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ORIGINAL RESEARCH

Exploring the ambient assisted living domain: a systematic review

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Abstract Ambient assisted living (AAL) is focused on providing assistance to people primarily in their natural environment. Over the past decade, the AAL domain has evolved at a fast pace in various directions. The stakeholders of AAL are not only limited to patients, but also include their relatives, social services, health workers, and care agencies. In fact, AAL aims at increasing the life quality of patients, their relatives and the health care providers with a holistic approach. This paper aims at providing a comprehensive overview of the AAL domain, presenting a systematic analysis of over 10 years of relevant literature focusing on the stakeholders' needs, bridging the gap of existing reviews which focused on technologies. The findings of this review clearly show that until now the AAL domain neglects the view of the entire AAL ecosystem. Furthermore, the proposed solutions seem to be tailored more on the basis of the available existing technologies, rather than supporting the various stakeholders' needs. Another major lack that this review is pointing out is a missing adequate evaluation of the various solutions. Finally, it seems that, as the domain of AAL is pretty new, it is still in its incubation phase. Thus, this review calls for moving the AAL domain to a more mature phase with respect to the research approaches.

Keywords Ambient assisted living · Active assisted living · AAL · Systematic literature review · Assistive technologies · Assistive needs · Elderly

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1 Introduction

The rise of life expectancy and the low birth rates are at the heart of the demographic change occurring in the world. Reports commissioned by the United Nations and the World Health Organization predict that the number of people aged 65 or older will triple by 2050 from 524 million in 2010, representing 8 % of the world population, to 1.5 billion in 2050, 16 % of the entire world population (United Nations 2002; World Health Organization 2011). This demographic transition results in the increase of the dependency ratio (i.e., the ratio between the number of people over 65 years old and those of working age) (Christensen et al. 2009), resulting in straightforward consequences: the number of people affected by chronic diseases will rise, as well as the number of health-related emergencies (Kleinberger et al. 2007). From a social perspective, people want to grow old preserving their autonomy and playing an active role in their life. From an economic perspective, the healthcare expenditure will augment since there would be a need for more caregivers, organizations, and infrastructures to cope with the challenges of an ageing society.

To face such societal changes, national governments, non-profit organizations and industries are promoting the Ambient Assisted Living (AAL) era by fostering research institutes and companies to propose solutions that can extend the time people can live independently in their preferred environment. For example, the European Union recognized the importance of AAL by founding the AAL Joint Association and by implementing a specific funding scheme, the AAL programme (since 2014 the EU switched from "Ambient-" to "Active and Assisted Living" Programme) (AAL EUROPE 2007), which aims at fostering the emergence of AAL services and systems for ageing

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well at home, in the community and at work. The programme gives a precise definition of the AAL through a series of objectives as follows:

– extending the time people can live in their preferred environment by increasing their autonomy, self-confidence, and mobility;
– maintaining health and functional capability of the elderly individuals;
– promoting a better and healthier lifestyle for individuals at risk;
– enhancing security, prevent social isolation and support the maintenance of a multifunctional network around the individual;
– supporting caregivers, families and care organizations;
– increasing the efficiency and productivity of used resources in the ageing societies.

AAL aims at improving the quality of life for both the elderly and their caregivers (Pollack 2005). AAL does this by monitoring the "Activities of Daily Living" (ADLs) of the elderly with the goal of tracking their health status and foreseeing the risks associated with ageing and living alone.

To fulfill its objectives, AAL is based on Ambient Intelligence (AmI) aiming at building unobtrusive, interconnected, adaptable, dynamic, embedded and intelligent environments around people (Sadri 2011). AmI enriches an environment with technology (Cook et al. 2009), in smart homes for the elderly while exploiting context-aware solutions (Fenza et al. 2012), yet, it can be applied to other domains such as transportation, healthcare services, smart workplaces and the entertainment industry. However, the AAL focuses on the elderly and their carers, exploiting AmI findings in that context. On a more general scale, the AAL uses intelligent products and Information and Communication Technology (ICT) tools to provide remote care services (Sun et al. 2009). Even human–computer interaction (HCI) is involved in AAL, so as to allow the users to interact with an AAL system in a more natural manner, as they would do with any other human (Kleinberger et al. 2007). However, it must be kept in mind that the elderly are the most prominent stakeholders for ICT developments in AAL (Holzinger et al. 2011). Furthermore, other kinds of end-users are involved in AAL with heterogeneous competencies, interests, and needs. These include patients, health operators, informal caregivers, medical specialists, relatives, care organizations and institutes, national governments and companies.

Even though the scientific literature recognizes the key role of end-users' needs (Calvaresi et al. 2014a), there is a lack of a systematic investigation on how proposed AAL solutions take into account such needs and assess their fulfillment. This is shown by the absence of a systematic review that examines the features of the proposed systems and how they satisfy users' needs. Instead, existing reviews explore in detail a specific technology, technique or system focusing on the technical details. Examples of well-organized, deep systematic reviews focused on the technical and technological details are available in the following scientific literature (Alam et al. 2012; Brownsell et al. 2011; Chan et al. 2009; Ding et al. 2011) where the authors provide a collection of research and projects regarding smart homes, describing the research on sensors, devices, algorithms and applications. However, as mentioned previously, only a limited consideration is given to the end users in such studies. To close the aforementioned gap this paper represents a systematic review to explore whether existing AAL solutions satisfy end users' needs. This review is based on the analysis of the AAL domain from ten years of scientific literature and classifies existing solutions on the basis of a set of apriori features, with no commitments to particular techniques, technologies, methods, systems, architectures, or users. The paper is structured as follows. Section 2 elaborates the applied methodology for performing the systematic literature review. In particular, it discusses the various stages and their settings, and it presents the results. Section 3 analyzes the outcomes of the applied methodology with respect to the research questions. Finally, Sect. 4 concludes the paper and points out future research directions.

2 The systematic literature review methodology

During the last decade, a prominent way of reviewing and analyzing existing literature follows a systematic literature review. This paper adheres the procedure suggested by (Kitchenham et al. 2009).

The approach exploited by this paper guarantees rigorousness and reproducibility. Figure 1 represents schematically the adopted procedure, which is mainly composed of three stages.

The first stage, named *Planning the review*, regards the definition of all the steps and constraints for the upcoming review. Such a phase consists of derivation and definition of structured research questions from generic ones, characterizing the whole search protocol, matching the requirements (rigorousness and reproducibility), and finally the resolution of the possible disagreements. Reproducibility is the possibility to repeat the same process with a different set of articles (e.g., changing the time window).

The second stage, named *Performing the review*, deals with the execution of the planned activities: collecting and selecting the papers, elaborating the papers, analyzing and mining the extracted features.

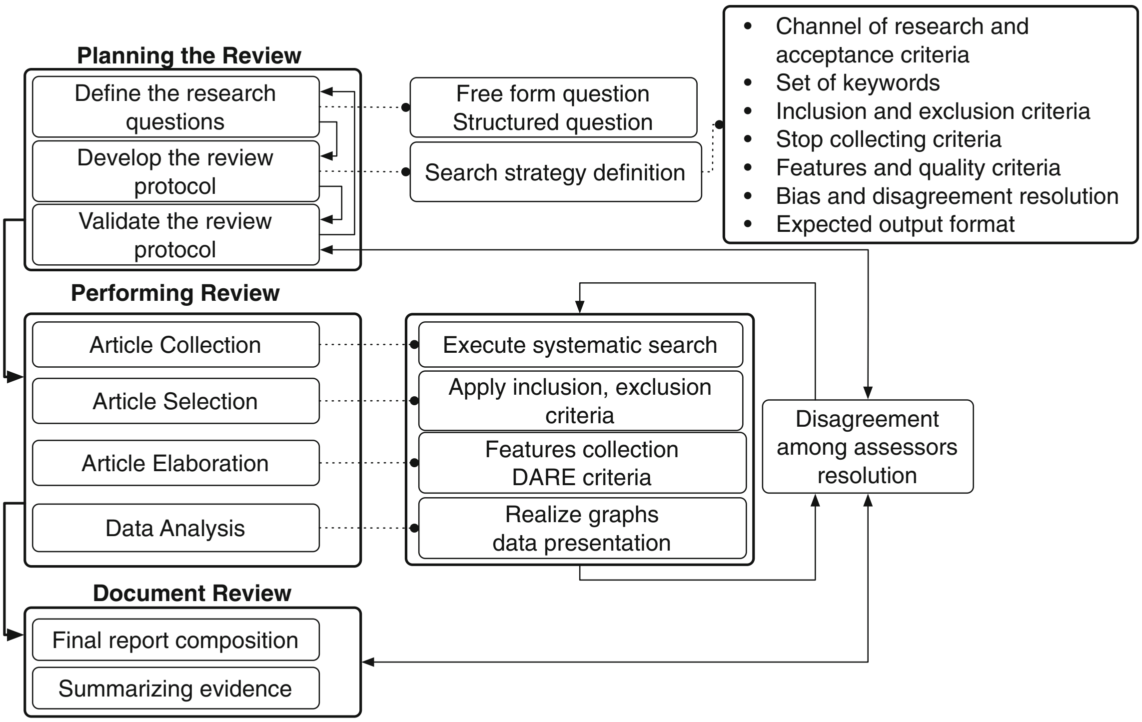

Fig. 1 Systematic literature review applied steps

The last step, *Document review*, simply deals with the documentation and the writing of the report, summarizing at the end the learned lessons.

