Reasoning in Multi-agent Based Smart Homes: A Systematic Literature Review

Dagmawi Neway Mekuria, Paolo Sernani, Nicola Falcionelli and Aldo Franco Dragoni

Abstract Multi-agent systems are widely used to model components of a smart living environment as autonomous intelligent agents. Accordingly, its advantages to achieve the comfort and efficiency goals of smart home systems are well-documented in many studies. However, there is a clear lack of systematic investigation targeted at exploring the reasoning modules integrated into these systems. To close this gap, this paper examines the literature on multi-agent based smart home systems and provides a comprehensive overview of the essential requirements, assumptions, strengths, limitations, challenges and future research directions of their proposed reasoning systems. Moreover, it identifies the main technologies used to represent the home environment as a multi-agent system and the reasoning approaches utilized to bring decision-making ability into the smart living environment. As a result, this systematic literature review identifies the ability to learn, plan, predict, explain and reason with incomplete knowledge as the major elements of a smart home reasoning system. In addition, the findings of this work revealed the application of standard rule conflict resolution strategies and sensor data contextualization as principal solutions to address some of the problems caused by conflicting rules and agent goals. Further, it underlines the importance of utilizing hybrid reasoning approaches and the need to handle overlapping multi-inhabitant activities to realize the true potential of smart homes.

Keywords Smart homes · Multi-agent system · Reasoning system

D. N. Mekuria (✉) · P. Sernani · N. Falcionelli · A. F. Dragoni
Università Politecnica delle Marche, Ancona, Italy
e-mail: d.n.mekuria@pm.univpm.it

P. Sernani
e-mail: p.sernani@univpm.it

N. Falcionelli
e-mail: n.falcionelli@pm.univpm.it

A. F. Dragoni
e-mail: a.f.dragoni@univpm.it

A. Leone et al. (eds.), *Ambient Assisted Living*, Lecture Notes in Electrical Engineering 544, https://doi.org/10.1007/978-3-030-05921-7_13

1 Introduction

The term "smart home" refers to a residence equipped with technology that facilitates monitoring of residents, promotes independence and increases residents' quality of life [16]. Recently, smart homes have been widely used to provide services such as energy management [34], healthcare [17], comfort [20] and entertainment [38]. To deliver these services, the home system must be able to perceive the state of the home through sensors and adapt the environment to its inhabitant needs through effectors.

One key feature of a smart home is the ability to reason, which enables the home system to make an appropriate decision towards achieving comfort and efficiency goals of its inhabitant and their surroundings. With this in mind, various artificial intelligence techniques have been applied to bring decision-making ability into the home environment. Among them, multi-agent system (MAS) architecture, which is based on the interaction of autonomous intelligent agents, is considered as an ideal candidate to cope with the dynamic and distributed nature of a smart home environment. As stated on [39], intelligent agents possess the following characteristics:

- **Autonomy**: agents operate without the direct intervention of humans or others, and have some kind of control over their actions and internal state.
- **Social ability**: agents interact with other agents (and possibly humans) via some kind of agent communication language.
- **Reactivity**: agents perceive their environment and respond in a timely fashion to changes that occur in it.
- **Pro-activeness**: agents do not simply act in response to their environment, they are able to exhibit goal-directed behaviour by taking the initiative.

Many studies have utilized these key properties of intelligent agents to demonstrate the advantages of modeling smart environments using MAS approaches. However, there is a clear lack of systematic investigation targeted at exploring their integrated reasoning systems. Most existing reviews present a comprehensive overview of the smart home system such as [3, 12] or explore in detail a specific smart home technology such as [8, 16]. While few others tailored their surveys to investigate the application of agent-based decision support system for specific domains such as medical data classification [30] and clinical management [18]. And, to the best of our knowledge, none devoted their work to examine the reasoning approaches of multi-agent based smart homes. To close the gap, this paper reports the preliminary results of a systematic literature review conducted to examine the previously mentioned domain. In this regard, it aims to explore:

- the main requirements of MAS based smart home reasoning system.
- the tools, technologies and methodologies used to develop the MAS environment, and the reasoning approaches integrated into it.
- the principal assumptions, strengths and limitations of the proposed techniques.
- and, the reported challenges and future research directions of the field.

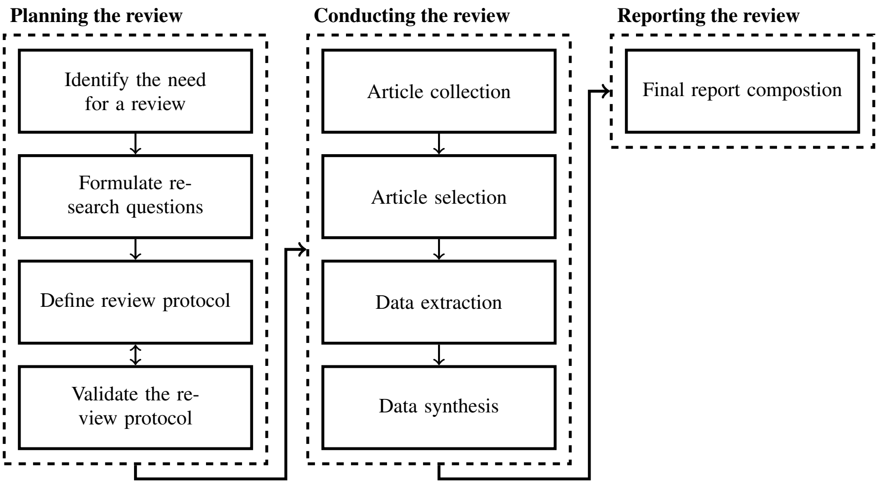

Fig. 1 The systematic review process

The rest of the paper is organized as follows: Sect. 2 describes the review process and the protocol underlining this systematic review. We present and discuss the review results and findings in Sect. 3 and we conclude and discuss future works in Sect. 4.

