnostopoulos, C., Hadjiefthymiades, S. (Eds.), *Intelligent Technologies and Techniques for Pervasive Computing*, IGI Global, **2013**, pp. 251-275. DOI: 10.4018/978-1-4666-4038-2.ch014, ISBN : 978-1-4666-4040-5.
- **JAIHC 2015** [114] : Najar, S.; Kirsch-Pinheiro, M. & Souveyet, C. "Service discovery and prediction on Pervasive Information System", *Journal of Ambient Intelligence and Humanized Computing*, vol. 6, issue 4, June **2015**, Springer Berlin Heidelberg, pp. 407-423. ISSN: 1868-5137. DOI: http://dx.doi.org/10.1007/s12652-015-0288-5

Table 7. Bibliometric analysis of papers related to the service prediction topic, based on Google Scholar data.

Reference	Year	Total	< 2016	≥ 2016	Self-citation
UbiMob 2012b	2012	2	2	0	0
ICWS 2014	2014	1	0	1	0
ANT 2014 :	2014	18	2	14	2
Chapitre IGI 2013	2013	2	1	0	1
JAIHC 2015	2015	8	0	5	2
Total / %		**31**	**16,13 %**	**64,52 %**	**19,35 %**

As can be seen from Table 7, the number of citations to these papers is still limited. The relatively recent nature of this work partly explains this phenomenon. Besides, one may observe in Figure 12 that most citations were made from 2016 onwards, suggesting a theme that is still in development. Indeed, the recent development of Machine Learning and Artificial Intelligence techniques could bring a new perspective to this work, carried out before the democratization of these techniques.

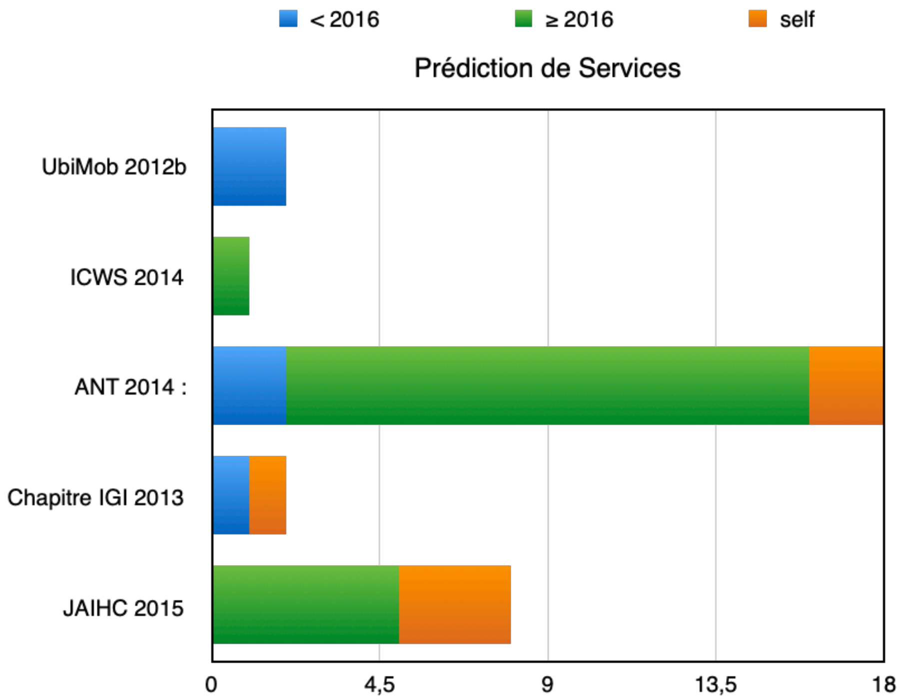

Figure 12. Evolution of citations concerning service prediction papers over the time.

3.5 Chapter Summary

In the previous sections, several contributions in the Pervasive Computing community have been highlighted: context mining by FCA, service selection based on the context of use and also service selection based on the user's context and intention, and finally service prediction. All these works were carried out between 2008 and 2014 (2012-2014 for context mining, 2008-2009 for graph selection, 2009-2012 for selection by intention and context, and 2012-2014 for service prediction), involving two Ph.D. thesis (Ali Jaffal 2012-2014 and Salma Najar 2009-2014), but also a European project (the IST-MUSIC project in 2008 for service selection with graphs).

The common denominator of these works, beyond the notion of context, is the use of the notion of service: the functionalities proposed by a system are encapsulated behind this notion. The service notion represents an interesting asset for the Pervasive Computing community, not only because of the interoperability services offer, but also because of the transparency they may provide, since different technologies can be hidden behind this notion. Besides, the loose coupling that characterizes service orientation enables better management of the dynamic nature of pervasive environments.

The various contributions presented here differs from others works considering context-aware services by considering the uncertainty of context data and the user's intention. Our works on service selection bring the idea of a required context, which explores the idea that a particular implementation is designed assuming a specific client-side execution context. Setting conditions to the user's context is a topic with limited coverage in the literature, mostly focused on the execution context at the provider side. Indeed, the numerous works involving SLA and QoS mostly focus only on the provider-side, considering whether or not the provider can provide the service as desired. However, taking the user's context into account in the service selection process opens the door to a better consideration of this user and places her/him in the center of the process. We find here the basis of a user-centered vision that particularly characterizes our work.

These works on service selection by intention and context have consolidated our user-centric vision, based on the assumption that a service is solicited to satisfy an intention in a given context. Intention emerges in this context, which also influences the service selection and its execution. This hypothesis remains innovative and opens up exciting perspectives for Information Systems, in which the notion of intention can easily be associated with expected or high value-added functionalities and services.

Besides, other aspects should also be emphasized in the contributions presented here, starting with the application of the FCA for the identification of usage situations from the observed data. The use of FCA is an innovative approach to context data mining since it allows a multi-class classification of these elements, which can be particularly interesting for the identification of complex situations. A situation can be seen as a set of context elements that characterize the circumstances of an action. The notion of situation allows representing a higher level of granularity than simple context elements. On this level, it is easier to assign a certain semantics from the user's point of view to this set of elements, hence the importance of the overlaying character of the FCA. Having possible overlaps between classes provides more flexibility for better identification of these situations. Nevertheless, the challenges for a fully automated (or semi-automated, with minimal human intervention) use of this method remain.

Finally, it should also be noted that the use of the triplet *"< intention, context, service >"*, especially in our work on service prediction, is one of the most characteristic features of these works. It is a rather innovative approach that foresees a more proactive functioning for Information Systems. More than anticipating the next service to be offered to a user, our work on prediction enables us to anticipate the user's next intention and a possible context for this intention to appear. We are again approaching the notion of situation, with a set of context elements now characterized by an intention. Furthermore, we find here again the user-centered vision that characterizes most of our work in this field. This vision is further developed in Chapter 4, which focuses on the Pervasive Information Systems.

4 Context on Pervasive Information Systems

The work described in this chapter focuses particularly on Information Systems and their "new generation", here called Pervasive Information Systems (PIS), in which the notion of context plays a central role.

In order to better understand this evolution of Information Systems (IS), we shall first look at the recent transformations undergone by IS. The last decade has witnessed several technological evolutions and new uses that have strongly impacted IS. Among the new trends that have emerged in recent years, we may cite 4G and BYOD, IoT, Big Data, Cloud Computing and Fog Computing, and the democratization of Machine Learning.