The rest of this section elaborates the various tasks performed during the systematic literature review of the AAL domain.

2.1 Planning the review

In this section, the plan of the review is laid out with particular emphasis on the definitions of the research questions and their contexts, the development of the review protocol presenting the search strategy, and the review protocol describing the biases and disagreement resolution.

2.1.1 Define the research questions

As discussed in Sect. 1, a number of key issues need to be addressed in the AAL domain. They can be summarized into the following questions:

- What are the users' needs that are currently tackled by AAL solutions?
- Which solutions were proposed by the scientific community?
- How are AAL solutions characterized?

Deriving from these issues, the main research questions are:

- What are the existing AAL solutions?
- What are the requirements that the AAL solutions are trying to cope with and to what extent do these adhere to the requirements?

Next, drilling down these two main subjects, a set of ten research questions were structured. For that purpose, the Goal-Question-Metric (GQM) approach proposed by (Galster et al. 2014; Kitchenham et al. 2010) has been adopted. In particular, the purposes, issues, objects, primary studies, authors' viewpoints, and motivations were investigated to set the following questions:

RQ1 To better understand the evolution of the AAL domain the question that has been set is: *How has the AAL domain been evolving over the years in terms of research topics and where (geographically) such a research has taken place?*

RQ2 To explore the extent to which the scientific community refers to various users and combination of them within the AAL domain, the following question arises: *How do AAL solutions address the ecosystems of the AAL stakeholders?*

RQ3 The needs of the various stakeholders within the AAL domain require to be explored, thus setting the question: *What kind of diseases* or *difficulties are addressed or discussed in the literature?*

RQ4 Being interested in exploring the evolution of AAL solutions and establishing a taxonomy about them, which might be useful for newcomers to the AAL domain, the following question is set: *What kind of supports for AAL are provided and how have the provided solutions evolved over the years?*

RQ5 To map out the technological infrastructure for the AAL domain, the following features need to be explored: *Which architectures, methodologies, techniques and technologies are used in the design, development and implementation of AAL solutions?*

RQ6 Following question RQ5, the quality of the proposed technologies leads to a key question: *What evidences are provided for the validity and usefulness of related technologies?*

RQ7 Furthermore, exploring the limitations of existing solutions, so that the reader would be able to better understand these challenges, sets the question: *What are the limitations of AAL solutions?*

RQ8 As many solutions emerged over the last decade, the exploration of the extent to which these cover the identified needs sets the question of: *What kind of needs in the AAL domain are taken into account, and to what extent they are actually supported?*

RQ9 As the needs and solutions are explored, the will to understand whether these are aligned sets the further question: *What is the coverage provided by AAL solutions with respect to the identified needs?*

RQ10 To further look ahead, the following question is set: *What are the stated future research directions and challenges for the AAL domain?*

2.1.2 Develop the review protocol

The *Search strategy definition* has been performed right after having set the research questions. The selected sources of information include: ieeeXplore,[1] Sciencedirect,[2] ACM Digital Library,[3] Citeseerx,[4] Pubmed.[5]

Next, a set of keywords was devised. They are selected on the reviewers' background and knowledge related to the AAL domain and based on preliminary screening of the domain. The set of keywords includes the following: AAL, Ambient-Assisted Living, Ambient Intelligence, Architecture, Caregiving, Multi-Agent System, MAS, SOA, Virtual Carer, Healthcare, e-Health, Computer Assisted Drugs, Computer Assisted Therapy, Monitoring, Ubiquitous, Computing, bed occupancy, Night-Time care, Recognition, Medical Informatics, Awareness, Data Collection, Disability, Decision Making, Machines Learning, Reasoning, Artificial Intelligence, Smart, Elderly, Surveillance, impairments, activities, Data Analysis, Ageing.

To perform the search, the keywords were aggregated rather than using them one by one, thus obtaining more accurate results. In the complete set of queries, some of the keywords, such as AAL, Ambient Assisted Living, Ambient Assistive were kept fixed when combined with the others. In the following few examples of the executed queries are presented:

1. AAL:
   (a) AAL,
   (b) AAL + healthcare,
   (c) AAL + caregiving,
   (d) AAL + Multi-Agent System, [...].
2 Ambient Assisted Living:
   (a) Ambient Assisted Living,
   (b) Ambient Assisted Living + healthcare,
   (c) Ambient Assisted Living + caregiving,
   (d) Ambient Assisted Living + Multi-Agent System, [...].
3. Ambient Assistive:
   (a) Ambient Assistive + healthcare,
   (b) Ambient Assistive + caregiving,
   (c) Ambient Assistive + Multi-Agent System, [...].

Each query produced a set of articles to be considered, and the lists of results were ordered by pertinence determined by the crawler. The following stop criterion was applied to each query: "stop the articles collection after a sequence of ten titles that were completely incoherent with the query performed appeared in results list". By "incoherence" it is meant that according to the reviewers' subjective view there was no adherence between the query performed and the title/abstract of the considered study.

2.1.3 Inclusion and exclusion criteria definition

The outcome of the initial search is 1104 papers, hereafter referred as primary studies. Thus, to identify possible unrelated papers an additional coarse-grained analysis was performed. This early analysis phase verified the pertinence of titles and abstracts with respect to the following inclusion criteria:

(A) Time: The aim was to review papers published between the years of 2004–2013 as the AAL domain has gained maturity in 2007 [4]

[1] http://ieeexplore.ieee.org/Xplore/home.jsp.

[2] http://www.sciencedirect.com/.

[3] http://dl.acm.org/.

[4] http://citeseerx.ist.psu.edu/index.

[5] http://www.ncbi.nlm.nih.gov/pubmed.

(B) Scenario: The primary studies should be related to one of the following contexts (several contexts which compose a wide scenario): (assistance at home, caregiving, patient monitoring, patient evaluation, communication, healthcare, companionship, theoretical scenario, hospital lane)
(C) Purpose: The purpose of primary studies should be related to one of the following goals: (improve patient life, provide support to physicians, improve relatives life)
(D) Users: The beneficiaries from the solutions presented in primary studies should be among: (Physician, Patients, Relative, Caregivers, Developers)

The selected articles must satisfy the (A) criterion and at least one of the (B), (C) or (D) criteria. The paper's compliance with the inclusion criteria was verified by three reviewers. Each reviewer worked independently while filtering out the list of papers. When all reviewers finished filtering the papers, the comparison was performed. Papers were included only if at least two reviewers agreed. In the case of conflicts among the reviewers' choices, a resolution process presented below was applied.

2.1.4 Features and quality criteria

Assess the quality of a primary study is a challenging task while performing a systematic literature review (Kitchenham and Charters 2007). Thus, once the filtering had been completed, the "Feature collection and quality criteria assessment" was performed. A common solution presented in literature (Galster et al. 2014) classify primary studies by rational, context, research justification, statement of findings, critical examination, and the presence of biases and possible limitations of credibility.

The performed investigations dealt with primary studies belonging to a widespread and heterogeneous domain. To answer the research questions the following set of features was chosen:

Publication year, geographical localization, main purpose, context, kind of users involved, scenarios, articles' abstraction,[6] architectures and designs, development methodologies, techniques, technologies and devices, users' needs covered,[7] need - offered support relation, kind of disease or difficulties supported[7], awareness provided, architectural evidence[7], technological evidence[7], technical evidence[7], architectural limitations[7], technological limitations[7], technical limitations[7], identified future AAL directions, identified future AAL challenges.

2.1.5 Biases and disagreement resolution

To reduce the biases and solve the reviewers' disagreements occurred during the feature classification procedure, particular expedients were adopted: the reviewers, working on the method development and on data elaboration, performed across information check for each task. The following were done:

- A simultaneous work was performed during almost the whole process execution. Referring to Fig. 1, such a simultaneous process was performed by the reviewer for each internal task of "Planning the review", and "Document review".
- The "Article selection" task was performed by three reviewers. The total number of collected articles was thus divided into three equal parts. Each set of articles was reviewed, applying the inclusion/exclusion criteria check, at least twice, by two different reviewers. The used values for the selection were Y for yes, N for not, and X for not sure. The single reviewer's choices were kept hidden to the other reviewers until all of them finished that task. At this stage, each article had two values related to the result of the inclusion in the final review process. If such values were discordant or at least an X value was present, an intervention of the third reviewer was required. His intervention definitively decided for the inclusion or exclusion of that article.
- The "Article elaboration" involved a collaborative disagreement resolution task, performed to define a common understanding for the elaboration of the features. In the case of doubts during the elaboration phase, more formal reviewers meetings' were organized.