2 The Review Process

A systematic literature review (SRL) is a method that enables the evaluation and interpretation of all accessible research relevant to a particular research question, subject matter, or event of interest. It aims to present a fair evaluation of a research topic by using a trustworthy, rigorous, and auditable methodology [24]. Most common reasons to perform an SRL are:

- The need to evaluate and summarize existing evidences concerning technology.
- And, to identify gaps in the technology that will potentially lead to topics for future investigations.

In this study, we have carried out an SRL by adapting the guidelines proposed in [24]. The review process (shown in Fig. 1) consists of three main phases: Planning the review, Conducting the review, and Reporting the review. The rest of this section discusses in detail our adopted approach and its principal components.

2.1 Planning the Review

Before conducting a systematic review, researchers should identify and examine existing systematic literature reviews on topic of interest, and ensure the need for a systematic review. However, the most important pre-review activities are defining the research question(s) that the review will address and producing a review protocol (i.e. plan) by defining the basic review procedures [24].

2.1.1 Formulating Research Questions

The most important activity during an SRL is to formulate the research questions [24]. Hence, we defined the goal of this review through Goal-Question-Metrics approach [37] as follow:

- **Purpose**: *Explore, Analyze, Characterize, and Compare*
- **Issue**: *Reasoning Systems*
- **Object**: *Multi-agent based Smart Homes/Smart Living Environments*
- **Viewpoint**: *Researcher's point of view*.

To identify the major requirements and purposes of MAS based smart homes reasoning systems, and to assess the contributions presented in the literature, based on the above-defined goal, we formulated the following six research questions (RQ).

RQ1: What are the central purposes of the smart home systems?
RQ2: What are the primary requirements of multi-agent based smart home reasoning system?
RQ3: What are the major technologies used to develop the multi-agent based smart home system? And, which reasoning approaches are used to provide agents decision-making ability?
RQ4: Which of the proposed systems are tested and/or integrated into a real-world living environment?
RQ5: What are the strengths, limitations and assumptions of the proposed (MAS based) reasoning systems?
RQ6: What are the main challenges and future research directions stated in the literature?

2.1.2 Define the Review Protocol

The review protocol specifies the methods to be followed while conducting the systematic review. Based on [24], a review protocol should define the following activities of the SRL: the strategy that will be used to search for primary studies selection; study selection criteria; study quality assessment criteria; data extraction and dissemination strategies. In the rest of this section, we discuss how we specify and perform each of these activities.

2.2 *Conducting the Review*

This phase is composed of the following main activities: article collection, article selection, data extraction and synthesis, where each of them is composed of several sub-activities.

2.2.1 Article Collection

The aim of an SRL is to find as many primary studies as possible related to the research question, using a repeatable search strategy [24]. Accordingly, to carry out a comprehensive and exhaustive search for the primary studies, it is necessary to define a search strategy and strictly apply it. Our article collection process consists the following two main sub-activities:

I **Definition of the search query**: to build the search query[1] shown in Fig. 2, we adopted the following steps recommended in [6].

- Derive major search terms from the research questions.
- Collect keywords from known primary studies for additional main search terms.
- Identify synonyms of the main search terms.
- Construct search strings using Boolean "AND" to join the main terms and "OR" to include synonyms.

II **Conduct the search**: with the aim of performing an exhaustive search, we identify the following six electronic databases: ScienceDirect, SpringerLink, IEEExplore, ACM Digital Library, Google scholar and Semantic scholar. Then, we perform an automated search on each of them, except ACM Digital Library.[2] When required, we adopt the basic search string to the search engine of each source.
The automated article collection is done through an in-house web crawler that able to detect and ignore article repetitions. It also stops the gathering process after detecting a sequence of ten articles that are unrelated to the query of interest. The crawler detects the "unrelatedness" of an article by matching the title of the paper with a predefined set of keywords.[3]

[1]The search query is defined for a larger SRL, that we are conducting on smart home reasoning systems. Therefore, it does not explicitly include MAS.

[2]ACM End-user policy specifically prohibits automatic downloading of articles.

[3]The set of related keywords was defined according to the reviewers' subjective knowledge and experience on the field.