The development of mobile technologies, including 4G, has contributed to the democratization of the Internet access with a reasonable bandwidth almost everywhere, which has also contributed to the adoption of the BYOD (Bring Your Own Device) practice. BYOD consists in using one's own personal computer at work. According to this practice, employees use their own personal terminals to work, navigating seamlessly between their private and work spaces, instead of accumulating multiple terminals according to circumstances, location or professional needs [27]. This mix of personal and professional hardware represents a significant change for organizations IT departments, which traditionally govern, deploy and control all technologies used by employees/collaborators for their professional activities [41]. Today, it becomes common (or usual) to use your own personal devices (which are no longer limited to laptops) to access your company's information system, wherever you are. A ubiquitous access "Anytime, anywhere" from any kind of terminal has become a reality. According to Andriole & Bojanova [4], the use of new devices such as Microsoft HoloLens, Apple Watch, and other Bluetooth devices, creates new opportunities for businesses as these new devices are changing the way we browse, search, shop, and even live. It is therefore natural to think that the arrival of these new personal devices in organizations can also change the way we work.

Similarly, IoT also offers new opportunities of interacting with the physical environment, and through these new interactions, it brings new business perspectives. According to Sundmaeker *et al.* [160], it is expected that IoT objects will become more and more active, participating in different aspects of society, through business, information and social process [160]. The informational aspect remains probably the most prominent one within today's organizations. Thanks to the IoT, it is possible to easily (and even continuously) collect information from the physical environment, but also to act upon this environment through sensors and actuators often connected to networked nanocomputers with some computing power. The physical environment can then become an integral part of business processes and, consequently, part of the Information System itself, as shown by the recent development of Industry 4.0, which heavily relies on the IoT and on the data coming from it, as observed by Lu [100].

The data collected from IoT objects enriches an already large set of available data within organizations. Big Data platforms allow to better control this impressive data volume and to exploit it properly. The recent success of Data Lakes [186], often built on the top of platforms such as HDFS, is an excellent illustration of the definitive adoption of Big Data into organizations. This massive volume of data is now available to data scientists, who can extract an added value from it, thanks to multiple data analysis techniques, including those derived from Machine Learning, whose success often depends on the availability of such a large volume of data. Nonetheless, the possibility of performing such analysis depends on the availability of an appropriate infrastructure allowing this kind of exploitation.

Last but not least, the rise of Cloud Computing has enabled many organizations to rationalize their IT infrastructure. Cloud Computing can be seen as the ability to access a pool of resources owned and maintained by a third party via the Internet. It is not a new technology by itself, but a new way of consuming computing resources [47]. In the cloud model, the resources no longer belong to the organization, but they are most often "leased" from one or more providers according to the organization's needs. Cloud resources are thus perceived as having a low maintenance cost, switching to an on-demand model in which organizations may adapt their consumption according to their needs and only pay for the resources they actually consume. However, the adoption of the Cloud model is often accompanied by some fears related to the outsourcing of data and data processing. These fears concern in particularly security, confidentiality and network latency issues. The choice between deploying a certain service in an internal organizational resource or outsourcing it into a public Cloud resource becomes now as strategic as technical. Consequently, resources are more and more visible and must now be managed from more than just a technical perspective.

Fog Computing, discussed in Chapter 2, has reinforced this point. Fog computing can be seen as a new paradigm for disseminating computing, storage and service management closer to the end user, all along the continuum between the cloud, and objects (IoT) and end devices. Indeed, thanks to Fog Computing platforms, it is possible to consider the use of proximity resources for the execution of certain services. This makes it possible to consider the use of resources other than those located in data centers or in cloud platforms to run services, offering new perspectives for further rationalizing the use of available resources.

All these new technologies and trends are gradually entering into the composition of Information Systems, leading to their evolution. Today, we are observing the emergence of a new generation of IS that could be called pervasive, both by their distribution beyond the organization's boundaries, and by the pervasive nature of the environment they integrate. Thanks to these new technologies and practices, Information System can extend well beyond the physical limits of the organization. They are now accessible everywhere, they include resources both inside and outside the organization, and they can even integrate the physical environment itself. Notions of what is inside or outside an organization have become blurred with processes that use resources other than those within the organization's traditional perimeter [25]. The environment has become more and more heterogeneous, integrating very different devices, which can moreover be mobile, adding dynamism to the heterogeneity. Thus, we have Information Systems that are increasingly confronted with a heterogeneous and dynamic environment, integrating resources and services internal and external to the organization, and even the physical environment surrounding both these resources and the users. We may we expect from these systems more flexibility and a certain "smartness" in order to better carry out the organization's activities and better satisfy user's and organization needs.

A Pervasive IS can thus be seen as an emerging class of IS in which IT is gradually embedded in the physical environment, capable of accommodating users' needs and desires when necessary [96]. The term "Pervasive Information Systems" was introduced by Joel Birnbaum in 1997 [13]. In this article [13], the author considers a technology that becomes pervasive, and thus invisible to the human eyes: "Today's schoolchildren don't think of TVs and telephones as technology-they can't imagine life without them. Tomorrow's children will feel the same way about computers, the networks connecting them, and the services they perform". This corresponds to the "cognitive invisibility" reported by Bell & Dourish [10]. These authors mention a technology that is invisible to us, since we use it continuously without necessarily perceiving it as computers. Birnbaum [13] talks about an information technology that should become intuitively affordable for everyone and that should bring enough added value to justify the necessary investments. Considering the aforementioned evolutions and trends, as well as the opportunities they offer to the organizations, we may say that this point has been reached. And the consequences for IS are not insignificant. Birnbaum [13] emphasizes in particular the expectations with regard to the services offered. For this author, in the same way that people expected (in 1997) to have a dial tone when they picked up a telephone handset, people will (nowadays) wait for useful information to be available and ready for use. To sum up, even if Birnbaum [13] does not precisely define the notion of PIS as Kourouthanassis & Giaglis [96] do, the elements that he enumerates in his article, *i.e.* the technology that becomes "invisible", the importance of services and the added value of information, the paradigm shift with people paying by use, modifying what was before a capital investment in service, etc., characterize quite well what today's information systems are becoming.

Therefore, we are confronted with the emergence of Information Systems that extend beyond the physical (and logical) boundaries of the organization, that integrate new technologies and an environment that has itself become pervasive (in the technologically charged sense) in a more or less transparent way, and from which we expect more intelligent behavior, both reactive and proactive. For Kourouthanassis & Giaglis [96], unlike traditional IS, PIS encompass a more complex and dynamic environment, composed of a multitude of artefacts (and no longer just desktop computers), capable of perceiving the users' context and of managing the mobility of these users. In the literature, the term "mobile" IS [98] is also employed, with the notion of mobility used in a broad sense: spatial, temporal, but also contextual. Krogstie *et al.* [98] refer to systems characterized by their dynamism, by frequent changes of context (spatio-temporal, environmental context, but also relative to users, their tasks and even available information), and thus requiring an important capacity of adaptation from the system to the users. Even if these authors [98] mention in particular the adaptation of interfaces for a better interactivity with users, whatever the terminals they use, it is easy to imagine that this adaptation should be extended to the proposed services and their implementation.

