Towards knowledge warehousing: application to smart housing

Hadjer Moulai* and Habiba Drias

Department of Computer Science, LRIA,
USTHB,
BP 32 El Alia Bab Ezzouar, Algiers, Algeria
Fax: +213-21-24-76-07
Email: hamoulai@usthb.dz
Email: hdrias@usthb.dz
*Corresponding author

Abstract: The terms data, information and knowledge should not be treated as synonyms in any context. In fact, a hierarchical order between these entities exists where data become information and information become knowledge. Massive amounts of data are analysed everyday in order to extract valuable knowledge to support decision making. However, the size of the extracted knowledge compromises the speed of reasoning and exploitation of the latter. In this paper, we propose the paradigm of knowledge warehousing to store and analyse big amounts of knowledge through online knowledge processing and knowledge mining techniques. Our proposal is supported by an original knowledge warehouse framework and a case study for the smart housing technology. A multi-agent system built on a knowledge warehouse architecture is illustrated where each agent has a knowledge base about his assigned task. The paradigm is expected to be applicable for other knowledge tasks and domains as well.

Keywords: knowledge warehouse; knowledge management; knowledge mining; warehousing technology; smart housing; agent technology.

Reference to this paper should be made as follows: Moulai, H. and Drias, H. (2021) 'Towards knowledge warehousing: application to smart housing', *Int. J. Data Analysis Techniques and Strategies*, Vol. 13, Nos. 1/2, pp.107–127.

Biographical notes: Hadjer Moulai earned a Master degree in Artificial Intelligence from the Computer Science Department of USTHB in June 2016. She is currently a PhD student at the Laboratory of Research in Artificial Intelligence LRIA/USTHB. Her research areas include computational intelligence, data mining and warehousing technologies.

Habiba Drias is a Professor of Computer Science at USTHB, Algiers, Algeria and the Director of the Laboratory of Research in Artificial Intelligence LRIA/USTHB. Her main interests are computational intelligence, swarm intelligence, multi-agent systems, data mining, information retrieval and the satisfiability problem. She has published three books and more than 200 research papers on these topics.

This paper is a revised and expanded version of a paper entitled 'From data warehouse to information warehouse: application to social media' presented at LOPAL'2018: The International Conference on Learning and Optimization Algorithms: Theory and Applications, Rabat, Morocco, 2–5 May 2018.

1 Introduction

Through the past decades, knowledge has established itself as the most valuable asset of modern organisations. In fact, it is the main resource decision makers and knowledge workers rely on to make critical and strategic decisions. However, knowledge is hard to find and manage as in most organisations it is a result of experience and long training. Data mining is one of the main tools for knowledge discovery and extraction as it analyses large amounts of data in order to uncover hidden patterns and relationships.

With the big data phenomena, massive amounts of data are generated every day at a very high rate. Most of the time, these data are analysed using mining techniques which results into big amounts of knowledge. In order to handle the latter, the data warehousing technology has proved to be an effective solution for storing and analysing data in big sizes. Nevertheless, it is not efficient to treat data, information and knowledge similarly and make them part of the same infrastructure. In fact, these entities are different whether in terms of characteristics or relevance. Data is not information, and information is not knowledge. In order to respect and preserve the value of each we introduced the paradigms of information and knowledge warehousing.

In this paper, we propose the paradigm of knowledge warehousing as a solution to the storage and analysis of big amounts of knowledge. A knowledge warehouse is a knowledge repository that holds historical records about knowledge utilisation and whose main goal is to extract meta-knowledge using knowledge mining techniques.

Meta-knowledge is knowledge about how to better use and exploit existing knowledge in order to achieve satisfactory results. Indeed, knowledge alone is not useful unless we can make connections between what we know, which is meta-knowledge. In organisations, it is the role of knowledge experts who accumulated years of experience that help them connect current and new knowledge to previous one. While knowledge are rules about how to use information, meta-knowledge are rules about how to use and control existing knowledge. Meta-knowledge also determines reliability of existing knowledge and priority among a set of knowledge, which is very useful in situations where multiple applicable knowledge choices are possible.

Multiple knowledge mining techniques (Drias et al., 2012), for the discovery of meta-knowledge, have already been proposed in the literature and can thus be integrated in the knowledge warehouse framework that we are proposing.

The rest of this paper is organised as follows. The next section reviews related work. Section 3 introduces the paradigms of information and knowledge warehousing. In Section 4, an original knowledge warehousing framework is presented and described. Section 5 illustrates the implementation of the proposed paradigm in the case of smart housing technology. Section 6 reports experimental results. In Section 7, we conclude this work and talk about perspectives.

2 Related work

2.1 Knowledge warehousing

Knowledge warehousing is a concept that emerged shortly after the data warehouse technology was introduced.

The first work on knowledge warehousing that we came across was Yacci (1999), where the author described a knowledge warehouse as an information repository that stores and catalogues knowledge-based materials in an organisation such as training programs and documentation, for reuse. The author gave a brief explanation of the difference between data, information and knowledge, and described the knowledge warehouse as an information repository composed of knowledge components. The latter are defined as the lowest level in which knowledge regarding a specific material, like a manual, is decomposed. The decomposition of knowledge is made in order to better respond to the user needs depending on his profile (technician, new user, etc.).