(("smart home" OR "smart building" OR "smart house" OR "smart living environment" OR "connected home" OR "context aware home" OR "context aware building" OR "context aware living environment" OR "building automation", "home automation" OR "domotic" OR "ambient assisted living" OR "active assisted living" OR "ambient intelligence") AND ("reasoning system" OR "decision support" OR "expert system"))

Fig. 2 Basic search strings

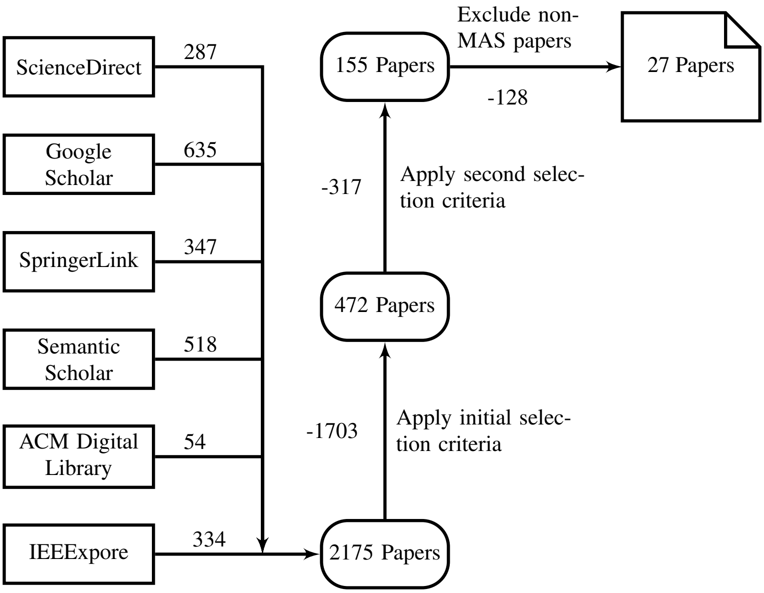

Fig. 3 Article collection and selection process

2.2.2 Article Selection

As shown in Fig. 3, our search process elicited 2175 articles. To select appropriate studies for inclusion in the review the following two sets of inclusion and exclusion criteria were specified:

I **Initial Selection**: as the number of collected papers are vast to consider for full text analysis, in this phase we evaluated the papers based on their abstract, title and list of keywords. The inclusion and exclusion criteria applied for this phase of selection are listed below. A paper was included if it met all inclusion criteria and eliminated if it met any exclusion criterion.

Inclusion criteria:

- Papers whose title indicates that it deals with reasoning systems in smart living environments.
- Papers whose keywords match with some of the search terms defined.
- Studies which presented very general decision support techniques for pervasive/ubiquitous environments and that can be directly applied to smart living environments.
- In addition, articles that focus on smart home inhabitants activity recognition, learning and monitoring are included as potentially relevant articles, to determine if their proposed technique can be applied to the problem domain.
- Similarly, studies on home appliance optimization, planning and scheduling are included, only if the results of these studies are used for decision making/reasoning processes in the home environment.

Exclusion criteria:

- Duplicates reports of the same study, in this case only the most recent and complete version is included.
- Papers that are not published in the English language.
- Studies that focused on smart grids, smart cities, non-residential buildings, and applied for outdoor intelligence services.
- Studies tailored for smart home appliances (e.g. smart fridge, smartphone, smart mirror, domestic robots…), but do not generalize their solution for smart living environments.
- Grey literature.

As abstracts might be insufficient to rely on when selecting, if there was any doubt whether a study should be included, it was added to the list of potentially relevant studies. The outcome of this selection stage was 472 papers, i.e., we have excluded 1703 papers.

II **Secondary Selection**: in this phase, the potential of an article to be included as a primary study assessed by skimming over the full-text of the contribution.An article must satisfy both of the following criteria to be part of in the primary study.

A **Contribution**: The primary contribution of the study should be towards the definition of theoretical foundation and/or the provision of empirical evidence (through implementation, tests, critical analysis, or critical evaluations) for constructing a reasoning system.

B **Context**: the study should be defined in the context of domotics and/or other closely related domain. In addition, a study proposed to address a broader concept but can be mapped into a smart home scenario, is considered to meet this criterion.

After the execution of this selection stage, we remain with 155 papers. However, as this SRL scopes on articles presented based on Multi-agent approaches, another 128 papers were excluded. Consequently, the articles to be explored reduced into 27 papers.

2.2.3 Data Extraction

To extract the data needed to answer our research questions the selected primary studies were read in-depth. Then, we kept a record of the extracted information in a spreadsheet for subsequent analysis. Some of the fields of our data extraction form are: *paper ID, publication year, targeted purpose, article abstraction, MAS technologies (i.e. tools, frameworks and techniques), reasoning technologies (i.e. approach, methodology, and tools), strengths, assumptions, limitations, future works and challenges*. The assumptions, limitations and strengths of an article were determined based on the knowledge of the reviewers, who are experts both in MAS and reasoning systems.

2.3 Data Synthesis

During an SLR, the extracted data should be synthesized in a manner suitable for answering the questions that an SLR seeks to answer [24]. For this SLR, we perform descriptive synthesis of the extracted data and present part of the result in a tabular and diagrammatic form.

To answer RQ1 (Sect. 3.1), we grouped purposes of the contributions into three categories. For the purpose of answering RQ2 (Sect. 3.2), "requirement" was considered as any property, characteristics or feature of the smart home reasoning system. And, to answer RQ4 (Sect. 3.3.1), we grouped the way an article is presented into three groups and explored in detail the employed MAS technologies and their reasoning systems. Whereas, RQ3 (Sects. 3.3.2–3.3.4), RQ5 and RQ6 (Sects. 3.4 and 3.5 respectively) are answered by performing descriptive synthesis of the extracted data and summarizing the results.

3 Review Results and Discussion

This section presents and discusses the findings of this review.