This new generation of Information Systems (the Pervasive Information Systems) can be distinguished from traditional IS by different characteristics, obtained from the analysis of the literature, which can be associated with requirements that must be observed when designing a PIS [112]:

- Heterogeneity: a PIS must support the heterogeneity of devices and technologies that compose up pervasive environments;
- Transparency: a PIS must be transparent, being able to hide from the users the heterogeneity of pervasive environments;
- Context-awareness: any so-called pervasive system must be able to accomplish the requested functionalities, despite changes in the surrounding conditions or in the state of the system [138]. A PIS must be able to perceive its execution environment and to adapt itself accordingly;
- Goal-oriented: A PIS must be designed to meet and satisfy the users' goals in their business activities;
- Predictability: A PIS is expected to meet the user's business goals in a predictable and controlled manner. While it must take advantage of the dynamic environment and the opportunities that such an environment may provide, the behavior of a PIS, with all services and functionalities it offers to its users, must remain predictable, in order to ensure the governance of these systems and the confidence the users would have on them.

Thus, we may refer to PIS as an IS particularly characterized by the heterogeneity and the dynamic nature of the environments and resources involved, but also by their need for adaptation and context awareness. Unlike traditional IS, in which the users have often to adapt themselves to the system, PIS must consider the environment and the context of use in order to adapt itself and to provide users with the service that best corresponds to their needs and current context. These are systems, whose intention would be to increase the productivity of the users (and infrastructures) by providing them with adapted services, has to consider the heterogeneity of the environment, which turns to a pervasive environment. Context awareness becomes thus a key element since it provides the possibility of adaptation at different levels: interaction modes, services and information access, but also the infrastructure itself.

This evolution of IS towards Pervasive IS leads to several challenges, for which new approaches, adapted to the characteristics and to the constraints of this new generation, are necessary. Among these challenges, two retained our attention from 2013-2014: the design and the management of these systems; and the necessary resource management on these systems.

The first challenge that we focus concerns thus the design and the management of such a new generation of Information System, faced with unprecedent heterogeneity and dynamism, but that is always subject to constraints (and practices) specific to an IS. Indeed, a PIS is above all an IS. Its main objective remains to propose to users the necessary functionalities for a smooth and efficient running of the organization and its processes. These functionalities may assume many different forms, depending on the components and on the available technologies, but also depending on the context in which they are invoked. The heterogeneity of the overall environment, which has become pervasive, leads to more variability. This variability becomes essential for the system to better adapt its behavior to both the organization's and the user's context and goals. The design and managing of such a PIS can then be seen as a complex problem, as it becomes necessary to identify which services should be accessible to users and under what circumstances, while considering the heterogeneity of the environment and of the services involved. PIS can thus be characterized by an increased need for transparency, both for end-users and for the designers themselves, as the complexity of the pervasive environment must be hidden without losing completely (mainly for designers). The question then is how to design such a system while mastering its complexity? Or, more precisely, how to manage the services that need to be offered in order to meet the system's needs, while at the same time guaranteeing the transparency required for these new IS?

We should not forget that we are considering here systems that already exist, that are present and well established in organizations, and that are destined to evolve. It is thus essential to guide this evolution, to move the existing services towards a wider and better adapted offer. The challenge is to make the wide range of services offered by the IS accessible wherever and whenever they may be needed, regardless of the technologies involved.

Unfortunately, only a few abstractions or conceptual tools exist today to help Information System designers (or managers) in this transition from a traditional IS to a Pervasive IS. The IT departments are often left by their own face this challenge. Therefore, the first contribution we present in this chapter tackles this issue, by proposing an abstraction for these systems. This abstraction, known as the "Space of Pervasive Service", is presented as a conceptual tool that can be used to better handle the complexity of a PIS, proposing a first step towards a better management of PIS as a whole.

The second challenge that we are focusing on here concerns the management of resources in a PIS. For years, the notion of resources (in the sense of IT resources) that enables the execution of services has received little attention in modeling and conceptualization of IS. This is mainly due to the fact that the resources available in an IS were mostly stable and homogeneous. This is particularly true when concerning "data centers" and similar structures, in which all services offered by the IS are executed. Consequently, resources were not perceived as something strategic for the IS: whatever the service is, it would be executed over a stable infrastructure. However, the introduction of Cloud Computing, and more recently of Fog Computing, is changing the way these resources are perceived. Moreover, the current trend towards increased use of micro-services in organizations, which advocate for a finer breakdown of functionalities, is enabling applications to be deployed more easily over differ kind of infrastructures. It is now possible, with the help of micro-services, to envisage an opportunistic use of available resources, as supported by [105,169]. All the conditions are thus in place to enable the dynamic deployment of IS services over resources as varied as cloud resources (private or public), traditional data center resources, network devices, IoT, or mobile terminals, in a transparent way. All these developments have transformed the nature of the resources available in Information Systems. These resources have become more distributed, heterogeneous, and organized in an infrastructure that has itself become more dynamic. The placement of services on these resources has thus become a non-trivial problem.

Although resource management and task placement are long-standing issues in distributed systems and in High Performance Computing (HPC), as demonstrated [149,162], the characteristics of the resources involved in a PIS make this task even more complex. The resources in a PIS are similar, in terms of heterogeneity, to those considered by Fog Computing. On the one hand, they include servers running in data centers, but also virtual machines running on Cloud platforms, as well as "micro data centers", server resources that are specially deployed close to users for Fog Computing. In addition, we may have resources such as RaspberryPi and other nanocomputers, often used for and by the IoT, as well as mobile and/or personal use resources such as laptops, desktops, tablets and even smartphones. Each of these resources can be both a source of information and an execution platform for some services since they propose some processing capabilities.

Therefore, we are confronted to a highly heterogeneous and dynamic pool of resources, since these resources can come and go, become available or disappear at any time, depending on circumstances (*e.g.* whether its owner/user moves or leaves, in case of connectivity or power supply problems, or even in case of an ending contract). Moreover, these resources are not necessarily dedicated to the execution of these services and do not necessarily belong to the organization. They may, for example, belong to partners or collaborators; they may be used for the execution of services specific to the organization but also for private tasks.

The resources available in a PIS can then be characterized by their heterogeneity and the dynamism of the environment, just like the resources considered by Fog Computing. Several authors [52,57,61] point out that these characteristics increase the hardness of resource management as well as the difficulty of placing tasks in these resources, especially when compared to Cloud Computing platforms.

We are particularly concerned by this problem in PIS. We are focusing more specifically on the question of opportunistic use of available resources. Indeed, like any IS, PIS have a large pool of available resources. As these resources may evolve very quickly, the question of their opportunistic use arises, as long as they remain available and provide suitable conditions for the execution of certain services. The last part of this chapter focuses on this question of an opportunistic resource management in PIS, with contributions that follow those proposed on the PER-MARE project, based on the CloudFit platform (cf. section 2.2), but which are still under construction, notably through David Becerra's PhD thesis, started at the end of 2016.