2.2 Review execution and results presentation

This section describes the tasks related to the execution of the review process, indicated as "Perform review" in Fig. 1. The set of keywords was used to perform the search phase on the channels listed in Sect. 2. A list of articles was collected respecting the stop criterion described in the methodology. Some research channels, such as ScienceDirect, suggest a set of "papers related to the searched topic". In this particular situation, the suggested articles were collected, applying the same stop criterion. In some

[6] The feature identified by (6) are classified with C, P, or T as possible values, that respectively stand for: C = conceptual; P = prototype architectures and frameworks, no results are provided; T = tested architectures and frameworks, results are provided.

[7] The features identified by (7) are associated to Y, P, or N values, that stand for: Y = information are explicitly defined / evaluated; P = information are implicit / stated; N = information are not inferable. This categorization of the collected features was performed according to the DARE criteria, elaborated and proposed by (Kitchenham et al. 2009).

cases, the queries on the crawlers produce a huge number of results. For example, on IEEE Xplore, queries such as “Ambient Assisted Living + caregiving” and “Ambient Assisted Living + Awareness” produced respectively 342 and 615 results, before the stop criterion is applied.

The semi-automatic search, including the application of the stop criterion, produced a total of 1104 articles. Next, each paper was analyzed primarily by two reviewers, while the third one was called into action only in case of conflict[8]. In cases where both reviewers expressed the same judgment (Y–Y, included or N–N, not included), there was no need for further reviews. On the other hand, conflicts were generated by the combinations Y–X, X–X, X–Y, N–X, X–N were checked by a third reviewer. Details regarding the article selection process are shown in Table 1, in which the reviewers are indicated by the letters A, B, and C.

In order to perform the aforementioned papers selection, the collected papers were listed in temporal order. Then, the papers were grouped in three sets with similar size and assigned to the reviewers according to the previously defined configuration. The second paper set is centered around the year 2007. Table 1 details the output of the papers selection for each set. It is worth to notice that the percentage of accepted papers in the first set is noticeably lower than in the second and the third one. Considering that year 2007 was the starting of the AAL Joint Association (AAL EUROPE 2007), this discrepancy between before and after 2007 seems rather reasonable.

Summarizing the effects of the filtering phase, only 236 papers out of 1104 were chosen for further analysis, corresponding to a final acceptance rate of 21.37 %. The features listed in Sect. 2.1.2, elicited from the articles, were collected in a tabular format.

In several articles the information was not always explicit, making the extraction an intensive manual process. Furthermore, classifying the features of the primary studies using the Y–N–P quality criteria often required to exploit the knowledge of the reviewers in order to interpret partial or unclear information.

Note that the quality of information about each elicited element is expressed in terms of Y–N–P, in accordance with the DARE criteria (Kitchenham et al. 2009).

Referring to question RQ1, the temporal and geographical distribution of works dealing with AAL topics are represented in Figs. 2 and 3.

The papers distribution over the years is shown in Fig. 2. It is worth to remark an increase of AAL publications over the years. The decreasing trend observed in the last couple of years is possibly due to the delay in the indexing performed by the selected sources.

[8] Possible evaluations: Y = Yes, N = No, X = Not sure.

Figures 3 and 4 show that Europe gains much more interest in the AAL research than the rest of the world. This phenomenon can be due to the resonance that AAL Program generated in the European Commission since its establishment.

To geographically localize the primary studies according to the country of the institutional affiliation of the first author, the number of papers per nation was collected. This classification is represented in Fig. 3.

Moreover, the selected studies were grouped by continent to track the contributes over the considered time interval. The results are represented in Fig. 4.

Referring to question RQ2, Fig. 5 depicts the various combinations of stakeholders that appear in the AAL state-of-the-art and the proportion they appear in the literature. The end users were classified into 4 categories. In the primary studies, such categories were taken into account singularly or combined, as presented in Fig. 5.

Referring to question RQ3, a graphical representation was used to show out how diseases and difficulties are differentiated and addressed in terms of scientific contributions and qualitative analysis. Figure 6 presents that information.

Referring to question RQ4, regarding the kind of provided supports, eight major categories of supports were identified:

– Activity recognition: n1 the identification of the activities of daily living (ADLs);
– Control vital status: all the supports related to the monitoring of the vital parameters of the patients, in particular from remote locations;
– Position tracking: all the supports which aim at finding or tracking patient’s position, both indoor and outdoor;
– Interaction: all the supports which allow the user to deal with assistive technologies;
– Multimedia analysis: all the supports which focus on multimedia data elaboration itself;
– Data analysis: all the supports related to discovery of relations, properties and knowledge inside different set of data;
– Data sharing: all the supports related to information and knowledge sharing among the AAL stakeholders/operators/end-users;
– Communication: all the supports which allow simplifying the collaboration between the end users.

The distribution of the quality evaluation for the elicited supports is presented in Table 2. Figure 7 presents that contribution graphically, whereas Fig. 8 shows the evolution of the above-mentioned list of supports over the years.

Referring to question RQ5, methodologies, architectures, techniques and technologies were mapped out.

Table 1 Summary of the inclusion/exclusion phase of the collected works

Reviewers	Conflict solver	Y–Y	N–N	Conflicts	Accepted out of conflicts	Total	Accepted	Acceptance percentage (%)
A, B	C	24	236	48	5	308	29	9.41
B, C	A	90	108	120	4	318	94	29.56
A, C	B	108	191	179	5	478	113	32.56
Sum		222	535	347	14	1104	236	21.37

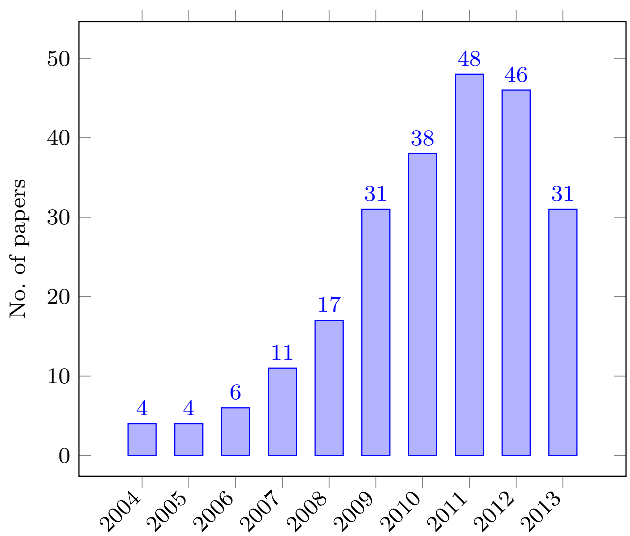

Fig. 2 Number of papers per year

Figure 9 shows that the most popular used architectures are ad hoc solutions (51 %), Multi-Agent Systems (MAS) (19 %) and Service Oriented Architectures (SOA) (12 %).

The majority of the papers (157) do not report on a particular methodology followed during the design of the proposed AAL services. Figure 10 shows the distribution of the primary studies explicitly expressing the methodologies: 53 papers follow a goal-oriented methodology while the rest are almost equally distributed among Agent-oriented methodology (9), Feature-oriented methodology (6) and Service-oriented methodology (7). Four papers provided different ad-hoc methodologies.

The techniques mentioned or described in the reviewed papers are numerous, and are grouped as represented in Fig. 11. The *Data computing* group (28.8 %) includes techniques such as data processing, data analysis, data fusion, sensor fusion, signal and image processing. The Activity recognition/identification group (21.1 %) includes heterogeneous techniques with the common purpose of recognizing or identifying the daily activities of the assisted people. For example pattern recognition, automatic speech recognition, continuous and real-time monitoring can be all instances of the Activity Recognition group. The Artificial Intelligence group (9.8%) comprises techniques such as neural networks, decision trees and, in general, machine learning methods, as well as decision support systems, reasoning engines, etc. The Networking group (9.9%) includes all the works done on communication paradigms and protocols, data sharing, synchronization, etc.

The technologies mentioned in the reviewed papers can be mainly grouped into two categories: Network technologies (43 % of the total mentioned technologies) and in Sensor technologies (41 %). These two categories represent the 84 % of the described technologies addressing the AAL needs, often used to perform remote AAL services such as monitoring. The composition of the main two groups are listed in Table 3. Network round, which is formed by boards and devices with connection capabilities, constitutes the 22 % of the Network technologies. However, the 41 % of the Network category is composed by communication protocols: Wireless and Wi-Fi-based technologies (15 % of the Network-based technologies), Radio Frequency-based technologies (10 %), Bluetooth-based technologies (9 %) and Zigbee-based technologies (7 %) are the most mentioned.

Referring to questions RQ6 and RQ7, which aim to elicit evidence that supports or opposes the used Architectures, Methodologies, Techniques and Technologies (AMT&T), the results were not quantifiable. Thus, an extensive discussion of the results is provided later. In most of the papers, no explicit evaluation is present, rather than only hints about the quality of the adopted AMT&T of the solutions. Thus, the reviewers had to use their own personal background and judgment to properly understand all the hints from the primary studies. An elaboration of the hints themselves, together with other information extracted from the papers, could further enhance the evaluation of the appropriateness of the adopted AMT&T.