3.1 Purposes of Smart Homes

As shown in Fig. 4, the majority of the analyzed papers are designed with the aim of providing classical home automation services. Mainly, they tackle the control

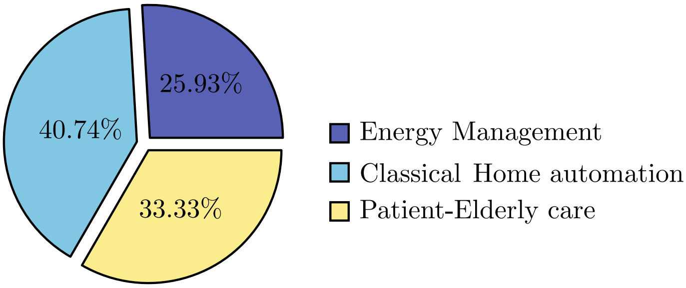

Fig. 4 Main purposes of smart homes

and management of context-aware lights, HVAC systems, consumer electronics and entertainment devices. In addition, our study identified home energy management, patient care and elderly assistance as the other most popular smart home services addressed by the examined articles.

3.2 Requirements of a Smart Home Reasoning System

A review on agent technologies application [22], stated the ability to perceive its environment and respond in a timely fashion to the changes that occur in it, as well as the ability to exhibit goal-directed behaviour by taking the initiative, as two most important properties of an intelligent agent. That means, an intelligent agent which controls a smart home has to be capable of selecting the most appropriate decisions based on the circumstances in the home environment, and autonomously work towards fulfilling its inhabitant preferences (e.g. thermal comfort) while maintaining its design objectives (e.g. energy efficiency). To realize such an intelligent behavior, it is necessary for an agent to possess a diverse set of reasoning skills. In the aim of identifying these fundamental expertises a smart home intelligent agent should be equipped with, we carefully gathered and summarized the following list of requirements from the primary studies investigated:

- **Learning ability**: the analysis of the studies highlights that self-learning is an essential component to be integrated into smart home reasoning system. Thus, the system will suit the dynamic household living patterns and adapt to small changes without being explicitly requested.
- **Planning ability**: some of the studies underlined on the need to integrate a planning component into the agent reasoning system. As a result, it will be able to develop task plans and provide proactive solutions.
- **Ability to predict**: many examined studies stressed that an agent should be able to make a prediction of inhabitants behaviour in the smart home environment.
- **Ability to explain**: few of the examined primary studies outlined the ability to explain its decision as another key requirement of an agent's reasoning system.

Specifically, they stated that an agent should be able to explain its behaviour by revealing relevant facts of its decision.

- **Ability to reason with incomplete knowledge**: examined studies [14, 33] describe the open and dynamic nature of the ambient assisted living environments and, the incomplete and ambiguous contextual knowledge generated from it. And, stressed the importance of integrating different reasoning strategies to make the agent reason with incomplete and inconsistent knowledge about the environment.
- **Adaptability**: though the ability to adapt hugely overlaps with learning abilities, some of the analyzed studies specifically pointed out on the need for an agent's decision-making system to perceive environmental changes and provide adaptive and proactive services to its users.
- **Configurability**: some of the investigated articles insisted that majority of smart home users are non-technical people. As a result, they recommended the reasoning system of a smart home to be highly customizable and easy to configure. Therefore, it will allow the user to express his/her desires in a simple and natural way, and integrate those changes with the rest of its behaviours.
- **Context-awareness**: almost all of the examined studies identified context-awareness as a fundamental attribute of a smart home reasoning system, despite the fact that, it highly overlaps with most of the aforementioned features. A specific reason for this can be the need for a reasoning system to acquire and utilize information about the context of the home environment. So that, it can provide efficient services that are appropriate to the particular people, place, time and event.
- **Non-disturbance**: another interesting but roughly defined concept for a reasoning system in a living environment by [20] is non-disturbance. The study insists on the fact that an agent should be non-disturbing. As a result, the agent should not bother the user more than necessary.
- **Conflict Resolution Strategy**: usually a multi-agent system environment is packed with autonomous agents, which work towards attaining conflicting objectives (e.g. a comfort agent tries to preserve inhabitant comfort by turning on a heater, while an energy saving agent attempts to turn it off). In order to avoid such conflicting situation [5, 34] underline on the need to have a global conflict resolution strategy in multi-agent systems. Whereas, many others stressed on the need to implement local conflict resolution strategy for the agent's own decision support system. So that, execution of conflicting actions that may result in an inconsistent state will be avoided.

Moreover, the analyzed studies specified other non-functional requirements to be considered including reliability, fast performance, satisfactory response time, extensibility, usability and interoperation with other already active client applications. Since also the computational capabilities of most devices in ambient environments are very restricted, [5] points on the need to keep the communication load not too heavy, so that the system can quickly reach a decision, taking into account all the available context information that is distributed between the ambient agents. In addition, [35] listed communication protocol, collaboration scheme, and resource management as the major issues need to be addressed when designing a multi-agent based smart home system. Whereas, [2] shares an interesting point of view, on assessing psychology and social sciences aspects of a reasoning system while designing ambient assisted living environments. It also points on the importance of some additional scientific backgrounds, which are necessary to model the emotional and psychological state of a generic user that interacts with an immersive computing framework.

3.3 Technologies for Multi-agent Based Smart Homes

This section discusses the technologies employed for building a multi-agent based smart homes. Specifically, it explores the development methodologies, frameworks and the reasoning approaches proposed to be integrated into it.