In Nemati et al. (2002), the authors described the knowledge warehouse concept as an extension to the data warehouse model. They explained that data warehouses do not provide enough useful information for decision makers as most of a company's assets and knowledge are not stored into computers but in the employees' minds. The knowledge warehouse would allow knowledge workers to easily access and update useful knowledge for decision making. The proposed architecture consists of an extension of the data warehouse framework where additional modules are included for knowledge management such as: knowledge acquisition, extraction, transformation, update, analysis, and a communication interface with the user. The authors concluded by suggesting research areas on knowledge warehousing such as knowledge mining.

Pedersen (2004) combined business intelligence (BI) techniques, artificial intelligence (AI) and knowledge management systems (KMS) in one framework in order to propose a knowledge warehouse for clinical reasoning where the stored knowledge consist of general information, guidelines and health records. The framework includes two levels: observation and opinion. Observations are defined as information that may be imprecise but considered certain in the reasoning process. The opinion level is the key component of the framework, where experts give their opinion and arguments on the patient case hypothesis in order to enhance the knowledge about its condition. The reasoning on a patient case is done through the use of case base reasoning (CBR) in order to find similar past cases. Furthermore, the information structure supports the creation of new generalised knowledge using data mining tools.

In Zhang and Liang (2006), the authors presented what they called a model of data warehouse based on enterprise resource planning (ERP) system. The main idea is to extend the data warehouse to handle knowledge, which results into a knowledge warehouse. The proposed architecture is based on ERP in order to provide effective support to decision support systems (DSS) or online analytical processing systems (OLAP). The data warehouse provides data and information to the data mining module that will extract knowledge and store it directly into the knowledge warehouse layer.

Amit and Campoy (2008) showed how organisational memory can serve as a conceptual model for knowledge articulation processes, in particular for the design, development and implementation of a firstly physical, then logical knowledge warehouse within the media industry in order to develop competitive advantage. The knowledge warehouse would gather all the organisational knowledge and make it available for employees. Relevant documents that have been used in the past as well as the evolution of new knowledge based on processes form the basis of a knowledge repository. The main goal is to provide employees with past experiences of the organisation in similar activities they are currently dealing with in order to make better decisions.

In Fu and Wei (2010), the authors presented a cognition inspired object oriented knowledge warehouse architecture inspired by the structure of human memory and data warehouse, in order to handle big amounts of conceptual and non-conceptual knowledge. The motivation for such an architecture is to provide an efficient storage structure of knowledge in order to speed up the process of reasoning and application. Using human memory and cognition analysis, the authors defined three types of knowledge according to the level of cognition. The latter are modelled into three correlated worlds which constitute, alongside operations on them, the core of the knowledge warehouse architecture. The three worlds are: perception world, scenario world and conceptualisation world. These are inspired by human cognition process in which an agent perceives its world, then comprehends the information perceived with the current state of its world and establishes scenarios. Finally, scenarios are analysed and new concepts are gained. Multiple artificial intelligence tasks can be carried out in the architecture at each world level.

In Hamad and Qader (2013), the authors proposed a knowledge-driven decision support system (KD-DSS), which provides specialised problem solving expertise stored as facts, rules, procedures, and recommends actions to managers. The proposed system has the capacity to self-learn, identify associations between the data, and perform heuristic operations, if required. These abilities make the DSS system more intelligent, increase the capacity of problem solving and improve suggestion accuracy. It is important to mention that knowledge representation plays a key role in the KD-DSS. Knowledge discovery techniques are used to build the knowledge warehouse, which is defined as an 'information repository' that consists of knowledge components.

In Memon et al. (2013), the authors presented a subject-oriented semantic knowledge warehouse (SSKW) framework. The goal is to provide relevant and precise knowledge to cognitive decision support systems (CDSS) and minimise loss of knowledge. In fact, the authors explained that there is an issue of communication between CDDS and the data warehouse due to their contradictory knowledge/data oriented nature. The SSKW consists of an OPER (object/process/event/relationship) model to store domain knowledge in a unified format, and a subjective view database containing opinions of stakeholders about various OPER knowledge elements. The knowledge warehouse is defined as a collection of knowledge bases where knowledge is organised, stored and disseminated. A case study to compare the performance of the SSKW-based CDSS against a data warehouse-based CDSS is performed demonstrating the efficiency of the proposed framework.

In Ayadi et al. (2015), the authors proposed a knowledge warehouse architecture and a unified model for knowledge representation, in order to achieve harmonisation of heterogeneous knowledge formalisms. The paper focused on the modelling with object types (MOT) representation language, and suggested a set of transformation rules that ensure the transition from the decision tree source model to the target MOT model. The authors argued that the existing knowledge warehouse definitions are not precise or complete. Then, they defined the knowledge warehouse as a repository for explicit knowledge that may come from multiple sources with heterogeneous formats that need to be unified and integrated in order to support decision making.

In Zhou et al. (2017), the authors proposed a new decision support system model that integrates data warehouse, knowledge warehouse and model warehouse. The proposed system is said to be more effective, efficient than the old decision support systems. The model warehouse that integrates model creating units strengthens the intelligence property of the DSS. The knowledge warehouse is described as an extended system of the data warehouse. The system also integrates data mining modules to extract new knowledge that are stored in the knowledge warehouse.

In Dneprovskaya and Shevtsova (2018), the authors showed how knowledge management techniques and knowledge warehousing can contribute to the improvement of smart education. The key element to the knowledge management system is a knowledge warehouse that holds education materials described using a meta-data model which allows to convert tasks into competences and professional activities to ontology. Each education material is stored in a file or a group of files with the corresponding set of meta-data joined by a single subject scope. Professors and research workers can update knowledge in the warehouse and consult its content for information retrieval.