Referring to question RQ8, the distribution of the AAL needs over the primary studies appears in Fig. 12. In Fig. 13 the extent to which the needs are motivated and explained were further analyzed. Even though these needs are clearly important, in most of the cases they are only stated (P): monitoring (50.6 %), communication (63.7 %), assistance (63.9 %), and interactivity (80 %).

Referring to question RQ9, the relationships among AAL needs and the solutions aiming at satisfying them are analyzed. The analysis is performed in terms of qualitative

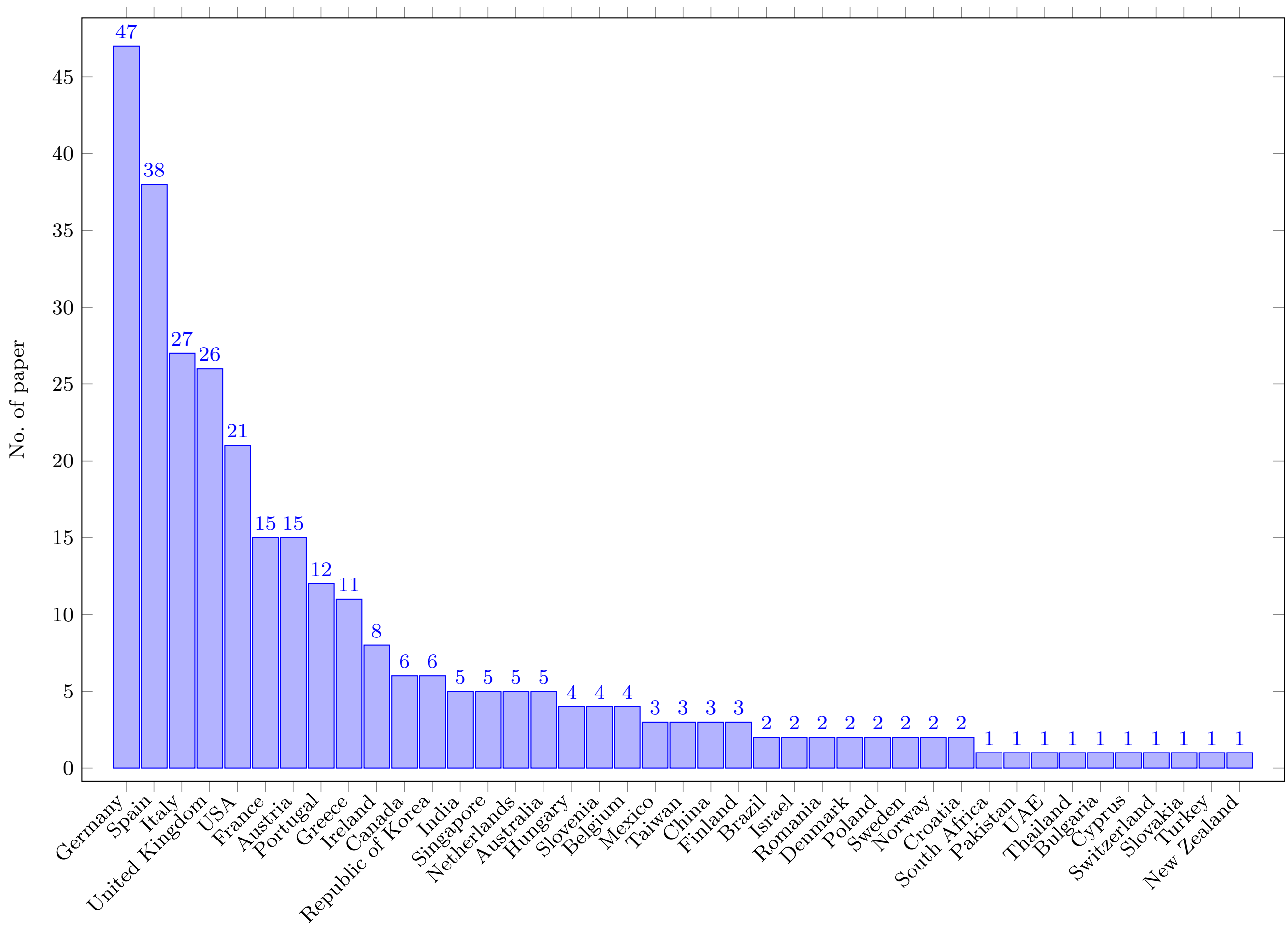

Fig. 3 Number of papers per country

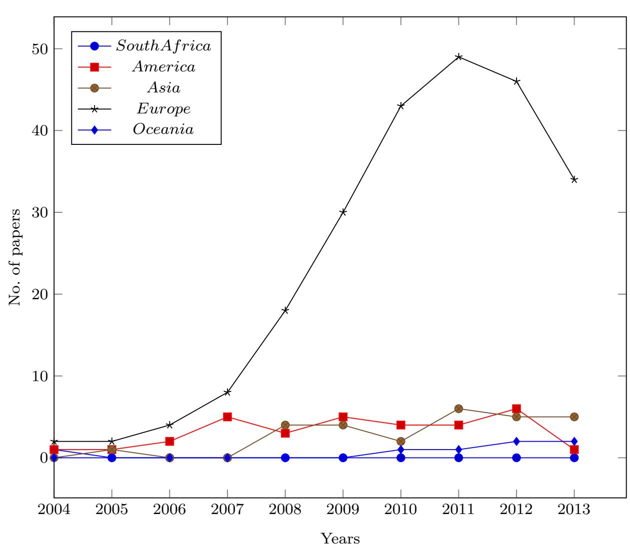

Fig. 4 Number of papers per continent per year

assessment. For each elicited AAL need, the distribution of the supports are represented in Fig. 14. The Y-N-P distribution presenting the quality assessment is represented in form of a pie graph reported in Fig. 15; with regard to the offered supports, there were 102 papers with indicated support (Y), 102 papers with partial support indication (P), and 32 papers with no support indication (N).

With respect to the needs covered, there were 77 papers that indicate coverage, 122 papers that indicate partial coverage, and 37 papers that did not provide information for such coverage.

The scientific community responded differently to the elicited needs. As visible in Fig. 14, there are several kinds of proposed solutions for each one of them, showing that different approaches are used trying to cope with the same need. Indeed, it is shown that the same approaches are differently distributed among them. In fact, the primary studies try to solve the following:

- Monitoring mainly with Activity Recognition (33 %), Control Vital Status (18 %), Position tracking (13 %), etc.
- Interactivity mainly with Communication (26 %), Data Sharing (21 %), and (16 %) for Activity Recognition and Data Analysis, etc.