3.3.1 Article Abstraction

To better study the feasibility of the research contributions, they were categorized into the following three groups:

- **Conceptual**: articles which presented only theoretical contribution.
- **Proof-of-concept (PoC)**: articles that illustrated the feasibility of its theoretical contribution with a PoC implementation.
- **Tested in a real-world environment**: articles that integrated and tested its proposed solution in a real-world environment.

And, as shown in Fig. 5, 44.44% of the examined studies presented an entire theoretical contribution, without any feasibility assessment of their proposed solution. Whereas, 29.63% of the articles experimented their contribution in a simulated environment. The rest 25.93% of the examined articles integrated their proposed multi-agent architecture either into a testbed or an actual home environment, and run a series of experiments.

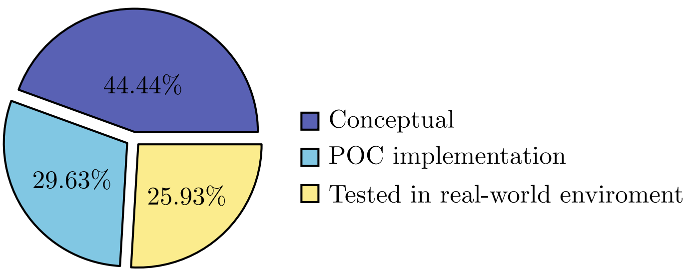

Fig. 5 Distribution of article abstraction

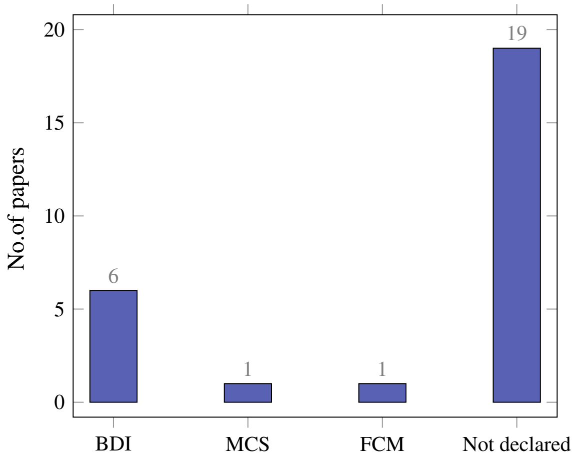

Fig. 6 Utilized multi-agent paradigms

3.3.2 Agent Models and Methodologies

Agent models are essential to describe the agent's internal structure (belief, plans, goals…), and their interaction in the environment [11]. Hence, six of the examined articles utilized BDI agent model [9] to design their proposed system in a standard way. On the other hand, [5] builds its solution based on Multi-Context Systems paradigm [21], in which local knowledge of ambient agents is encoded in rule theories (contexts), and information flow between agents is achieved through mapping rules. Whereas, agents in [2] are modeled as Fuzzy Cognitive Maps. As depicted in Fig. 6, none of the other examined articles specified the agent modeling technique adopted for their work.

In addition, [26, 29], which adopted ASEME and Prometheus methodologies respectively, were the only two articles claimed to design their solutions by adopting a standard agent-oriented methodology.

3.3.3 Frameworks

As depicted in Fig. 7, six of the proposed solutions were built on top of the well-known Java Agent Development Framework (JADE) [4]. And, [19] demonstrated its multi-agent based smart home system using Jadex agent framework [7]. Whereas, [31] developed a PoC implementation of their systems by combining JASON [10] and JADE technologies. However, the majority of the examined contributions were presented as ad-hoc. Their choice of using tailor-made solution was justified by successfully achieving the objectives of their study. Nonetheless, not embracing a proven framework (e.g. JADE) will restrict the robustness, scalability, and interoperability of the proposed solution.

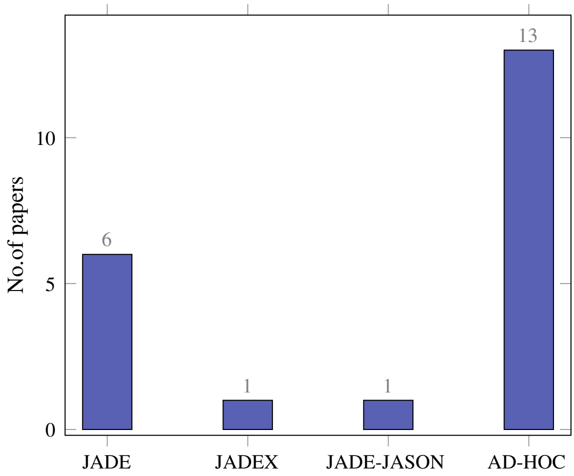

Fig. 7 Multi-agent frameworks

3.3.4 Reasoning Approaches

To effectively present the reasoning approaches integrated into the examined multi-agent based smart home systems, we categorize them into the following three groups:

- **Symbolic approaches**: This group contains all symbolic artificial intelligence techniques used to provide decision support abilities for the proposed systems. Knowledge-based systems, Semantic web and ontology technologies, Search, Optimization, and Planning techniques, are all grouped here.
- **Statistical approaches**: this group contains all modern decision support techniques based on statistical artificial intelligence such as Artificial neural networks, Bayesian networks, and Machine learning algorithms.
- **Hybrid approaches**: this group comprises reasoning techniques, which utilized a combination of the above two approaches.