2.2 Smart housing

Smart housing is a technology that aims to integrate intelligence into houses in order to provide comfort, security, healthcare and energy conservation for a better quality of life, and to make life easier for the house inhabitants in general (Raisul et al., 2012). This goal is achieved through a set of appliances and devices that monitor and control the smart home environment.

In Yamazaki (2006), the author addressed the main issues that smart homes technologies might encounter. He insisted that researchers should not focus into building a totally automated home where all tasks are computerised. Instead, the focus should be put on the interactions between the inhabitants and the smart home where interface technologies, such as sensors and detectors, discern humans' intentions and feelings in order to respond adequately.

In Kofler and Kastner (2010), the authors introduced a global knowledge base system for the control and optimisation of energy consumption in a smart home. The knowledge base includes information on user-profiles, building information (architecture, materials, etc.), building automation networks, energy information and electrical consumers and producers. The collected information is then transformed to the web ontology language. Reasoning and requesting upon the knowledge base, the system makes decisions to ensure energy-saving of the smart home.

In Nazerfard et al. (2011), the authors introduced an approach based on association rule mining and clustering techniques for the discovery of temporal relations between daily activities of inhabitants in a smart home. The proposed approach namely TEREDA (temporal relation discovery of daily activities), has been validated on four months of real data collected from a real smart home environment.

In Fahad et al. (2014), the authors proposed an activity recognition approach that combines classification and clustering to achieve a better accuracy. Information on inhabitants activities is collected from sensors in the smart home. First, similar and non-similar activities are clustered using the Lloyd algorithm. Then classification of activities within each cluster is performed using K-nearest neighbour algorithm. A comparison of the authors' approach with existing methods showed that the proposed method achieves a better recognition rate.

Intelligent assistant such as Google Home (Google, 2018b), Google Assistant (Google, 2018a), Alexa (Amazon, 2018), Siri (Apple, 2018) and Cortona (Microsoft, 2018), are smart devices that are part of the smart home environment. In fact, the assistance they provide to the inhabitants by providing services on different areas (cooking, music, entertainment, etc.) contributes to the comfort of the latter and to the home intelligence.

In Hossen et al. (2018), the authors proposed a smart home management system for scheduling appliances based on a deep learning approach. The goal is to predict the daily energy usage of all appliances in the smart home in order to reduce the peak load and allow inhabitants of the house to make savings. Key parameters such as price, demand and equipment rating were used in the linear programming-based optimisation model that generates the appliances schedule.

In López et al. (2018), the authors performed a comparative study of speech-based natural user interfaces (NUI). The study compared the most popular NUIs nowadays which are: Alexa, Siri, Cortana and Google's Assistant. The results showed that despite the many services these NUI's provide and master, improvements on the usability of these systems are required, as these human assistants are based on applications that require specific parameters to function.

Through the related work we observe that knowledge warehousing have inspired a wave of research that tempted to introduce the paradigm and show its importance. Unfortunately, the community do not seem to agree on a specific definition or the main purpose of a knowledge warehouse as each author uses it in a specific context with a different definition. In fact, there are definitions that consider it as an information repository or an extension of the already existing data warehouse, while others describe it as a standalone infrastructure. Moreover, the artificial intelligence aspects of a knowledge warehouse are not very much discussed, and meta-knowledge is not mentioned at all.

In our vision, a knowledge warehouse is a knowledge repository and its main goal, besides fast and easy access to knowledge, would be to use *knowledge mining* techniques to retrieve meta-knowledge from big amounts of knowledge in order to better use the available knowledge. In fact, it is sometimes complicated and not easy to understand or figure out how to use the knowledge we have extracted through analysis, because knowledge by itself is not useful unless we can make connections between what we know and figure out when and how to use it. It is a decision layer that gathers knowledge from different sources such as data mining results, domain experts, etc., in one unique storage. These heterogeneous sources have to be consolidated as each come in a different knowledge representation language.

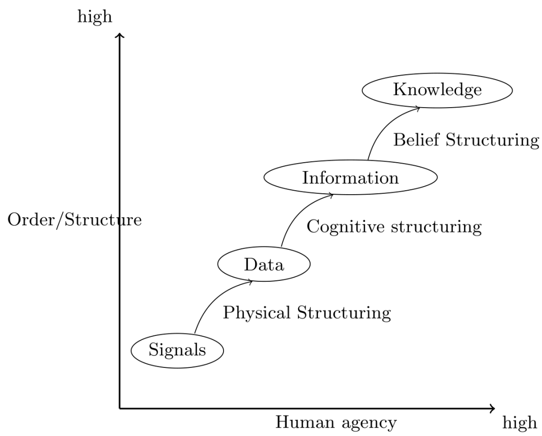
Exploiting the very popular smart housing technology, that has been gaining a lot of attention as we've seen through the related work, we can apply the knowledge warehousing paradigm and demonstrate how the proposed framework can work in this real-life context.