4.1 Space of Pervasive Services

4.1.1 Problem statement

As discussed in the previous section, PIS are characterized by their heterogeneity. This heterogeneity affects both the available services and their implementations as well as the resources used for their execution. The technologies involved are multiple and lead to increased complexity. This complexity makes difficult for both, end-users and those who have to design and manage such systems, to understand and assimilate the system. As Dey [38] has pointed out, when users experience difficulties in establishing a mental model of how applications work, they are less disposed to adopt and use them. A misunderstanding of a PIS and how it works may affect the acceptance of such a system (entirely or of some of its components), and thus compromise its adoption and the transition from a traditional IS to a PIS. Given the strategic role of Information Systems (and therefore PIS) within organizations as a support to their activities, the consequences of not adopting such a system can be very significant.

It is important for PIS users to understand these systems it without having to know or understand the technologies involved on those. Similarly, designers need to be familiar with PIS and its functionality, without necessarily being encumbered by the details concerning the involved technologies. In other words, transparency is the key to mastering the complexity of a PIS. Transparency is necessary to hide the heterogeneity that characterizes these systems and that affects their resources, infrastructure, services and uses. This transparency is necessary for both: in order to enable users to focus only on the tasks they have to perform and not on the technologies behind those tasks; and in order to make it easier for designers to think about the services that might be offered and under which circumstances, without also having to focus, at a first moment, on the technologies needed for those services.

In order to achieve this level of transparency, abstractions are needed to enable the representation of these systems. The Space of Pervasive Service proposal represents a first step in this direction, presenting a conceptual tool allowing an abstract representation of a PIS with the functionalities it is supposed to fulfill and the resources considered to enable their execution. In its first version (published in 2013-2014), the abstraction of Space of Pervasive Service allowed to represent, in an abstract way, the notions of "services" and "sensors", to which the notion of "resource" was added in 2019. Indeed, each of these notions were used to represent a role that an entity composing a PIS may assume. Even if a given entity may assume several roles, the fact of pulling a part each role allows to simplify the analysis through simple yet powerful abstractions. The Annex X presents the paper published in RCIS 2014 [112] which details the first version of the Space of Pervasive Service abstraction.

- **RCIS 2014** [112]: Najar, S.; Kirsch Pinheiro, M.; Le Grand, B. & Souveyet, C., "A user-centric vision of service-oriented Pervasive Information Systems", *8th International Conference on Research Challenges in Information Science (RCIS 2014)*, IEEE, **2014**, 359-370

4.1.2 Bibliometric

As for the previous chapters, the work described in this section has produced a few publications. These have been analyzed, using the scholar.google.com website, in relation to the number of citations. Table 8 details the results of such analysis. These publications are mostly recent and target mainly the French community, which explains the limited number of citations to these papers. Another factor contributing to this number is the lack of a widely accepted terminology for Pervasive Information Systems. This term is not yet widely adopted by all communities dealing with Information Systems, other terms are also used. For example, Hauser *et al.* [58] and Schreiber *et al.* [145], as well as Kourouthanassis *et al.* [96, 97] and Birnbaum [13] speak of "Pervasive Information System", Bell [9] and Maass & Varshney [101] refer to "Ubiquitous Information System", while Neumann *et al.* [121] use "Evolutionary Business Information Systems". The first two terms remain the most used (more than 900 references for each according to the site scholar.google.com), the latter being largely in the minority (barely 34 mentions according to the same site). In terms of community, the first one, "Pervasive Information System", seems to be the most used in the field of Computer Science, while the others seem to be more used by researches in Management Sciences. This topic remains a recent and relatively restricted topic in the IS community, for which there is not yet a real consensus in the community. It is a subject that will certainly evolve, in our opinion, in the coming years.

- **INFORSID 2013** [81] **:** Kirsch Pinheiro, M.; Le Grand, B.; Souveyet, C. & Najar, S., « Espace de Services : Vers une formalisation des Systèmes d'Information Pervasifs », *XXXIème Congrès INFORSID 2013 : Informatique des Organisations et Systèmes d'Information et de Décision,* **2013**, 215-223
- **UbiMob 2013** [113] **:** Najar, S.; Kirsch Pinheiro, M.; Le Grand, B. & Souveyet, C., « Systèmes d'Information Pervasifs et Espaces de Services : Définition d'un cadre conceptuel ». *UbiMob 2013 : 9èmes journées francophones Mobilité et Ubiquité,* Jun **2013**, Nancy, France. Disponible sur https://ubimob2013.sciencesconf.org/19119.html (Last visit: août 2020)
- **RCIS 2014** [112] : Najar, S.; Kirsch Pinheiro, M.; Le Grand, B. & Souveyet, C., "A user-centric vision of service-oriented Pervasive Information Systems", *8th International Conference on Research Challenges in Information Science (RCIS 2014)*, IEEE, **2014**, 359-370
- **INFORSID 2019** [83] : Kirsch-Pinheiro, M. & Souveyet, C., « Le Rôle des Ressources dans l'Evolution des Systèmes d'Information », *Actes du XXXVIIème Congrès INFORSID (INFORSID 2019),* Paris, France*,* Juin 11-14 **2019**, 85-97
- **Atelier 2019** [150] : Souveyet, C.; Villari, M.; Steffenel, L. A. & Kirsch-Pinheiro, M., « Une approche basée sur les MicroÉléments pour l'Évolution des Systèmes d'Information », *Atelier Évolution des SI : vers des SI Pervasifs ?, INFORSID 2019,* **2019.** Disponible sur https://evolution-si.sciencesconf.org/data/book_evolution_si_fr.pdf (Last visit: août 2020)

Table 8. Bibliometric analysis concerning the Space of Pervasive Services proposal

Reference	Year	Total	≤ 2016	> 2016	Self-citations
INFORSID 2013	2013	1			1
UbiMob 2013	2013	2	1	1	
RCIS 2014	2014	3		2	1
INFORSID 2019	2019				
Atelier 2019	2019				
Total / %		**6**	**16,67 %**	**50,00 %**	**33,33 %**

4.2 Opportunistic resource management on Pervasive Information Systems

4.2.1 Problem statement

As discussed at the beginning of this chapter, PIS are characterized by the heterogeneity and the dynamism of their environment. Like the environments considered by Fog Computing, the environments involved in a PIS contain a varied and variable set of resources, which may include resources ranging from high-performance servers and virtual machines in the cloud to tablets and nanocomputers for the IoT. Many resources are already available and integrated into this environment. They are not necessary placed in a data center. These resources can be disseminated all along the organization, and even beyond, and they can be dedicated (or not) to different uses. Indeed, these resources are not always dedicated exclusively to certain services or tasks, and even if they are not always very powerful, they still offer significant power computing. Unfortunately, except for data center and cloud resources, many of the resources available in a PIS are often underused.

Many of these resources can be available only on a temporary basis, while others can be available in a more permanent way. These resources are very heterogeneous, they can be mobile and have very distinct characteristics. Their computing capacities can also vary over the time, since they are not necessarily resources dedicated to a specific task, and can therefore carry out different tasks simultaneously, which may affect their available capacities.