As shown in Fig. 8, this result is unsurprising, considering the strong and long-established bond between knowledge-based systems and multi-agent technologies. And, the fact that statistical approaches suffer from the problem of reusability and scalability, … i.e a model for an inhabitant may not be applicable for another, and since every activity needs to be learned makes the adoption of such approaches limited.

3.4 Evaluation of the Presented Solutions

This section summarizes the assumption made by the analyzed articles and discusses the strengths and limitations of the proposed multi-agent based reasoning systems.

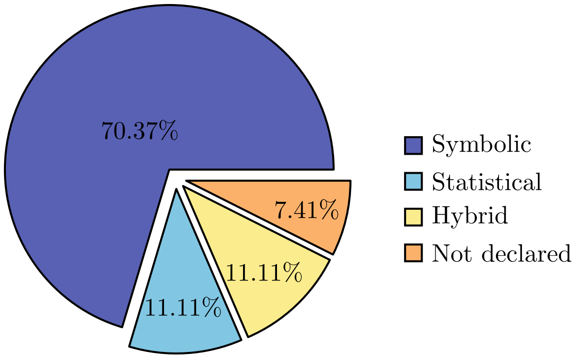

Fig. 8 Reasoning approaches in smart homes systems

Table 1 Summary of assumptions

Assumption	Class	Assumption	Class
Collaborative	Agent	Ability to reason	Agent
Ability to predict	Agent	No conflicting context	Reasoning system
Rationality	Agent	known inhabitant state	Agent
Ability to send unlimited messages	Agent	Single inhabitant	Reasoning system
Reliable communication channel	Agent	Consistent context	Reasoning system
Willingness to share information	Agent		

3.4.1 Assumptions

Table 1 shows the summary of assumptions made by the examined studies. To effectively denote wherein the system these assumptions are made they are marked either as agent or reasoning system. The ones marked as an agent are the assumptions listed in some of the papers to describe the behaviour of the intelligent agents in the proposed smart living environment. Moreover, as most of the evaluated papers neither address conflicting agent interests nor consider multiple inhabitants behaviour, the assumptions marked as reasoning system were made to present their solutions.

3.4.2 Strengths

Most of the articles reviewed highlights the advantages of modeling smart home environment as a Multi-Agent System by mapping some key features of ambient intelligence such as autonomy, distribution, adaptation, proactiveness, interoperability and responsiveness with the properties of software agents. Cavone et al. [13] states that decentralized solution is a suitable alternative given the largely open and pervasive nature of smart environments. It has also some clear advantages, such as system scalability and the benefits to avoid a single point of failure. Further, [1] took the full advantages of MAS, by proposing an open and extendable solution, which allows new devices to join and leave the system without completely redefining the control mechanism. Another reviewed paper, [32] applies the concept of agent negotiations for the decision-making purposes. Whereas, [5] attempts to deal with some key concerns in ambient intelligent environments such as uncertainty, ambiguity, and conflict in intelligent environments by proposing a solution based on argumentative agents. In addition, [34] demonstrated how agent-based systems enable simultaneous usage of distinct technologies by integrating two complementary but mutually exclusive rule-based approaches to enforce energy saving policies.

Fraile et al. [19] proposed a solution to enhance the planning and learning abilities of agents. To achieve its objective, it incorporates Critical Path Method (CPM) into the case-based reasoning—belief, desire, intentions (CBR-BDI) agents. Some other reviewed articles approached the issue of rule conflicts by applying defeasible logic techniques [28] and by defining superiority relation between them. To deal with a similar problem, [5] proposes four alternative conflict resolution strategies, which vary in the type and extent of contextual information that is used to evaluate the quality of imported knowledge. Whereas, agents in [23] utilized semantic web technologies to contextualize low-level sensor data into more meaningful outputs. It also utilized the same technologies to develop ontologies which provide a context model for supporting information exchange and interpretation of contexts. On the other hand, agents in [2] exploit a novel extension of Fuzzy Cognitive Maps benefiting from timed automata and formal method theories to represent human moods and enhance users' comfort accordingly. In addition, it uses emotional, environmental and temporal features of the ambient environment to distribute the most suitable and personalized smart home services.

3.4.3 Limitations

The imperfect nature of contextual information generated within the AmI environment causes serious problems such as uncertainty, ambiguity, inconsistency and, conflicting rules and agents goals. However, the majority of the reasoning approaches investigated in this study either simply neglect the need to address these problems or handle them with ad-hoc solutions that cannot deal with the problem inherently. For instance, the algorithm proposed by [36], picks one rule randomly, if two or more rules have the same priority value. If not addressed properly using a standard conflict resolution strategy this kind of solution can raise several issues. In addition, most of the articles presented the decision process of an agent that can handle only a single inhabitant situation and do not put into consideration multiple inhabitants and overlapping user activities in the living environment. And, almost all of the examined contributions do not mention about sensor data contextualization. This most likely leads to the generation of massive amounts of data, that needs to be handled by the reasoning system.

In addition, most symbolic reasoning systems proposed in the reviewed literature, are based on the assumption of perfect knowledge of the environment with a set of predefined static rules, and no self-learning capabilities. This makes achieving the above-mentioned requirements of smart home reasoning systems very difficult, if not impossible. On the other hand, the investigated statistical approaches require a suitably large amount of dataset to learn from. Moreover, the reusability of the generated activity is limited to the environment and scenarios that have produced the dataset.