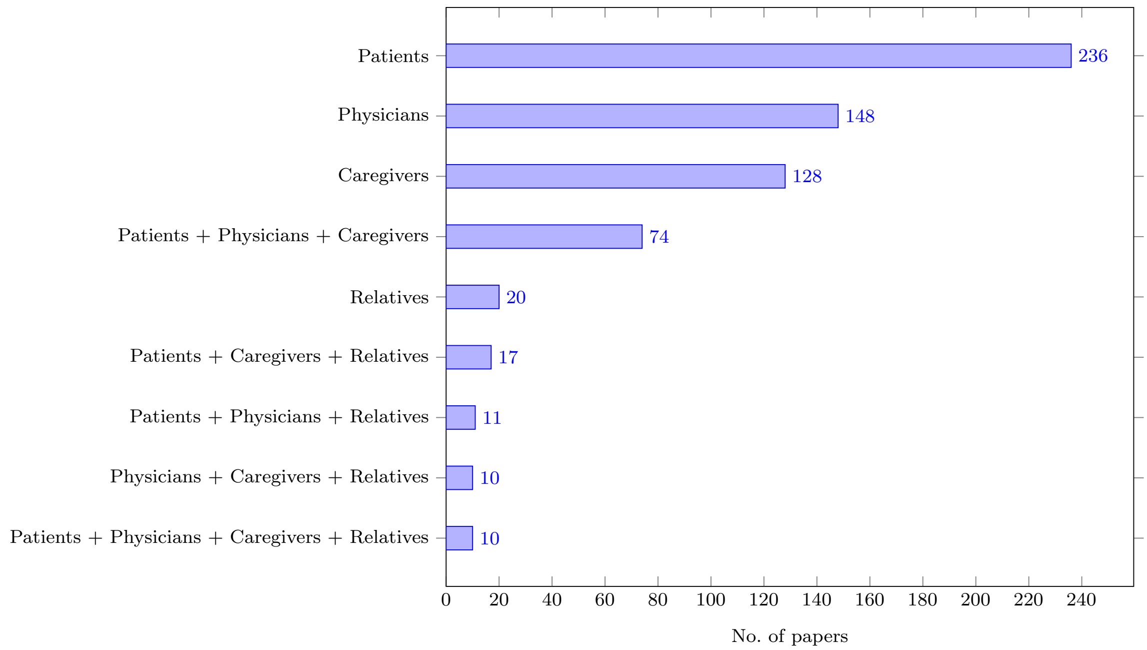

Fig. 5 Number of papers per end users combinations

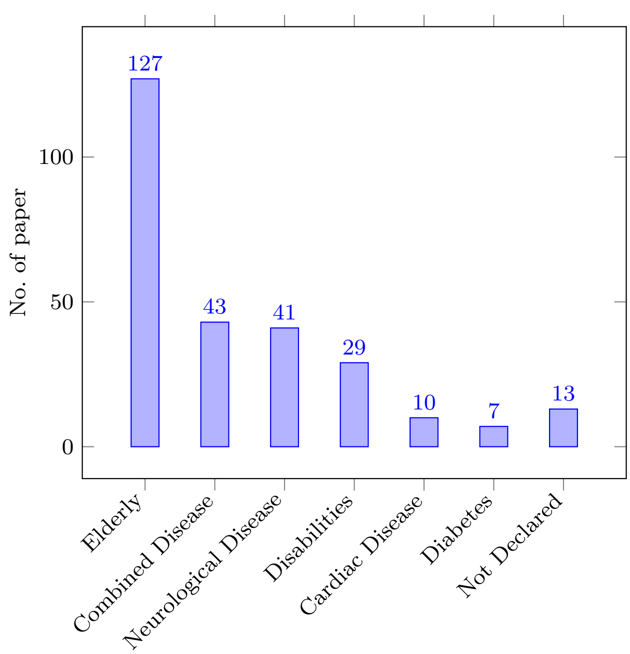

Fig. 6 Contributions per kind of disease

- Communication mainly with Data Sharing (25 %), Interaction (25 %), Control Vital Status (25 %), etc.
- Assistance mainly with Interaction (31 %), Multimedia Analysis (14 %), Communication (14 %), etc.

Referring to question RQ10, looking for research directions and open challenges for the AAL domain: the theoretical papers aim at obtaining empirical data. The papers presenting existing solutions aim at improving algorithms' precision, devices' usability, extending functionalities and enhancing the solutions' interoperability with healthcare systems while entering in the real market. Those results are not quantifiable, hence, it is not possible to provide any table or chart form of the results. An extensive discussion related to these results is provided later.

3 Results analysis and discussion

This section discusses the results of the ten research questions investigated in this paper. The treated topics are: (1) the distribution of the scientific contributions, (2) the stakeholders considered by the primary studies, (3) the main investigated diseases and difficulties characterizing the AAL domain, (4) the dynamics and the evaluation of the objectives of the considered AAL solution, (5) the evidences and limitations about architectures, techniques, technologies and methodologies of the solutions, (6) the evaluation of the addressed needs of the AAL domain, and (7) the evaluation of the connections among AAL needs and offered supports.

3.1 Distribution of scientific contributions

Investigating the scientific contributions to the AAL domain, especially for the time frame 2004–2013, on which this review is focused, the number of scientific papers focused on the AAL domain increased over the

Table 2 Support evaluation

Kind of support	Tot	Supports Evaluation					
		Y articles	P articles	N articles	Y %	P %	N %
Activities recognition	106	51	47	8	48.1	44.3	7.5
Control vital status	62	38	23	1	61.3	37.1	1.6
Position tracking	47	23	20	4	48.9	42.6	8.5
Interaction	43	14	24	5	32.6	55.8	11.6
Multimedia analysis	36	19	17	0	52.8	47.2	0
Data analysis	35	14	17	4	40	48.6	11.4
Data sharing	30	11	16	3	36.7	53.3	10
Communication	30	7	17	6	23.3	56.7	20
Not declared	13	/	/	/	/	/	/

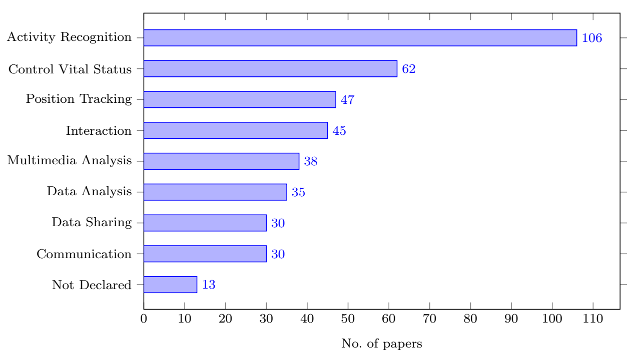

Fig. 7 Number of supports of the identified AAL needs

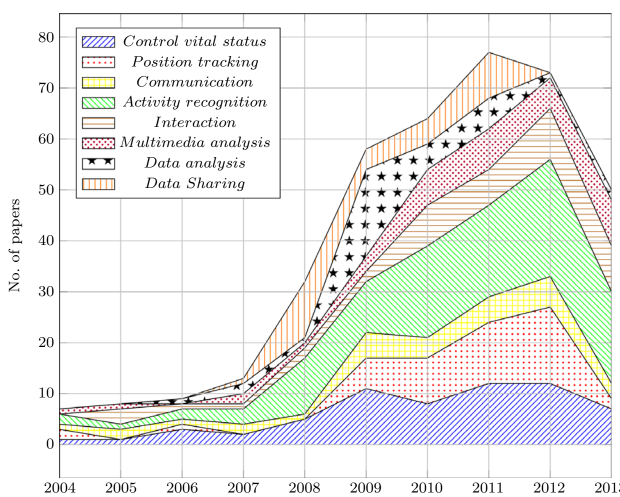

Fig. 8 Evolution of offered supports over the years

years, as depicted in Fig. 2. In particular, although some contributions were already given during the period between 2004 and 2006, the actual period during which the contributions significantly increased is between 2007 and 2009 where they almost doubled each year. Furthermore, during the later observed period, between 2010 and 2012, the increase slowed down and finally reached a

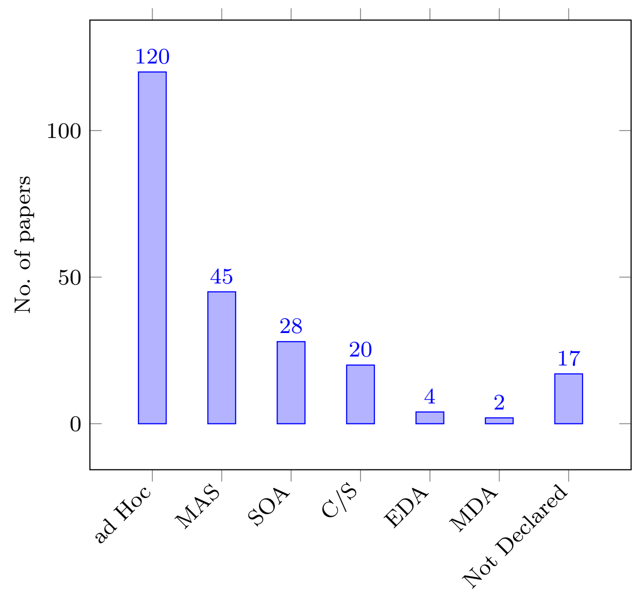

Fig. 9 Number of solutions per kind of architectures

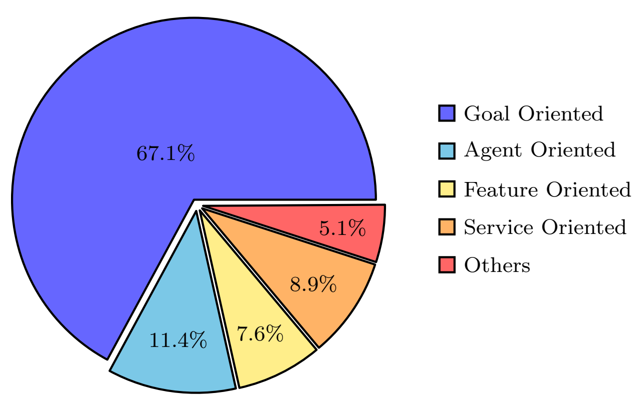

Fig. 10 Kind of methodologies adopted to design AAL supports

stable condition within a range of 45–50 papers per year after the year 2011.

Finally, it seems that the total number of collected articles in 2013 would not respect the trend observable

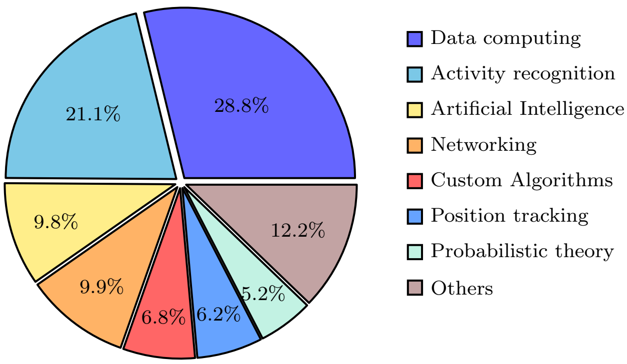

Fig. 11 Kind of techniques adopted to design AAL supports

until the year 2012. However, it is worth noting that the article collection phase, as already described in Sect. 2, was performed until December 2013. The observed behavior may be due to the lateness of paper publication, by editors, and of indexing, by web collectors.