3 Introducing the paradigm of knowledge warehousing

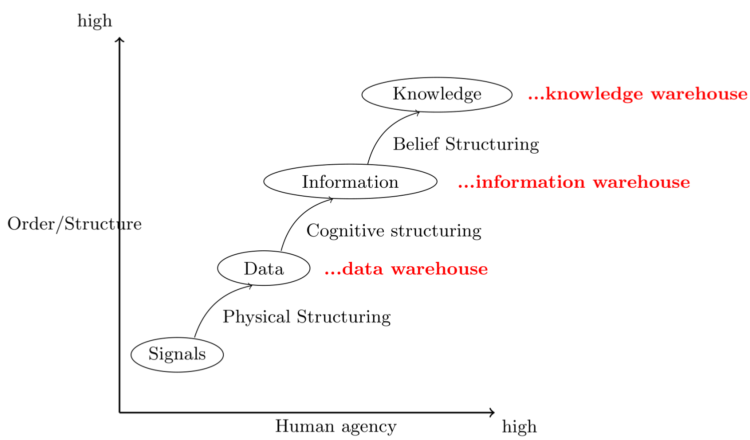
In knowledge management and artificial intelligence, it is often pointed out that it is fundamental to differentiate data, information and knowledge. According to Choo

(2006), these three entities are related through a series of transformations which results into a hierarchical order as shown in Figure 1(a).

Figure 1 Data, information, knowledge hierarchical order by Choo (2006) and the proposed warehousing paradigms, (a) data, information and knowledge (Choo, 2006) (b) the proposed paradigms (see online version for colours)



(a)



(b)

First, signals, which are different perceptions of the outer world, are collected and organised into packets of data depending on beliefs and environmental materials such as noise and lightning. For example marks on a paper are recognised as words.

Then, data is categorised according to its content which gives it meaning and significance and turns it into information. Examples are text, images and videos. Finally, information is turned into knowledge when it becomes a justified true belief. Three conditions are thus necessary for an information to become knowledge: truth, justification and belief. Among these conditions, justification is the most important. Indeed, it is not sufficient to believe that a proposition is true as the truth is relative (depends on the person's beliefs), and beliefs highly depends on states of the mind. Justification however, gives an adequate evidence that a proposition is true.

These definitions are proofs that the scaling of these concepts is very relevant and treating them as synonyms is not effective, particularly when integrating technologies like the warehousing technology. Thus, we proposed the paradigms of information and knowledge warehousing as illustrated in Figure 1(b). In recent previous works (Moulai and Drias, 2018a, 2018b), we have introduced and described the first paradigm which is information warehousing for the case of social media information.

In the present study, we introduce the paradigm of knowledge warehousing, supplied by a case study for the smart housing technology.

4 The knowledge warehouse

4.1 From database to knowledge base

As we explained in the previous section, data, information and knowledge are different constructs that cannot be treated similarly. This implies that they should not be stored using the same infrastructure. Hence, the necessity to move from the traditional database to a knowledge base.

Databases are the first storage model that was adopted to store any type of data. In conventional computing data in a database are stored into tables that are organised into rows and columns where each column is an attribute that might take different values, and each row represents an instance where each attribute is assigned a specific value. The nature of the data that we usually find in databases is flat data like numbers and text. According to oxford dictionary a database is: "a structured set of data held in a computer", with data being: "a set of facts and statistics collected together for reference or analysis".

However, with the rise of data mining analysis and knowledge discovery techniques, knowledge became more predominant due to its influence on strategic decision making.

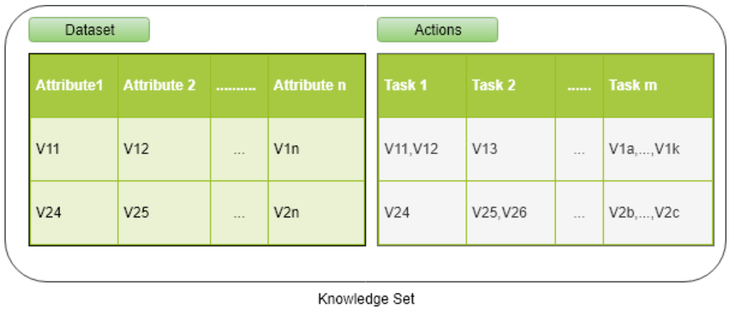
A knowledge base consists of a set of facts or knowledge statements that are either provided by experts or the results of data mining. In expert systems these statements are facts about the world that the inference engine reason on by using inference rules in order to deduce new facts or discover inconsistencies within the world. According to the oxford dictionary, a knowledge base is: "the underlying set of facts, assumptions, and rules which a computer system has available to solve a problem".

These definitions exhibit the main difference between a database and a knowledge base, by showing the purpose of the latter which is problem solving. It is a level above a database as the latter only stores flat data while the former stores knowledge which is valuable information with meaning.

4.1.1 Knowledge set

In the proposed paradigm knowledge in knowledge bases is represented by a knowledge set. A knowledge set is composed of two blocks: dataset and actions. Each knowledge (text, video, image) in the knowledge base is represented by a dataset and a set of actions on the latter. These actions are rules or instruction on how to use the dataset to achieve a specific action. For example in case of recipes, the dataset are the ingredients while the actions are the ordered instructions on how to proceed to prepare the recipe. And in case of an image or a video, the action would be to play or display it in a specific screen (tablet, TV, etc.).

Figure 2 Knowledge set: a knowledge representation technique (see online version for colours)



As shown in Figure 2, to each instance in the dataset corresponds a set of actions which consists into tasks that require attributes to be performed. In fact, each task can be written in the form: if $(V1 \wedge V2)$ then $Task1$.