Considering the availability of all these resources, it is possible to envision the use of proximity resources for the execution of services on behalf of the PIS, in a similar way that resources in Fog platforms. However, this use would require a resource management that is opportunistic, since it should be guided by the availability of these resources and their available capacities. The objective is not necessarily to optimize the use of a fixed pool of resources, as it is often the case in data centers or in Cloud platforms [149, 162], but it is to try to make an effective use of a pool of heterogeneous resources, whose composition and available capacity can vary over the time and whose use is not dedicated to the execution of the considered services. Similar to resource management on Fog platforms [52,61], managing resources in such a pool is a complex problem, especially when compared to Cloud platforms.

In this section, we tackle this issue, focusing on an opportunistic use of resources in a PIS, which means using such resources for service execution while they are available, according the capacity they offer at a given moment. In our view, a full deployment of Pervasive Information System will require a context-aware management of available resources, which should consider particularly the heterogeneity and the dynamism of PIS environment. This research addresses this issue, focusing notably on the placement of services within the available resources and on the architecture required to meet PIS requirements. In this way, we pursue the vision initiated by the Space of Pervasive Services (see section 4), by focusing more on this specific point of the architectural view, which is necessary for the executability of the defined space of services.

The work related to the PER-MARE project (cf. section 2.2), carried out between 2013 and 2016, has revealed new perspectives for us concerning the resource management in Fog Computing environments. Since PIS are characterized by the same heterogeneity and dynamism as these environments (Fog Computing being part of the ecosystem fomenting the emergence of PIS), it appeared logical to continue our research on this topic beyond the PER-MARE project (which ended in 2014). Since 2016, we have continued our researches on this topic, using the CloudFIT platform proposed during PER-MARE project. This work highlights an observation, also reported by nowadays literature, concerning the difficulties of placing tasks in a Fog Computing environment [16,42,61,99,146] for which PIS are also concerned. Since 2016, we started to further explore the impact of heterogeneity in the execution of tasks in this type of environment, in order to better understand its effect in the case of a PIS, which is also characterized by this heterogeneity.

Thus, we have studied, on the one hand, the effects of heterogeneity on the execution of tasks in these environments, and on the other hand, the requirements and characteristics for resource management in general and on PIS. To do this, we have first carried out a set of experiments in a real environment (not in a simulator) using the CloudFIT platform, which complemented the results of the PER-MARE project (see section 2.2). Then we carried out a literature review on resource management, both in "traditional" computing environments (HPC and Cloud Computing) and in Fog Computing environments. The results of these two works led to the definition of a conceptual architecture for resource management in a PIS, which is part of David Beserra's PhD thesis (thesis still in progress).

Several lessons could then be learned from these experiments. First of all, it is possible to obtain, by observing context information, a reasonable use of available resources, which would avoid over-consumption of low-powered resources, while still taking advantage of their computing power. Experiments have also shown that the placement of the services consuming and/or producing data can be highly influenced by the placement of these data and by the volume of involved data, which is highly dependent on the application. Different strategies for service placement are thus possible and should coexist in a PIS. Furthermore, a totally distributed architecture, without any central elements, such as proposed by the CloudFIT platform, has proved to be particularly interesting for managing dynamic environments and for managing the scalability required to cover a PIS. Nevertheless, this kind of architecture comes at a price: it is certainly less sensitive to failures and provides better scalability than architectures that depend on a central element (a server, a broker or a proxy), as Ghobaei-Arani *et al.* [52] have pointed out, but it remains sensitive to network partitioning. In these cases, the tasks are still performed, but the risk incurred is a certain waste of resources.

All this demonstrates the complexity that can surround opportunistic resource management in a PIS. Our experiments suggest that this management is influenced by multiple factors involving resources and their execution context, but also applications (services). Multiple strategies remain possible, which leads us to believe that a configurable policy system, considering different factors, is necessary. These factors can go beyond the purely technical aspects. For example, although the use of cloud servers for storing large volumes of data may be technically attractive, it may not be suitable for some organizations, depending on the cost of the cloud itself or on data privacy. Conversely, even if it is possible to use locally available resources to run a service, this might be discouraged, depending, for example, on the resource ownership (e.g. resource belonging to another organization or for personal use only). The ability to define resource management policies in a flexible and configurable way is therefore a necessity for PIS.

Based on this study, we may consider resource management in a PIS as a special case of resource management in which we have:

i. A heterogeneous and dynamic resource pool;
ii. A pool that can belong to different owners;
iii. An on-demand service execution scheduling (with service requests that cannot be necessarily anticipated);

And for which it is also required:

iv. A service placement policy that does not necessarily aim at optimizing resources, but rather at an opportunistic use of these resources;
v. Criteria (or metrics) to be observed that can vary according to the services requested; the same for the decision-making criteria that can vary according to the resources;
vi. Significant scalability and evolutivity, given the dimensions that a PIS can take on.

The first two points (*i* and *ii*) can be seen as a consequence of the way in which PIS are built: through the introduction of different technologies and new practices (or partnerships), which complement those already in place and add complexity to the resulting environment, while bringing new opportunities (*e.g.* new services, new business processes, etc.) to these systems. The third point corresponds to the need of providing these systems with greater flexibility, thanks to services that can better adapted to the demand. The fourth point is a consequence of the dynamic environment of PIS, which is more propitious to an opportunistic use of available resources than to an "optimal" use of those. The objective is not necessarily to optimize the use of resources (*e.g.* load balancing among resources, or minimizing the number of resources used), neither optimizing pure performance indicators (*e.g.* minimizing execution time, or maximizing compliance with SLAs), but above all to be able to use resources when they are available and thus avoid a certain "waste" of underused resources inside the organization. To do this, different information can be observed and used for decision making, since different strategies can be considered, depending on the service requested, and on the resources considered for its execution. This variability on the criteria that could be used leads to the need for configurable policies, both for services and resources, which should consider context information among these criteria, with a real context management (and especially Quality of Context concerns) associated with it.

Finally, the last point considers the need for evolutivity and scalability that can characterize a PIS. When talking about an IS, it is already possible to envisage a very large number of resources and services. The dynamic nature of an PIS only reinforces this point and emphasize the importance of considering scalability as a key aspect: a PIS must be able to evolve in response to changes in its environment, but also to changes in business strategy that may be decided at a business level. Even if PIS resources are organized into multiple spaces of services, scale remains an important factor. As is evolutivity: criteria that are important today in the management of certain resources (or services) may change and be replaced by new criteria in the future, as the organization itself evolves.

All of these considerations point to four major characteristics for an opportunistic resource management in a PIS: *dynamism, contextual awareness, flexibility, and scalability*. Only a few studies in the literature consider all these aspects. Taken together, these points considerably distinguish resource management in a PIS from resource management in Cloud Computing, or even Fog Computing platforms.

These points have inspired the definition of a conceptual architecture for an opportunistic resource management in a PIS. The definition of these components is accompanied by the definition of an expected behavior of each component and their interactions. This dynamic behavior establishes is supposed to ensure, among other things, a distributed decision making between the different resources. This decision making is based on policies, which can be divided into several categories: those applicable to services and those applicable to resources, but also policies defined for a particular resource (called "local" policies) and those defined for an entire organization (called "global" policies). All of these policies may be based on a variety of information, including context information. We are therefore approaching the definitions gave by the Space of Pervasive Service abstraction, with notably constraints that apply to a resource or to a service. On the basis of these policies and the observed context information, three decisions can be made: immediate execution of a service, its delegation to a neighboring resource, or putting it on hold. Each time a service is delegated or put on hold, its priority is increased to ensure that it will be executed in a near future. The idea would be to execute a service that is considered a priority, even if some policies are not all met.