One of the reasons for the increased interest in AAL is the establishment of the European AAL Joint Association in 2007, which also explains the gap between the European countries contributions and to all the others. Another explanation for that gap is the differences between the European healthcare systems, which are vastly public, and the other healthcare systems, which are mostly private.

Table 3 Kind of technologies

Single instance of group, Technological and devices	Tot (%)	Network (%)	Sensors (%)	Other (%)
Environmental sensor	12.13		29.52	
Health sensor device	11.32		27.55	
Network round	9.56	22.22		
Mobile device	7.35	17.09		
Generic sensor	9.47		15.74	
Inertial sensor	5.29		12.88	
Gateway	5.07	11.79		
Camera	5.0			31.48
Wireless	5.00	11.62		
RF technology	4.12	9.57		
Wearable sensor	3.90		9.48	
Bluetooth	3.75	8.72		
Zigbee	2.94	6.84		
IR technology	2.65	6.15		
Actuators	1.91			12.04
Position sensor	1.99		4.83	
White goods	1.69			10.65
Microphone	1.40			8.80
Wi-Fi	1.40	3.25		
Back-end	1.25			7.87
Touch screen	1.03			6.48
NFC	0.81	1.88		
Robot	0.59			3.70
Tablet	0.51			3.24
ICT technologies	0.51			3.24
O.S.	0.51			3.24
Front-end	0.37			2.31
Laser technologies	0.29			1.85
Radar systems	0.29	0.68		
Arduino	0.15			0.93
LED	0.15			0.93
MEMS	0.15			0.93
Photocell	0.15			0.93
Blinder	0.07			0.46
Braille	0.07			0.46
Voip	0.07	0.17		
Wii remote	0.07			0.46

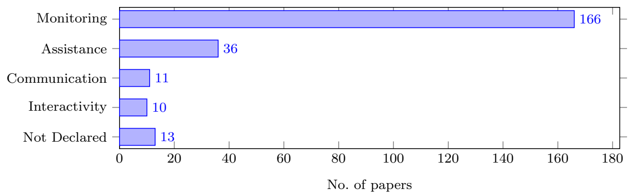

Fig. 12 Distribution of the AAL needs contributions

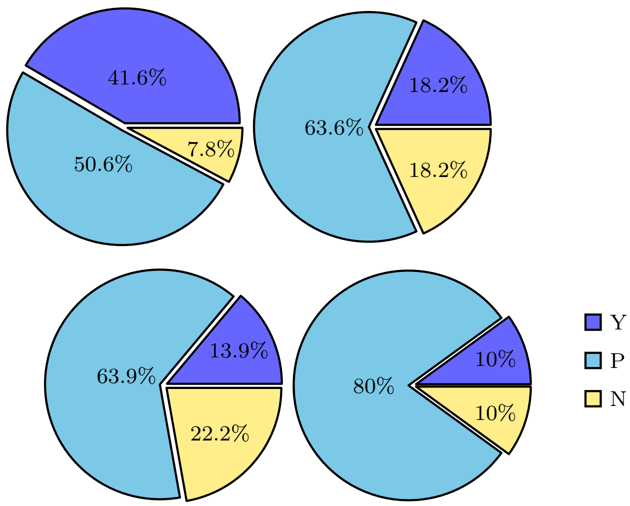

Fig. 13 AAL needs evaluation

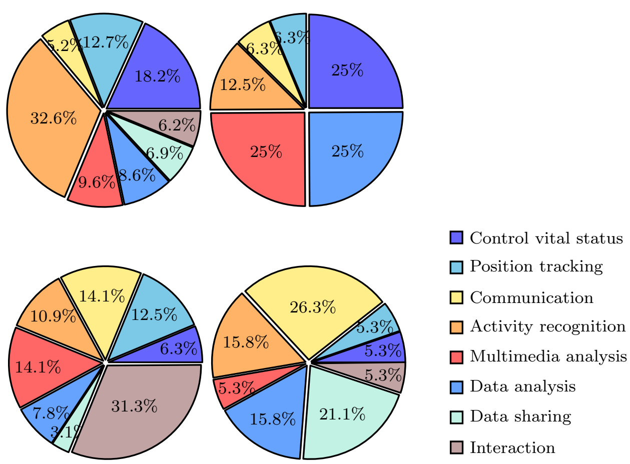

Fig. 14 Proposed solutions per AAL need

3.2 AAL stakeholders

The stakeholders considered in this work are those who might be interested in the solutions taken into account in this review. It should be kept in mind that they can be physicians or caregivers, patients (elderly, disabled, long-term ill) and their relatives (parents, sons) or any combination of such categories. As shown in Fig. 5, the analyzed papers took into account the categories "Patients, Physicians" and their combination, much more than the other categories.

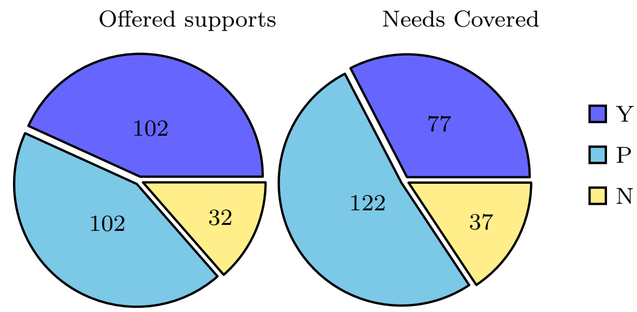

Fig. 15 Y–P–N evaluation of offered supports and needs coverage

A tight coupling has been noticed between Patient–Caregivers, and Patient–Relatives and their combinations. Furthermore, only 10 articles took into account the entire AAL ecosystem (patients, physicians, caregivers, relatives) at the same time. Such studies propose monitoring services to support all the people involved in the care of patients, exploiting the potential of internet of things and sensor technology; see for example (Dohr et al. 2010; Rocha et al. 2013). This limited attention might evidence some technical or technological immaturity or lacks in AAL needs and requirements analysis. Further research is required in order to understand the situations and the needs of all the above-mentioned stakeholders.

3.3 Diseases and difficulties evaluation

Being elderly is considered a life stage, however, as the general trend confirmed (Lutz et al. 2008; World Health Organization 2011), ageing is nowadays often considered as the main "disease" to be treated by technology in the coming years. In this case, the required technological tools should cope with more than one disease at a time. Thus, over the time, the incremental impact of commodities will require further analysis and supports. RQ3 aims at eliciting diseases and difficulties addressed by the solutions of the analyzed papers. Regarding the treatment of the specific diseases, the main diseases addressed have a neurological origin, followed by reduced mobility, cardiological problems and, finally, those related to diabetes. According to the current trends and technological state, these diseases are the ones that are most suitable to be treated outside the hospitals. For instance, the combination of sensor networks with data processing techniques (Bourennane et al. 2013) and symbolic approaches (Coronato and De Pietro 2013) allows to detect abnormal behaviors, which might be the sign of cognitive deterioration. However, attention is still required by the scientific community since they are coupled with patient ageing and the proposed solution must take into account the specific needs of this particular age class.

3.4 Dynamics and evaluation of AAL solutions' objectives

As described before, solutions for the AAL domain refer to several aspects. These include: control vital status, multimedia analysis, position tracking, activity recognition, data analysis, data sharing, interactivity, and communication. The number of contributions that are relevant and tangible (presenting concrete data or results) is limited. It was observed that in most of the studies, evidence of the promised supports is lacking. This lack of evidence might be due to several reasons:

– studies suggest to adapt an existing technique, technology or system to an AAL use case, without analyzing the users' needs in advance; for example in (Martin et al. 2009; Cruz-Sanchez et al. 2012), well-known communication protocols are used to address interoperability issues in sensor networks;
– studies focus on describing the system and do not cover the needs addressed by the proposed solution (although in this case they may have actually modeled the system starting from users' needs), as in papers presenting large research projects, such as (Stroulia et al. 2009; Kilintzis et al. 2013);
– studies describe techniques, technologies or systems that support the actual users' needs, but they fail to provide explicit information, simply stating that further information could be evidenced from other fields, such as Ambient Intelligence (Zhou et al. 2011; Mowafey and Gardner 2012).

Analyzing the information along the categories, diversity, in the evidence provided (see Fig. 16), was found. Also, as the AAL domain keep gaining its maturity, the provided evidence increases (see Fig. 17).