4.2 Architecture

A knowledge warehouse is a repository that is exclusively dedicated to the storage and analysis of big sizes of knowledge. The latter are stored into knowledge bases and managed by a knowledge base management system (KBMS). The main goal is to speed the access and exploitation of knowledge through online knowledge processing and exploit the historical records for the discovery of meta-knowledge.

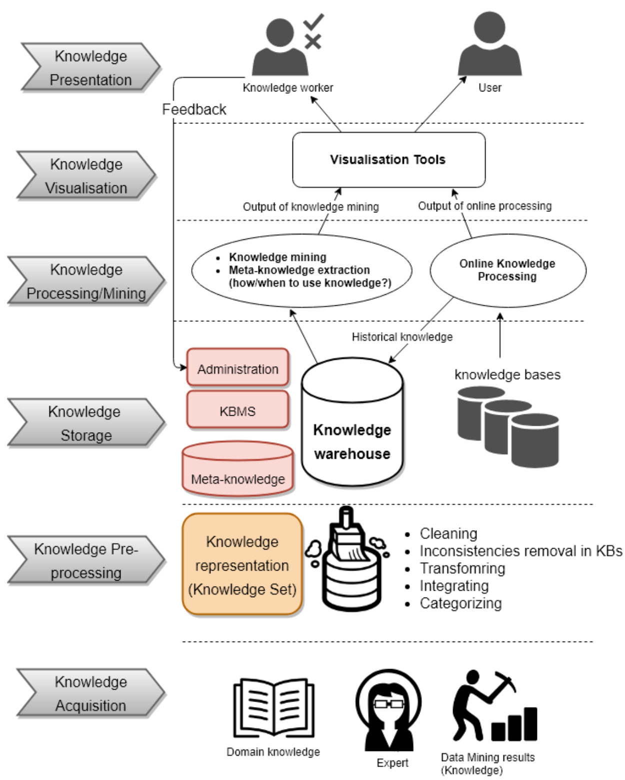
In an organisation a knowledge warehouse would be an interactive system where experts on different departments exchange and store their knowledge referring to a specific task. This knowledge is considered as an expertise that can be used by other employees to solve specific problems. It includes facts, rules, procedures, etc., based on which it can recommend actions to decision makers. The proposed architecture is illustrated in Figure 3 and includes the following layers:

- *Knowledge acquisition:* this layer includes the different knowledge sources such as: experts, cognitive agents, data mining results, domain knowledge, etc.
- *Knowledge pre-processing:* in this layer the collected knowledge is cleaned, transformed and integrated to the same knowledge representation language, which is a knowledge set, before it is loaded into the knowledge bases. To the existing pre-processing and ETL techniques, as we are dealing with knowledge here, we need to add knowledge base inconsistencies removal. The latter issue can be tackled using MAXSAT in order to keep the knowledge bases consistent.
- *Knowledge storage:* at this level knowledge is stored into different knowledge bases. Each base contains knowledge that refers to a certain domain, a specific task or profession. A first classification can be run at this stage in order to partition knowledge sources in the knowledge bases according to their similarities.

We also find a knowledge warehouse that is responsible of periodically storing historical data on different operations run on the knowledge bases. The warehouse has a meta-knowledge repository which is knowledge about knowledge in the warehouse such as its sources.

- *Knowledge processing and mining:* this layer includes two different knowledge analysis techniques. The first one is knowledge mining techniques that are used to extract meta-knowledge from the historical knowledge in the warehouse. The second one is online knowledge processing which consists on reasoning and querying the knowledge bases.
- *Knowledge visualisation:* this layer is responsible of deciding on the best and most suitable way of presenting the results of knowledge mining and processing to the destined front end user. Natural language processing and deep learning techniques can be used in cases where the results consist into a vocal response for example.
- *Knowledge presentation:* in the last layer we find two different actors. The first is the knowledge worker who will receive the results of knowledge mining and have the possibility to give feedback to the administrator of the warehouse. The second actor is a simple user who has queried the knowledge base and will thus receive the results of online knowledge processing.

Figure 3 Basic knowledge warehouse architecture (see online version for colours)



Knowledge tables can be connected through relations such as:

1 task or routine: the task or routine that involves the use of a particular set of knowledge
2 context: the conditions under which knowledge can be used or has been learned
3 subject or profession: The profession that knowledge refer to.

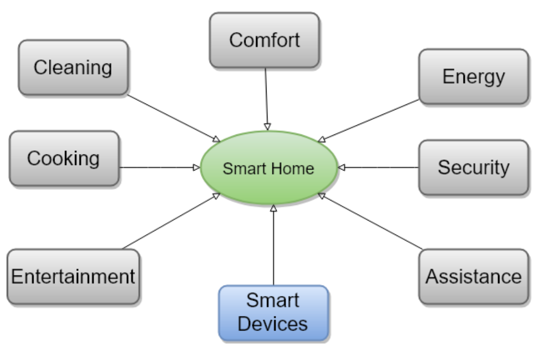
These relations, although very useful, do not replace meta-knowledge that answers questions such as which knowledge is more important (most used) or what knowledge is the most appropriate when having multiple knowledge options to apply given a certain context.