Therefore, in order to achieve all the above-identified requirement and make the smart home environment adaptable to its user's need, it is essential to combine the advantages of both approaches.

3.5 Challenges and Future Research Directions

Most of the conceptual contributions examined in this study identified as their immediate future work the PoC implementation of their proposed architectures using standard multi-agent design methodologies (e.g. Prometheus) and frameworks (e.g. JADE and EMERALD). Whereas, the evaluated empirical studies targeted to perform extensive experiments on the testbed. In addition, [25] aims at the development of user behaviour pattern recognition agents and the integration of existing medical and smart environments domain ontologies into the system. [15, 19] plan to test their solutions on increasingly complex environments with multiple inhabitants.

Among the other investigated articles, [27] describes the need to include self-learning abilities in the AAL system. And, it plans to apply data mining techniques to automatically extract context patterns from the occupant's habits. On the other hand, [33] aims to integrate statistical artificial intelligence techniques for the integration of hybrid agents into its proposed architecture. And, [5] outlines the need to deal with incomplete, ambiguous, inaccurate and erroneous context knowledge in ambient intelligence domain as the key subjects to be addressed in the near future.

The other most critical challenges of contextual reasoning in smart living environments are the heterogeneity of local context theories and the potential conflicts that may arise from the interaction of different agents [5]. On top of this, [34] insists conflict resolution is the biggest challenge for agent scheduling and resource allocation in the ambient assisted domain. It also aims to explore the applicability of agent negotiation strategies for conflict resolution, by integrating more instances of the same or different agent. Specifically, each agent will be assigned a sub-task or a region within the building, and negotiate with the others towards achieving a certain goal (e.g. comfort and/or energy savings).

Furthermore, [14] identifies an explanation feature, through a mechanism of queries, where users cannot only trace the internal reasoning of agents but also ask them for specific explanations as part of its future works.

4 Conclusion

This paper presents the preliminary results of a systematic literature review in the smart home domain. The review was performed to identify and characterize the reasoning systems of multi-agent based smart homes. It was focused to answer six research questions and our main findings are:

- Most smart homes are designed to provide classical home automation services such as light and HVAC control. Nevertheless, patient-elderly care and energy management are also the most popular services of smart homes.
- The main requirements of a smart home reasoning system include the ability to learn, plan, predict, explain and reason with incomplete knowledge. In addition, the reasoning system should be context-aware, adaptive, configurable and non-disturbing. Moreover, it needs to be equipped with standard conflict resolution strategy.
- Most proposed solutions are presented as conceptual contributions. Whereas, a great deal of the empirical contributions were presented as ad-hoc solutions, i.e. without adopting any standard agent models and frameworks. In addition, most of the reasoning systems integrated into the MAS were based on symbolic approaches, while few others presented their contributions based on either statistical or hybrid approaches.
- And, most studies presented their solution by making an assumption of single inhabitant behaviour and non-conflicting contexts in the home environment.

In performing this review we also noted a clear need:

- To address conflicting rules and agents goals, which is caused by the imperfect nature of the data generated in smart homes. A starting point in overcoming these problems can be the application of standard conflict resolution strategies and contextualizing sensor outputs.
- To integrate the best of symbolic and statistical reasoning techniques, thus most of the above-mentioned requirements will be successfully achieved.
- And to propose more solutions which are capable of handling overlapping multi-inhabitant behaviours.

The results reported in this paper are preliminary results of a larger systematic review of smart home reasoning systems. In our future analysis, we aim to further evaluate the remaining 128 articles of our primary studies and present a more fine-grained view of the reasoning techniques proposed to give true intelligent behaviours for the home.

References

1. Abras S, Pesty S, Ploix S, Jacomino M (2008) An anticipation mechanism for power management in a smart home using multi-agent systems. In: Information and communication technologies: from theory to applications. IEEE, pp. 1–6
2. Acampora G, Liao V, A V (2011) Distributing emotional services in ambient intelligence through cognitive agents. Serv Oriented Comput Appl 5:17–35
3. Alam MR, Reaz MBI, Ali MAM (2012) A review of smart homes-past, present, and future. IEEE Trans Syst Man Cybern Part C (Appl Rev) 42:1190–1203
4. Bellifemine F, Bergenti F, Caire G, Poggi A (2005) JADE-a java agent development framework. In: Multi-agent programming. Springer, pp 125–147