The analysis shown in Fig. 17 raises several additional questions: how did the topics change in terms of naming, techniques or AAL needs coverage, over the years? What happened in 2009 correlated with the drop of data analysis contribution in 2010? Is there a correlation among topics with respect to their support? What are the reasons for the change in focused topics? Possible explanation for that might be the expansion of certain categories and position those differently. For example, Activity Recognition can be considered as a specification of the Data Analysis. Hence, starting from 2009, a drop of the Data Analysis contribution, as well as, an increase of the Activity Recognition contribution can be seen. Another possible explanation is that some topics have reached a satisfactory level of the proposed solutions. For example, the advent of cloud-based

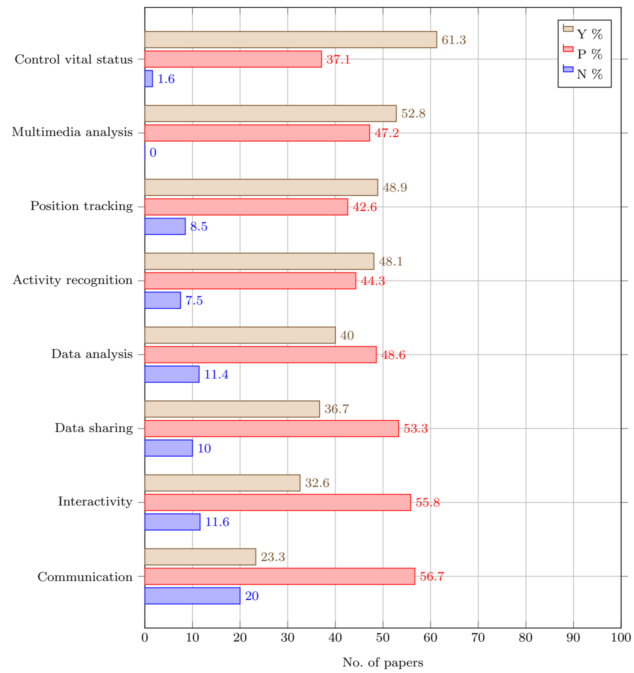

Fig. 16 Qualitative assessment of the kinds of provided supports (Y–P–N criteria)

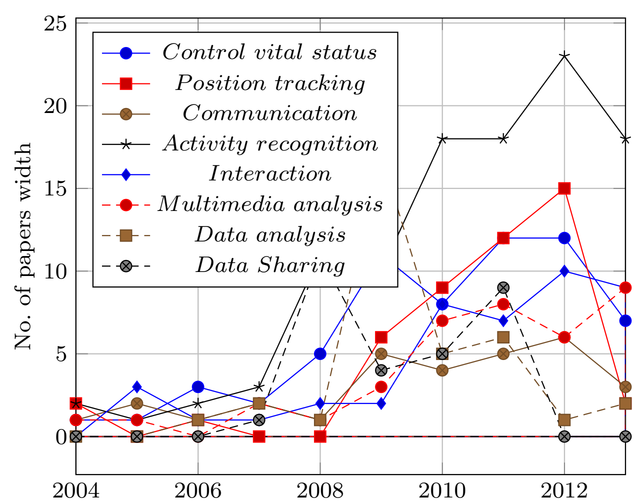

Fig. 17 Evolution of the offered supports over the years

solutions can be viewed as a technical solution that allows performing the Data Sharing task, even if privacy concerns, especially for health-related data, need to be tackled. Moreover, technologies such as passive infrared (PIR) sensors, cameras, depth sensors, radio frequency identification (RFID), allow to reliably perform indoor position tracking.

The evolution of the offered supports, shown in Fig. 17, is re-organized in Fig. 18 with emphasis on the proportions of the different supports rather than their occurrences per

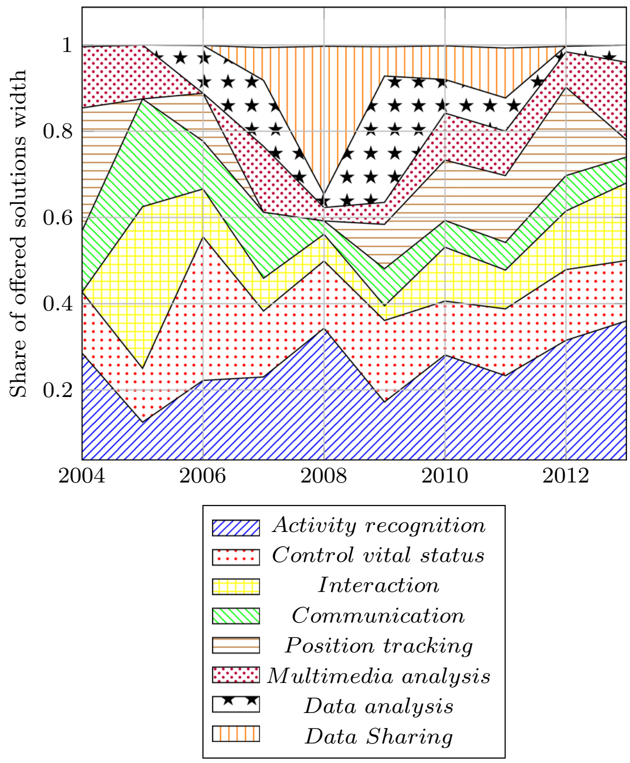

Fig. 18 Proportion between offered supports over the years (Expressed in absolute number)

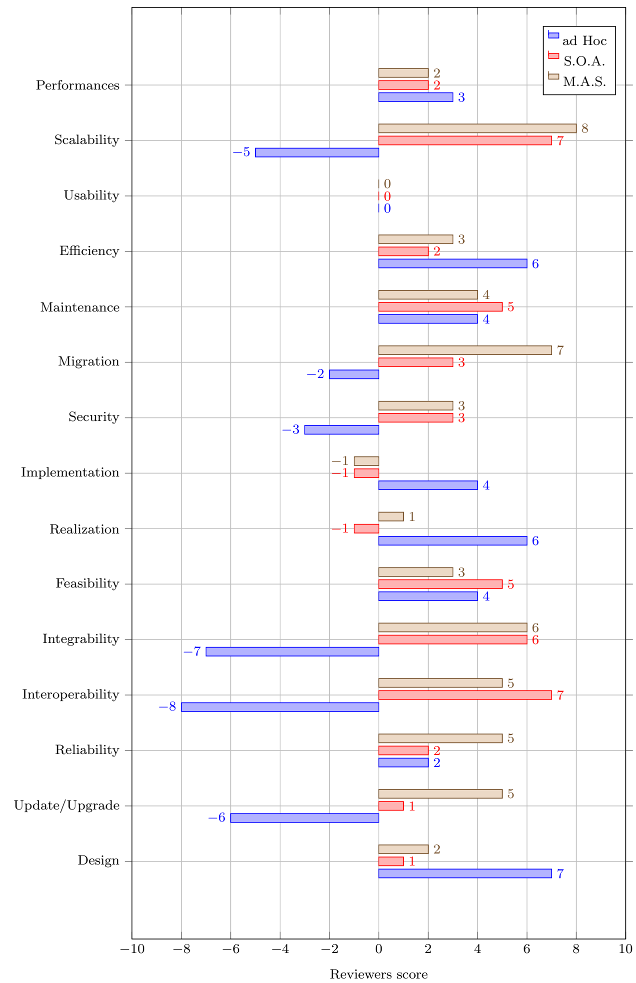

Fig. 19 Architecture evaluation: evidence and hints elaborated by the reviewers

year. Thus, single factors like the influence received by Activity Recognition from the advent of Data Analysis becomes more evident. Nevertheless, in the same year, both of them received more supports with respect to the others.

3.5 Evidence and limitations in solutions implementation

The solutions aiming at supporting the different AAL needs can be characterized by both hardware and software elements. In this study, the focus was on the software aspects, dealing with: Architectures, Techniques, Technologies and Methodologies.

3.5.1 Architectures

The results indicate that most of the AAL architectures are ad-hoc. On the one hand, AAL systems should be tailored to the end-users' needs and a pre-defined architecture might not be completely fitted to such needs. So, a high number of ad-hoc architectures might correspond to a high number of different needs. On the other hand, the lack of a systematic requirements analysis might result in a mixture of ad-hoc architectures that respond to what the designers perceive as end-users' needs. This limits their interoperability and the possibility to be merged, which is considered important (AAL EUROPE 2007). Large platforms that provide multiple services are typically based on ad-hoc architectures: "the MonAmI" platform (Šimšík et al. 2012) combines comfort applications with health monitoring and activity detection. Nevertheless, the review revealed also platforms based on Multi-Agent Systems (Ayala et al. 2012; Spanoudakis and Moraitis 2013) and Service-Oriented Architectures (Forkan et al. 2013; Stav et al. 2013) to implement heterogeneous AAL services, such as Activity Recognition, Control Vital Status, and Communication.

The various architectures in light of the following factors are further analyzed: design, update/upgrade, reliability, integrability, interoperability, feasibility, realization, implementation, security, migration, maintenance, efficiency, usability, scalability, and performances as depicted in Fig. 19. The scores in Fig. 19 are the average of the scores assigned by the three reviewers to each architecture, based on the information provided in the paper. Unfortunately, only 35.6 % of the papers report an explicit evaluation of the proposed architectures, 55.9 % of the papers provide an implicit evaluation (i.e., mainly just stated) and 8.5 % of the papers do not propose any evaluation of the architectures. Again, a lack of explicit evaluation of the proposed solutions, especially with respect to the end-users' needs, is identified.