This architecture is still under definition as part of David Beserra's PhD thesis. We are currently working on the definition of policies and on a formalism allowing their expression. It is important that these policies can express constraints on the use of resources, but also in relation to services, following the same principles established by the Space of Pervasive Services (cf. section 4.1). Thus, the same notions of required context, constraints and properties, as defined on [83], are explored on the policies definition. The scheduler becomes a key element of such architecture, resolving these definitions in such a way as that the resource will remain in a state considered acceptable, while executing services on behalf of the PIS.

This research represents an ongoing work for which only a few publications are available. Among those, the paper published at EUSPN 2018 [157], included in the Annex XI, contains interesting insights about how heterogeneity and dynamicity of the environment could impact resource management of such environments.

- Steffenel, L.A. & Kirsch-Pinheiro, M., "Improving Data Locality in P2P-based Fog Computing Platforms", *9th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN 2018)*, Leuven, Belgium, November 5-8, **2018**. DOI: doi:10.1016/j.procs.2018.10.151

4.2.2 Bibliometric

As a work in progress, this contribution has been the subject of only a very few publications. Some results, still considered as preliminaries, could not be submitted for publication yet. We can only cite here the publications involving experiments carried out with the CloudFIT platform. As with the definition of the Space of Pervasive Service (cf. section 4.1), these publications aimed at primarily the French community, in order to gather from this community a feedback that we consider was mandatory for the development of the proposal. These publications are listed below and their impact, in relation to the number of citations, is summarized in Table 9. As expected, a very small number of citations were identified, without prejudging the impact that this work may have on the Information System community in the future.

- **UbiMob 2016** [159]: Steffenel, L.A. & Kirsch-Pinheiro, M., « Stratégies Multi-Échelle pour les Environnements Pervasifs et l'Internet des Objets ». *11èmes Journées Francophones Mobilité et Ubiquité (Ubimob 2016)*, 5 juillet **2016**, Lorient, France. Paper n°6. Disponible sur https://ubimob2016.telecom-sudparis.eu/files/2016/07/Ubimob_2016_paper_6.pdf (Dernière visite: aout 2020)

- **EUSPN 2018** [157]**:** Steffenel, L.A. & Kirsch-Pinheiro, M., "Improving Data Locality in P2P-based Fog Computing Platforms", *9th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN 2018)*, Leuven, Belgium, November 5-8, **2018**. DOI: doi:10.1016/j.procs.2018.10.151
- **IJITSA 2018** [158]**:** Steffenel, L.A.; Kirsch-Pinheiro, M.; Vaz Peres, L. & Kirsch Pinheiro, D. "Strategies to implement Edge Computing in a P2P Pervasive Grid", *International Journal of Information Technologies and Systems Approach (IJITSA)*, IGI Global, 11(1), **2018**, 1-15. DOI: doi:10.4018/IJITSA/2018010101
- **COMPASS 2019** [156]: Steffenel, L.A. & Kirsch-Pinheiro, M., « Accès aux Données dans le Fog Computing : le cas des dispositifs de proximité », *Conférence d'informatique en Parallélisme, Architecture et Système (ComPAS'19)*, 25-28 July 2019, Anglet, France. Disponible sur https://hal.univ-reims.fr/hal-02174708 (Last visit: aout 2020)

Table 9.Bibliometric analysis of citations related to our research about resource management on PIS.

Reference	Year	Total	≤ 2018	> 2018	Self-citation
UbiMob 2016	2016				
EUSPN 2018	2018	2		2	
IJITSA 2018	2018	2		2	
COMPASS 2019	2019				
Total / %		**4**	**0 %**	**100 %**	**0 %**

4.3 Chapter summary

Unlike the previous chapters, the contributions presented here are still under development. The concept of the Space of Pervasive Services, even if it was the subject of a few publications, is still evolving. Several aspects related to this concept still require attention, notably the design methodology, which needs to be extended in order to take into account the resources definition.

Executability of such spaces remains also an open issue. Our research on an opportunistic resource management is a first step towards this direction. This work began with an empirical phase, based on the experiments we have performed using the CloudFIT platform. This empirical phase was followed by a literature review considering scheduling mechanisms and policies on Cloud and Fog Computing. These first phases allowed us to acquire the knowledge necessary to move towards the definition of a conceptual architecture for an opportunistic resource management on SIP. This architecture is still under construction as part of David Beserra's PhD thesis. We expect that this work will represent a basic foundation for the construction of a true execution platform for PIS.

Several issues still have to addressed in order to achieve this vision of Space of Pervasive Service at runtime. Not only the management of resources in dynamic environments needs to be considered, but also the execution business processes using the proposed services. The collaboration started with the Università di Messina is part of this context. The use of micro-containers [150] to encapsulate and organize services and sensors in process segments represents a first steps, which must be further developed in a near future.

The preliminary nature of the researches presented in this chapter does not allow us to propose a clear evaluation of the impact these researches may have, particularly in the IS community. Nevertheless, these researches still represent a first step towards a fully definition of PIS. Through the challenges considered in this chapter, we wanted to emphasize the importance of establishing a conceptual vision of these systems, but also of improving the coverage of the technical aspects necessary to achieve our vision of PIS. This work also demonstrates the highly multidisciplinary nature of PIS. The development of these systems brings several challenges for which skills from the different communities of Computer Science (and event beyond) will be necessary. This multidisciplinary can be illustrated by our research on opportunistic resource management, for which skills from the HPC and Cloud Computing communities, and more generally from Distributed Systems, have had to be mobilized.

The multidisciplinary of Pervasive Information Systems is perhaps the most striking feature of these systems. We strongly believe that the challenges that emergence together with these systems will only be addressed by a global and multidisciplinary approach.

IV Conclusion & Perspectives

All along this document, different contributions have been discussed. These range from 2002, when my PhD thesis began, to the present days. All these contributions have in common the notion of context, which has been applied to different communities of Computer Science.

Indeed, I have started my research in the CSCW (Computer Supported Cooperative Work) community by applying the notion of context to the adaptation of group awareness information (chapter 1). The main outcomes of this research were an object-oriented context model and a filtering process whose principles inspired other works years later. Then, chapter 2 presents my research works regarding pervasive environments. These researches have targeted directly the Ubiquitous Computing community. Here again, the notion of context was used, first in a peer-to-peer distribution mechanism for context information, and then in the use of context information for resource management during the PER-MARE project. This project was one of the precursors in exploring the use of Fog Computing for Big Data applications. This work opened up several research perspectives considering an opportunistic use of available resources thanks to the observation of the context in which these resources are employed.