5 Application to smart homes

Smart Home refers to the concept of including smartness or intelligence into a home environment in order to maximise the inhabitants comfort and optimise the home usage. The goal is to cover all the inhabitants' needs and thus ensure comfort, security, healthcare and energy conservation (Raisul et al., 2012)

Managing a smart home environment involves different tasks where the realisation of each contributes to the home maintenance and optimisation. Each task includes knowledge on how it can be achieved.

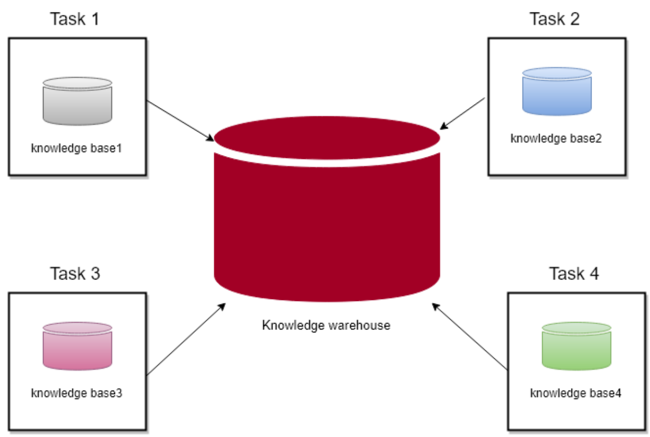
Figure 4 Smart home tasks (see online version for colours)



In Figure 4, we illustrate the different tasks that can be encountered in a typical smart home. It includes tasks that are targeted towards the inhabitant such as cooking and entertainment, and others that are targeted towards the home maintenance and usage optimisation such as energy. A smart home also includes a number of smart devices that contribute to make the home intelligent and comfortable for the inhabitant such as a smart refrigerator.

The smart housing technology can be modelled using the knowledge warehousing paradigm, where knowledge regarding each task is stored into a knowledge base that can be queried, and historical data on the operations on each task is stored into the knowledge warehouse for meta-knowledge extraction. Figure 5 gives an illustration of the described smart home framework using the knowledge warehousing technology.

Figure 5 Knowledge warehousing paradigm applied for smart housing technology (see online version for colours)

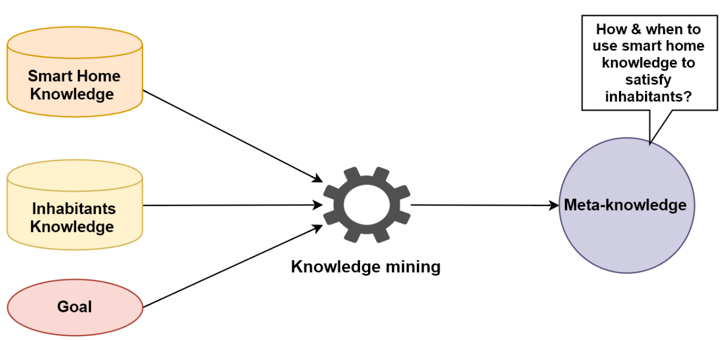


5.1 *Online knowledge processing based on agent technology*

Because of the nature and size of the smart home problem, it can be effectively approached using the agent technology, where intelligent agents with different assigned tasks are integrated in the environment. In our case, the idea is to build agents which act on behalf and for the inhabitants without overriding their needs or compromising the goal of home usage optimisation.

Initially, each agent is assigned a specific task supported by knowledge on how to perform it independently from the inhabitants. In fact, the basic knowledge set that an agent has on his task does not depend on the inhabitants. This set can be viewed as the default starting pack to manage a smart home, autonomously from the inhabitants.

Figure 6 Meta-knowledge production in a smart home (see online version for colours)



When the inhabitants integrate the home, they will generate scenarios and activity historical data that will be periodically sent to the knowledge warehouse where knowledge mining techniques will be applied in order to predict the inhabitants behaviour for example, as shown in Figure 6. The agents will then adapt their knowledge to the inhabitants depending on this meta-knowledge. In other words, the agents will know how to use their knowledge in order to satisfy the occupants of the smart home and meet the goals of comfort and efficiency.

In the next section, we are going to illustrate the application of the agent technology to online knowledge processing in a smart home built on a knowledge warehouse architecture.

5.1.1 Smart home agents

In our study we have distinguished the following artificial agents for a smart home environment:

- *Kitchen agent:* this agent has knowledge about food, recipes, kitchen utensils and any other intelligent device such as a smart refrigerator, oven and microwave. A smart refrigerator monitors food availability and consumption, detects expired food items, creates shopping lists, and provides advice on meal preparation based on items stored in the refrigerator and pantry.
- *Cleaning agent:* this agent is responsible of maintaining the smart home clean. It has knowledge on when, what, where and how to clean the home. It also has knowledge on the objects it recognises and where to put them (towels in the bathroom, clothes in the closet, etc.), on the cleaning products and how to use them, and on the smart cleaning tools such as the dishwasher, washing machine, air purifier, vacuum cleaner, etc.
- *Entertainment agent:* this agent is responsible of the entertainment of the inhabitants. It proposes TV shows, films, documentaries, etc., based on their rating and relevance. It also has knowledge on external entertainment materials such as concerts, operas and films currently displayed in theatres, etc. When the inhabitants integrate the smart home, it will adapt to their preferences.
- *Energy agent:* this is one of the most important agents in the smart home. In fact, it has the task of saving energy while assuring the comfort of the inhabitants.