5. Bikakis A, Antoniou G, Hassapis P (2011) Strategies for contextual reasoning with conflicts in ambient intelligence. Knowl Inf Syst 27:45–84
6. Brereton P, Kitchenham BA, Budgen D, Turner M, Khalil, M (2007) Lessons from applying the systematic literature review process within the software engineering domain. J Syst Softw 80:571–583
7. Braubach L, Lamersdorf W, Pokahr A (2003) Jadex: implementing a BDI-infrastructure for JADE agents. Citeseer
8. Brownsell S, Bradley D, Blackburn S, Cardinaux F, Hawley MS (2011) A systematic review of lifestyle monitoring technologies. J Telemed Telecare 17:123
9. Burmeister B (1995) BDI agents: from theory to practice. ICMAS 95:312–319
10. Bordini RH, Hübner JF, Wooldridge M (2007) Programming multi-agent systems in AgentSpeak using Jason, vol 8
11. Birgit B (1996) Models and methodology for agent-oriented analysis and design. Work Notes KI 96:06–96
12. Calvaresi D, Cesarini D, Sernani P, Marinoni M, Dragoni AF, Sturm A (2017) Exploring the ambient assisted living domain: a systematic review. J Ambient Intell Humaniz Comput 8:239–257
13. Cavone D, De Carolis B, Ferilli S, Novielli N (2011) An agent-based approach for adapting the behavior of a smart home environment. In: WOA, pp 105–111
14. Chen L, Nugent CD (2010) Situation aware cognitive assistance in smart homes. J Mob Multimed 6:263–280
15. Cook DJ, Youngblood M, Heierman EO, Gopalratnam K, Rao S, Litvin A, Khawaja F (2003) MavHome: an agent-based smart home. In: Proceedings of the first IEEE international conference on pervasive computing and communications. IEEE, pp 521–524
16. Demiris G, Hensel BK, and others (2008) Technologies for an aging society: a systematic review of “smart home” applications. Yearb Med Inform 3:33–40
17. Falcionelli N, Sernani P, Brugués A, Mekuria DN, Calvaresi D, Schumacher M, Dragoni AF, Bromuri S (2017) Event calculus agent minds applied to diabetes monitoring. In: Agents and multi-agent systems for health care. Springer, pp.40–56
18. Foster D, and others (2005) A survey of agent-based intelligent decision support systems to support clinical management and research. In: Workshop on multi-agent systems for medicine, computational biology, and bioinformatics
19. Fraile JA, De Paz Y, Bajo J, De Paz JF, Pérez-Lancho, B (2014) Context-aware multiagent system. Plan Home Care Tasks 40:171–203
20. García-Herranz M, Haya PA, Esquivel A, Montoro G, Alamán, X (2008) Easing the smart home: semi-automatic adaptation in perceptive environments. J UCS 14:1529–1544
21. Ghidini C, Giunchiglia F (2001) Local models semantics, or contextual reasoning = locality + compatibility. Artif Intell 127:221–259
22. Iglesias CA, Garijo M, González JC (1998) A survey of agent-oriented methodologies. In: ATAL, pp 317–330
23. Jih W-R, Hsu JY-J, Lee T-C, Chen L-L (2007) A multi-agent context-aware service platform in a smart space. J Comput 18
24. Kitchenham B (2004) Procedures for performing systematic reviews, vol 33. Keele, pp 1–26
25. Kuusik A, Reilent E, Lõõbas I, Parve M (2010) Software architecture for modern telehome care systems. In: 2010 6th international conference on networked computing (INC). IEEE, pp 1–6
26. Marcais J, Spanoudakis N, Moraitis P (2011) Using argumentation for ambient assisted living. In: Artificial intelligence applications and innovations. IEEE, pp 410–419
27. Muñoz A, Augusto JC, Villa A, Antonio J (2011) Design and evaluation of an ambient assisted living system based on an argumentative multi-agent system. Pers Ubiquitous Comput 15:377–387
28. Nute D (2001) Defeasible logic. In: International conference on applications of prolog. Springer, pp 151–169

29. Reinisch C, Kofler MJ, Kastner W (2010) ThinkHome: a smart home as digital ecosystem. In: Digital ecosystems and technologies (DEST). IEEE, pp 256–261
30. Salem H, Attiya G, El-Fishawy, N (2015) A survey of multi-agent based intelligent decision support system for medical classification problems. Int J Comput Appl 123
31. Sernani P, Claudi A, Palazzo L, Dolcini G, Dragoni AF (2013) Home care expert systems for ambient assisted living: a multi-agent approach. In: Technological roles and opportunities for artificial intelligence
32. Sierra E, Hossian A, Rodríguez D, García-Martínez M, Britos P, García-Martínez R (2008) Intelligent systems applied to optimize building's environments performance. In: IFIP international conference on artificial intelligence in theory and practice. Springer, pp 237–244
33. Stavropoulos TG, Rigas ES, Kontopoulos E, Bassiliades N, Vlahavas I (2014) A multi-agent coordination framework for smart building energy management. In: Database and expert systems applications (DEXA). IEEE, pp 126–130
34. Stavropoulos TG, Kontopoulos E, Bassiliades N, Argyriou J, Bikakis A, Vrakas D, Vlahavas I (2015) Rule-based approaches for energy savings in an ambient intelligence environment. Pervasive Mob Comput 19:1–23
35. Sun Q, Yu W, Kochurov N, Hao Q, Hu F (2012) A multi-agent-based intelligent sensor and actuator network design for smart house and home automation. J Sens Actuator Netw 2:557–588
36. Uddin I, Rakib A, Haque HMU (2017) A framework for implementing formally verified resource-bounded smart space systems. Mob Netw Appl 22:289–304
37. Van Solingen R, Basili V, Caldiera G, Rombach HD (2002) Goal question metric (GQM) approach. Encycl Softw Eng 22:289–304
38. Velasco JR, Marsá-Maestre I, Navarro A, López-Carmona MA, de Vicente AJ, De La Hoz E, Paricio A, Machuca M (2005) Location-aware services and interfaces in smart homes using multiagent systems. PSC 5:104–110
39. Wooldridge M, Jennings NR (1995) Intelligent agents: theory and practice. PSC 10:115–152