In chapter 3, my research works integrating the SOC (Service Oriented Computing) community were presented. Most of these works are the result of my integration into the laboratory "Centre de Recherche en Informatique" (CRI), at the University of Paris 1 Panthéon Sorbonne. This research work can be characterized by the combination of the notion of intention, coming from Requirement Engineering community, to the notion of context in the service orientation. This triplet "< *intention, context, service* >" has been used as a basis for my contributions on service discovery and prediction. This work has allowed me to consider from a new perspective the question of the user's habits and practices. It also tackles the question of the relevance of context information: how to recognize whether a given context element may characterizes or not the choice (and then the use) of a given application or service by a user? My work on context mining brings some insights concerning this issue, thanks to the application of FCA (Formal Concepts Analysis) in a continuous improvement process. This work has also opened the perspective to a deeper reflection about the applicability of Machine Learning techniques to context data in a very large scale, in what we call a "context facility".

All these contributions converge towards the notion of Pervasive Information Systems (PIS), which is the subject of my latest researches, presented in chapter 4. These systems represent the new generation of Information Systems (IS). It is not a matter of new systems that would be created from scratch, but rather the evolution of existing systems, which are now being overturned by the arrival of new technologies and new practices. All these evolutions (Fog Computing, IoT, Big Data, Machine Learning, etc.) are driving these systems well beyond the boundaries traditionally accepted (and handled) by the IS still in place today. Pervasive Information Systems go well beyond the limits of the organization, integrating the physical environment, mobile technologies, Fog and Cloud Computing. Even if the data represents an important concern on these systems, notably thanks to IoT and Big Data related technologies, this evolution cannot be reduced to the availability data everywhere. It is not only a matter of data, it is also about a whole Information Systems that can be deployed everywhere, available all the time. In short, it is about the Weiser's [171] vision of Ubiquitous Computing becoming reality over current Information Systems.

At the heart of all these evolutions leading current Information Systems into PIS, there is an environment that becomes eminently dynamic and that must be mastered. This dynamism brings the promise of more flexibility for Information Systems, which could be able to easily (or more easily) adapt themselves to changes. The notion of context can thus play a key role in this transformation from so-called "traditional" IS to Pervasive Information Systems. The aim is to allow more adaptability to these systems at every level, from infrastructure to management, including event the business support functions. We consider here context information in a broader sense, resulting from the observation of the users, the physical environment, as well as the organization itself, as considered in my PhD thesis work (chapter 1). Each level of a PIS can thus benefit from context information for its own adaptation, as illustrated by the contributions discussed in this document. Each at its own level, these contributions suggest that it is actually possible to bring more reactivity to infrastructures, services and applications by considering the context information.

However, the real challenge does not lie in adapting each level separately, in an independent way, but in creating a real synergy between the IS levels. Each level should be able to adapt itself according to its own conditions and goals, but also according to observed context information and changes coming from the neighboring levels. It is an entire dynamic between the different levels of an Information System that can be obtained from a global management of the notion of context.

Even if context information is seen here essentially as a trigger for adaptation purposes, it is not a question of automating everything in a PIS. A PIS is an Information System that evolves, and the very nature of these systems requires them to be predictable and manageable. One must be able to control an IS, its applications, processes, services, infrastructure, etc., in any situation. We must be able to manage a PIS despite the heterogeneity and the dynamism of the involved environment. Adaptation within a PIS can be led automatically, but it can also come from an active management from decision makers. Our research works on group awareness (chapter 1) and context mining (chapter 3) suggest the potential of context information for decision making. Context information can then become the cornerstone of a continuous improvement process that will undoubtedly be essential to the emergence and survival of future PIS.

All of this leads almost inevitably to the generalization of the context support to the entire Information System. This means considering this context support as a "facility" available to all Information System components. This idea, introduced in [11] (chapter 3), represents, in my opinion, the keystone of Pervasive Information Systems. If we see a PIS as a city, context management should be like a "facility" integrated into the city, such as water or electricity, a service available to all members of the community. Thinking of context management as a "context facility" implies generalizing this notion to the entire system. Everything may become observable. Each element in a PIS could thus be observed, become a source of context information, and at the same time, a consumer of this kind of information for different uses, from adaptation to decision-making.

This vision of a "context facility", available for an entire PIS, raises several challenges, particularly related to the scale that this vision implies: it is no longer a particular application or service that benefits from such a platform, but potentially all the elements of a PIS, whatever their level. This can be illustrated by group awareness information. On the one hand, this information may be considered as organizational context in order to be better exploited in groupware applications, which will no longer have to deal with the management of this information, on the other hand, it may also be considered as a condition for the using certain services or resources, as the required context defined on [118] (chapter 3). Context information is no longer captured for a specific use, but for many different uses, even future ones. This raises the question of how to model this information, how to store it, but also how to process it on a very large scale.

Through this idea of a "*context facility*", everything becomes a possible source of context information. This information can thus be fed back to all levels of a PIS and launch reactions on these levels, from adaptation to decision-making, reactions that may, in their turn, trigger new changes. It is through the notion of context as a "facility" that the synergy between all levels of a PIS can be created. Figure 13 illustrates this idea of a synergy among all PIS levels. In the lower part of the picture, we may observe different elements acting as a source of context information and feeding this "facility", which in its turn makes this information available at all levels of the system. At each level, this information can trigger changes, which will feed back to this base new information, improving thus a dynamic interaction among PIS levels.

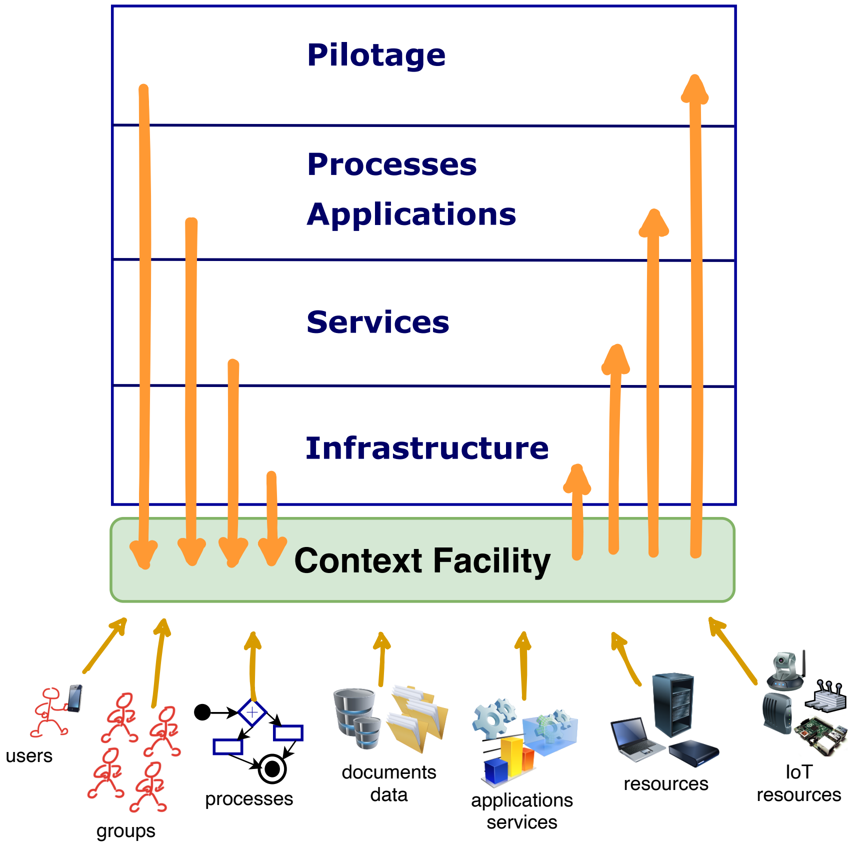

Figure 13. Context facility on a PIS.