  It has knowledge on the home building plan to predict how much energy and time it will take to heat or cool the home for example. Knowledge on the price calendars of different providers of gas, water and electricity in order to avoid peaks of consumption and for example program the washing machine. Knowledge on the different energy consuming materials in the smart home such as: TV, microwave, dishwasher, vacuum cleaner, laptops, etc. But also, knowledge on exterior factors such as the weather because the building behaves differently according to outside conditions.

  When the inhabitants come into play, the agent will use knowledge on their schedules, preferences and context in order to save energy. For example the heating of a room can be reduced if the inhabitant performs physical activities like sport or cooking or if there are a lot of people in the same room.
- *Comfort agent:* this agent is responsible of making sure that the inhabitants always feel comfortable in the smart home and that the other agents does not

affect their comfort. Comfort for an inhabitant is often related to room temperature, humidity, lightning, cost and noise. It communicates with other agents in order to ensure maintenance of comfort. For example minimise noise when the inhabitant is taking a nap.

- *Security agent:* this agent is responsible of maintaining the smart home a secure place for every inhabitant in the house, when they are home and when they are not. It has knowledge on the inhabitants such as facial, voice and hand recognition, and any noise that might seem suspicious. It prevents home accidents such as fire and floods, and relies on the weather and climate knowledge in order to prevent house damage such as blinds, doors or cars parked outside in case of extreme weather conditions. It also includes knowledge on the inhabitant safety regarding their health. For example if an inhabitant falls unconscious it calls the ambulance.
- *Assistant agent:* this agent is responsible of reminding the inhabitants of appointments, and important dates for them such as meetings, birthdays, a blood test, a homework, work out, etc.

Figure 7 Architecture of an intelligent agent inside a smart home based on knowledge warehousing (see online version for colours)

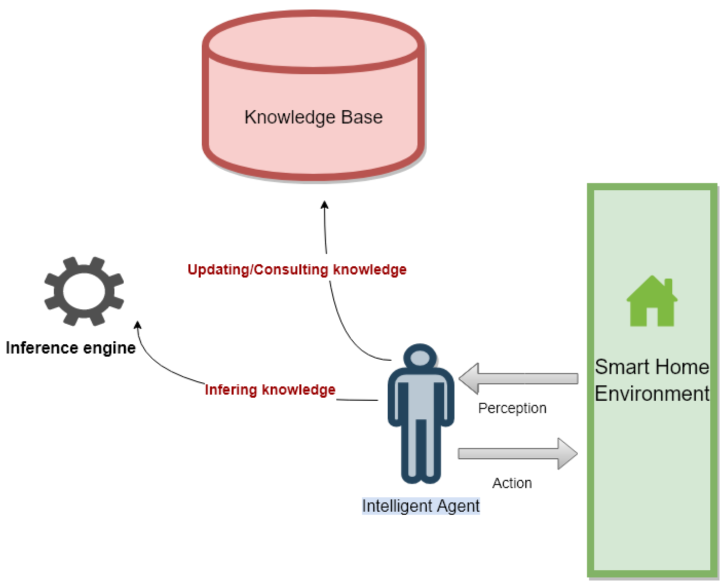


Figure 7, depicts the general framework of each agent in the smart home. It includes the following components:

1. Smart home environment: each agent is constantly interacting with its environment, perceiving the changes in it and reacting to the latter.
2. Knowledge base: the knowledge base of each agent includes all relevant knowledge to the task he is responsible of. The agent consults his base in order to respond to the user queries which involve information retrieval techniques.

3 Inference engine: The inference engine allows the agent to reason on his knowledge base in order to decide on the action to perform on his environment.

Many of the decisions or actions that an agent would take depending on his knowledge, are highly influenced by the context which are perceptions of his world. For example the energy agent must be aware of the real time context that the inhabitant is cooking in order to cool down the kitchen. Each agent is aware of the context in which he evolves and the real time behaviour of the inhabitants. Context consists of external factors like time, location, weather, etc. It is a deterministic factor to the efficiency of the decisions the agents take.

The smart home agents reason about their assigned tasks using knowledge in their knowledge bases and select candidate actions based on the occupant's preferences and the availability of resources.

6 Experiments

To give an illustration of the proposed smart home knowledge warehouse system, we implemented a multi-agent system using Jason which is a platform for the development of multi-agent systems. Jason uses an extension of the AgentSpeak agent-oriented programming language to program intelligent agents. It is based on the belief-desire-intention (BDI) model which assumes that each agent has a reasoning cycle where it has beliefs on its world, then grows desires based on these beliefs and its perception of events in the world, and finally intentions which are goals towards which the agent is committed to achieve using a specific plan (Bordini et al., 2007).

Figure 8 Security agent initial beliefs and plans (see online version for colours)

```
/* Initial beliefs */

fire_alarm(off).

security_alarm(off).

/* Plans */
+~at(inhabitant,home)[source(global)]: true
                                        <- !secure(home).

+!secure(home): true
            <- .println("Secure home: lock the windows and outside doors, set the alarm on.");
               +locked(frontdoor);
               +closed(windows);
               +security_alarm(on).

+at(inhabitant,home)[source(global)]: true
                                        <- -+security_alarm(off).
+at(inhabitant,bed)[source(global)]: true
                                     <- .println("The inhabitant is about to sleep: securing the home.");
                                        -+security_alarm(on).

+fire_alarm(on): at(inhabitant,home)
          <- !inform(inhabitant);
             .println("FIRE detected! Waking up the inhabitant.").

+!inform(inhabitant): at(inhabitant,home)
                   <- vocal _message; display_message_on_screens.

+fire_alarm(on): ~at(inhabitant,home)
          <- !call(firefighters);
             .println("FIRE detected! Calling firefighters.").
```

Beliefs are the result of the agent's perceptions of his environment, himself and other agents. Desires are generated in a response to the events it perceived and consist in achievable goals. Intentions represent action plans that the agent can follow to achieve a certain desire (Bordini et al., 2007).