3.5.2 Methodologies:

The analysis of the studies highlights that only 33 % of them provide information on the adopted methodology. Most studies do not provide details regarding the design process. Thus, such a low portion might indicate a major drawback: the systems are not systematically designed based on end-users' needs. Instead, it seems that systems are tailored on specific solutions and try to adapt existing techniques and technologies to what they perceive as the end-users needs, rather than starting by analyzing actual end-user needs. Nevertheless, the 79 papers which provide the information on the design methodology show promising results: the majority (75 %) focuses on the goals to be achieved with the suggested solutions, for example, in (Su and Wu 2011; Ayala et al. 2012), the authors base the design of agents on the goals they need to achieve. Following that approach, the first step is to model the goals that the system should achieve, and then to choose the techniques and the technologies that are required for implementing the solution. Here again, the major hint is the gap in evaluating the adopted methodologies. One reason for such a gap could be the existence of another work presented by the same author in a field dedicated to system design [(e.g., (Rumbaugh et al. 1991; Yu et al. 2011)].

3.5.3 Techniques

Data Computing and Activity Recognition/Identification represent the 50 % of the used techniques. They aim at using sensor data, contextual information, data mining, computer vision, etc. to reconstruct scenarios. Such scenarios include the detection of emergencies and potentials risks at home and reconstruction of suggested treatment as proposed in (Allègre et al. 2012; Ângelo Costa et al. 2012). This result indicates the importance of automatic assessment within the context of the AAL field. Artificial Intelligence-based techniques, as well as, network-based techniques, are around 10 % of the used techniques. This indicates the importance of providing AAL with the ability to perform autonomous actions based on inference and reasoning in general. It is worth to note that Probability Theory has been separated from the rest of Artificial Intelligence techniques even though some researchers tend to assign it to the same category.

The main limitation that emerges from the data is the lack of studies that describe, not even qualitatively, how much the proposed techniques satisfy the needs of the end-users. In reviewers' opinion, the need for performing remote monitoring, addressed by the Data Computing and Activity Recognition techniques in conjunction with the Network-based techniques can be considered as an exception.

3.5.4 Technologies

The results highlight a large amount of different technological solutions to provide remote services; nevertheless there is not a prevailing technology to provide network services, even if there is a predominance of Wireless technologies (Corchado et al. 2009; Martínez et al. 2011). Two are the main hypothesis:

- the majority of the proposed technologies is proprietary/customized, resulting in a high number of used protocols.
- different Network technologies are required to fulfill different end-users' needs (and thus to provide different AAL services) or are more suitable to different environmental conditions;

The variety of the Network technologies reveals the main limitation: the complicated integration of different network devices to jointly provide several AAL services. Mobile Devices, which sum up to the 17 %, including smart phones, PDAs or platforms based on mobile operating systems were included in the Network group. The majority of the Sensor technologies is composed by Environmental Sensors (30 %) and Health Sensor Devices (28 %), which further confirms the relevance of monitoring services in the AAL field. There are relevant results even in the other group. Cameras are the 31 % which could be higher but most likely limited due to privacy concerns. Despite the significant portion of Mobile Devices among the Network-based technologies, there are few papers dealing with Touch Screen technologies to serve the AAL (6 % of the Other group, 1 % of the total). One reason could be that the devices on the market are not suitable to end-users needs; interfaces might not be ready, especially for the use by elderly. A similar hypothesis can be made for Microphones. In addition, there is the problem of performing automatic speech recognition of elderlies, since ageing changes speech production.

3.6 Evaluation of addressed needs in the AAL domain

The majority of the papers (70 %) deals with monitoring, indicating that this need is perceived as an important one. Monitoring deals mainly with the home environment, applying many environmental sensors (temperature, pressure, humidity, proximity, gas leakage, doors/windows position, light, water flow, etc.), web cams and microphones, and new wearable sensors (heart rate, respiratory rate, ECG, HRV, VO2 max, recovery, ventilation, position, steps, distances traveled, etc.) in order to develop a comprehensive and up to date view of what is going on inside the house and with its inhabitants. However, monitoring would be useless if nobody could intervene. In fact, 15 % of the papers deal with (external) assistance, i.e., with the definition of processes, workflows, and protocols intended to make the transition from monitoring to action more effective, for example using activity recognition to provide caregivers with a summary of the health conditions of patients (Kwon et al. 2012). These papers refer to the necessity of improving communication and filtering of false positives and false negatives. The improvement of the communication need is addressed by four percent of the papers while another four percent deal with interactivity, which means how to let the assisted persons interact with the overall system in an effective and usable way (Miñón and Abascal 2011). Smart interactivity and filtering out false alarms require Artificial Intelligence techniques, in particular, diagnostic reasoning and automated learning.

3.7 Offered supports and needs coverage

Referring to the connection among AAL needs and the related solutions, the different kinds of supports provided by the various studies, coupled with the needs that such studies address, has been shown in Fig. 14. The need to perform remote monitoring (which is the most addressed need, as highlighted by the results for RQ8), is achieved with the support of Activity Recognition or Control Vital status in 50 % of the cases: studies associate the Monitoring need with the identification and recognition of the patient's cognitive and health status. Typically, the recognition of activities of daily living is used to predict cognitive decline and biometric parameters to detect potential risks for the patient (Fernández-Llatas et al. 2011; Coronato and De Pietro 2013). Such a trend is also confirmed by the rest of supports for the Monitoring need: Position Tracking (12.7 %) can complement the Activity Recognition; Multimedia Analysis (9.6 %) and Data Analysis (8.6 %) offer support to process the extracted data.

The main support to Assistance, as expected, is provided by Interaction (31.3 %). In fact, user-to-user and user-to-machine interactions can facilitate the decision-making process in providing Assistance.

Interactivity represents the possibility of having an actual synergy among users and assistive technologies. The major contributions regarding the interfaces and the communication focused on treating the data that have to be shared. Furthermore, assistive technologies will generate an ever-growing amount of data that need to be shared, accessed, read, stored, and used. A key issue of modern systems is indeed making the interaction with this data as easy and seamless as possible.

Regarding the Communication, the biggest effort is equally given to Data Sharing, Interaction, and Control Vital Status. In fact, the most important data to be shared are the vital parameters obtained through the monitoring. Finally, there is still an open question: "where does data have to be elaborated?" and a big effort is spent in this direction. Once such data will be available, readability and reliability will become more relevant issues.

3.8 Needs and solutions evaluation

Providing both theoretical and concrete solutions, the authors often neglect the need to evaluate their works using various evaluation techniques. Nevertheless, some of the studies did perform such evaluations and interesting techniques were observed. This include accuracy check with simulated or estimated data (Tapia et al. 2004), test-bed (De et al. 2012), clinical trials (Fayn and Rubel 2010), and field experiment related to human–machines interfaces (HMI) (Spanoudakis and Moraitis 2013). The used metrics include performance, usability, security, etc., allowing further improvements and comparisons. Some of the evaluations were performed upon data gathered in a reasonable temporal window, testing different setup and configuration while performing a longitudinal analysis (Kealy et al. 2013). Considering software solutions, the compliance with stakeholders' needs and systems' requirements (Calvaresi et al. 2014b) can be assessed using formal verification and model checking (Augusto and Hornos 2013; Benghazi et al. 2012). However, as highlighted in Fig. 13, the level of using formal methods for assessing the fulfillment of such needs is still low. Concerning the supports provided to satisfy the stakeholders' needs as listed in Table 2, simulation and benchmarking with similar systems are well suited for data analysis (Winkley et al. 2012; Yuce 2010). The papers providing a concrete evaluation of the offered supports identify the need of participatory evaluation (Demiris et al. 2008), especially for the control of patients' vital status. For example, in (Jara et al. 2011) a group of users consisted of patients, nurses, and physicians provided feedback about a personal device in order to improve the insulin dosage calculation. In addition, in order to evaluate a device with respect to self-recording of ECGs, 108 patients have used the device in an early trial (Fayn and Rubel 2010).

4 Conclusions

This paper presents a systematic literature review in the domain of AAL, which is performed to investigate, study and understand how the scientific community interprets and addresses the emerging needs. The review was focused on ten research questions and the main findings are:

- most of the papers were written in Europe, in particular in Germany and published after 2007;
- the solutions are mainly patient and physician centered, neglecting other recipients of the AAL ecosystem;
- the solutions are mainly focused on patients monitoring and activity recognition;
- the solutions often consist of ad-hoc architectures;
- there is a lack of concrete evaluation concerning the actual usability, effectiveness and efficiency of the proposed solutions in achieving the emerging needs;

The review indicates a clear need for:

- rigorously evaluating and validating both new and existing AAL solutions;
- investigating and better understanding the relationships among the actual user's needs and the proposed solutions.

In conclusion, a solution would be more effective if designed with less technological and technical commitments, giving more room to the actual "needs/goal" analysis of the involved end users. For example, the evidence raised in this review suggests as promising future direction the empowerment of the interaction among all the AAL actors throughout a single solution, that, nowadays is still missing.

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