This synergy could provide Pervasive Information Systems with the flexibility they will need to better take advantage of the opportunities offered by the new technologies to come and by the environment's own dynamics, whether physical, logical or organizational. Nevertheless, the challenges to make this vision a reality are numerous and particularly important. First of all, there are the challenges that can be described as technical, including the definition and the development of the platforms and methods that will be necessary for implementing this vision. The development of a platform that could be capable of executing the Space of Pervasive Services, mentioned in Chapter 4, or the definition of a platform capable of scaling up Machine Learning techniques, as discussed in [11] (Chapter 3), may be cited as examples of these technical challenges. However, it is worth noting that these challenges mentioned in this document are far from being the only ones. Questions concerning data and infrastructure security, or the robustness of these highly dynamic environments are just starting to be felt now in today's organizations.

These technical challenges are accompanied by methodological challenges, including the development of models and methodologies for managing and steering PISs. The definition of the Spaces of Pervasive Services theory (Chapter 4) represents a first step in this direction, which needs to be further explored in the next years.

Finally, PIS and this vision of a "context facility" also raise questions on a social and human acceptance levels. Are we ready to accept such a high level of observation of our daily business life? Will we be able to accept the increasing automation of our work environment? Like any new technology, like any change, all these upheavals bring with them hope and fear, which we, as a society, should learn to balance. These latter challenges are largely beyond my current areas of expertise, but I am curious to know where the future will take us.

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Annexes

Annex I

Paper

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Annex II

Paper

Kirsch-Pinheiro, M.; Gensel, J. & Martin, H., "Representing Context for an Adaptative Awareness Mechanism". In: Gert-Jan de Vreede, Luis A. Guerrero, Gabriela Marín Raventós (eds.), 10th International Workshop Groupware: Design, Implementation and Use, **CRIWG 2004**, LNCS 3198, 339-348 (**2004**)

Annex III

Paper

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Annex IV

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Annex V

Paper

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Annex VI

Paper

Ben Rabah, N.; Kirsch Pinheiro, M.; Le Grand, B.; Jaffal, A. & Souveyet, C., "Machine Learning for a Context Mining Facility", *16th Workshop on Context and Activity Modeling and Recognition, 2020 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops)*, **2020**, pp.678-684.

Annex VII

Paper

Kirsch-Pinheiro, M.; Vanrompay, Y. & Berbers, Y., « Context-aware service selection using graph matching ». In: Paoli, F. D.; Toma, I.; Maurino, A.; Tilly, M. & Dobson, G. (Eds.), *2nd Non Functional Properties and Service Level Agreements in Service Oriented Computing Workshop (NFPSLA-SOC'08), at ECOWS 2008*, CEUR Workshop proceedings, vol. 411, **2008**.

Annex VIII

Paper

Najar, S.; Kirsch-Pinheiro, M.; Souveyet, C. & Steffenel, L. A., “Service Discovery Mechanisms for an Intentional Pervasive Information System”. *Proceedings of 19th IEEE International Conference on Web Services (ICWS 2012)*, Honolulu, Hawaii, 24-29 June **2012**, pp. 520-527.

Annex IX

Paper

Najar, S. ; Kirsch-Pinheiro, M. & Souveyet, C., “A context-aware intentional service prediction mechanism in PIS”, In: David De Roure, Bhavani Thuraisingham & Jia Zhang (Eds.), *IEEE 21st International Conference on Web Services (ICWS 2014)*, 27 June - 2 July **2014**, Anchorage, Alaska, USA, IEEE CS, pp. 662-669. DOI : 10.1109/ICWS.2014.97

Annex X

Paper

Najar, S.; Kirsch Pinheiro, M.; Le Grand, B. & Souveyet, C., "A user-centric vision of service-oriented Pervasive Information Systems", *8th International Conference on Research Challenges in Information Science (RCIS 2014)*, IEEE, **2014**, 359-370

Annex XI

Paper

Steffenel, L.A. & Kirsch-Pinheiro, M., "Improving Data Locality in P2P-based Fog Computing Platforms", *9th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN 2018)*, Leuven, Belgium, November 5-8, **2018**. DOI: doi:10.1016/j.procs.2018.10.151

Annex XII

Publication list

Publication list

Synthesis

Table below synthetises all my publications, organized according the period of my career: before 2008, when I integrated the University Paris 1 Panthéon Sorbonne; between 2008 and 2014, representing the first part of my career in this university; and from 2015 until now.

	Total number of publications	Publications until 2008	Publications 2008 < x ≤ 2014	Publications after 2014	Publications classed ERA[3] A	Publications classed ERA B
Book chapters	9	0	7	2	N/A	N/A
Journal papers	12	3	3	6	1	2
International conference papers	48	14	20	14	4	8
National conference papers	13	3	5	5	N/A	N/A
Reports & dissertations	5	4	1	0	N/A	N/A
Total	87	24	36	27	5	10

Book chapters

2018 Steffenel, L.A., Kirsch-Pinheiro, M., Vaz Peres, L., Kirsch Pinheiro, D. "Strategies to implement Edge Computing in a P2P Pervasive Grid", In Mehdi Khosrow-Pour et al. (Eds.), **Fog Computing: Breakthroughs in Research and Practice**, IGI Global, pp 142-157, 2018, doi:10.4018/978-1-5225-5649-7.ch006.

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[3] The ERA ranking corresponds to an international recognized publication ranking proposed by the Australian CORE (*Computing Research and Education Association*). It is available at https://www.core.edu.au/conference-portal, but also at http://www.conferenceranks.com, which is a Web site regrouping several other rankings, such as the Brazilian Qualis ou the MSAR, proposed byMicrosoft.

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Ait-Ali-Slimane, A., Kirsch-Pinheiro, M., Souveyet, C., "Considering Quality of a Service in an Intentional Approach", In: Stephan Reiff-Marganiec and Marcel Tilly (Eds.), **Handbook of Research on Service-Oriented Systems and Non-Functional Properties: Future Directions**, IGI Global, pp. 334-351, ISBN 978-1613504321, DOI: 10.4018/978-1-61350-432-1

2010 Kirsch Pinheiro, M., Carrillo-Ramos, A., Villanova-Oliver, M., Gensel, J., Berbers, Y. "Context-Aware Adaptation in Web-based Groupware Systems", In: JingTao Yao (Ed.), **Web-based Support Systems**, Series: Advanced Information and Knowledge Processing, Springer, mars 2010, ISBN: 978-1-84882-627-4, pp. 3-31. DOI: 10.1007/978-1-84882-628-1_1

2009 Carrillo-Ramos, A., Kirsch Pinheiro, M., Villanova-Oliver, M., Gensel, J., Berbers, Y., "Collaborating agents for adaptation to mobile users", In: Max Chevalier, Chantal Soule-Dupuy, Christine Julien (Eds.), **Collaborative and Social Information Retrieval and Access: Techniques for Improved User Modeling**, IGI Global, 2009, ISBN 978-1605663067.

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