In our case, the knowledge base of each agent will be represented by his beliefs base and plans which is knowledge on how to achieve a certain task. The belief base also includes knowledge that has been communicated or gained by the agent recently through his interactions with its environment and other agents. An example is given in Figure 8.

The agents communicate with each other in order to cooperate. The veracity of communication is important in order to make sure that each agent communicate something that he believes to be true.

6.1 The implemented scenario

In this section we are going to give a detailed scenario of a morning day in a smart home that is managed by a multi-agent system built on a knowledge warehouse architecture. Our scenario includes one inhabitant that we called Tom.

The scenario involves the following actors: inhabitant, kitchen agent, energy agent, cleaning agent, security agent, comfort agent, smart closet.

6.2 Scenario

The energy agent based on his knowledge about the smart home building materials knows that it takes 15 minutes for the home to warm up. Having also knowledge that the alarm goes on at 6:00am, the agent starts heating up the home according to the preferred temperature of Tom which is communicated to him by the comfort agent. Otherwise the energy agent has a default rule of heating up the home according to the outside temperature.

The alarm goes on at 6:00am, Tom can immediately turns it off and wake up or wait for it to keep repeating. Tom turns off the alarm at 6:15, which triggers the comfort and kitchen agents. The first one starts gradually turning the bedroom lights on instead of opening the blinds because it is cloudy outside. The second turns the coffee maker on. As soon as Tom steps into the bathroom the lights goes on and when he is under the shower the entertainment agent, aware of the context, turns the bathroom TV on and starts displaying the morning news because Tom likes to watch the news while showering. Also, the temperature in the bathroom is decreased by two degrees by the energy agent because of the steam resulting from the hot water.

When Tom finishes showering, he goes into his smart closet where he can choose from a selection of outfits that the closet has selected using its knowledge on trends, Tom's personal style and the weather. Tom finishes dressing up and leaves the bedroom triggering the energy agent to turn the lights off in the bedroom and bathroom. The hallway lights do not turn on and instead the blinds are opened by the energy agent as the lighting outside is good enough, same thing in the kitchen where the blinds are opened. Tom goes down to the kitchen where he asks the kitchen agent for a healthy breakfast recipe, the kitchen agent displays a set of top rated recipes that Tom can choose from and guides him through the preparation.

While having his breakfast, Tom asks the assistant agent about his schedule for the day which is displayed by the agent on Tom's tablet. When Tom finishes his breakfast, he asks the assistant agent to send a message to his office saying he will be 10 minutes late. When Tom is about to leave the assistant agent reminds him to take his umbrella because the weather forecasts 53% chances of rain.

Tom leaves for work, causing the security agent to set the home alarm on and secure the home by closing the garage and any backyard door that was left open or downstairs windows. Meanwhile, the cleaning agent aware that Tom has left starts cleaning the home. Using its knowledge, the agent can detect any disorder it comes across in the smart home like a piece of paper on the floor or a shampooing bottle that was left open. First it starts with cleaning the bedroom which consists in:

1 doing the bed
2 changing the bed sheets if necessary by consulting its knowledge on the last time it was changed or if there is any stain on it
3 cleaning the bathroom; which includes disinfecting toilet, putting dirty towels in the dirty clothes bin and hanging new ones in the towel rack, and cleaning the shower and sink drains.

When putting the dirty towels in the dirty clothes bin, it notices that the bin is almost full and decides to put the clothes into the washing machine. It then informs the energy agent, which using his knowledge on energy consumption and off peak times of energy providers, decide to turn the washing machining on. Once the cleaning agent is done with the bedroom it goes to the living room, sees that a pillow lies on the floor, picks it up and put it on the couch. Moving to the kitchen it starts by putting all the used ingredients, like butter and coffee into their storage. It then grabs the cup and plate where Tom had his breakfast and put them into the dishwasher. It informs the energy agent that there are dirty dishes in the dishwasher as he is responsible of scheduling the dishwasher too. The energy agent decides to schedule it for later in order to save money on water consumption. Once it is done cleaning, the agent turns on the smart vacuum cleaner that will start with the downstairs floor. After that, the energy agent, knowing that the home is empty and that according to Tom's schedule he will not be back home before 6:00 pm, it decreases the temperature of the home in order to save energy.

6.3 Jason multi-agent implementation

The implemented system includes all the different agents mentioned in the scenario including the inhabitant in order to simulate the communication of the later with the smart home agents. We also included a smart device which is a smart closet.

Figure 10 shows the Jason multi-agent system console for the execution of the implemented scenario where agents have the possibility to print messages and report on what they are doing or the actions they intend to undergo.

The scenario described in the previous section was implemented and Figure 9 gives a snapshot of the execution of the multi-agent system under Jade environment in order to illustrate the communication that goes between the agents which consists in exchanging messages and beliefs about the smart home environment.

Figure 9 Snapshot of the JADE development environment (see online version for colours)

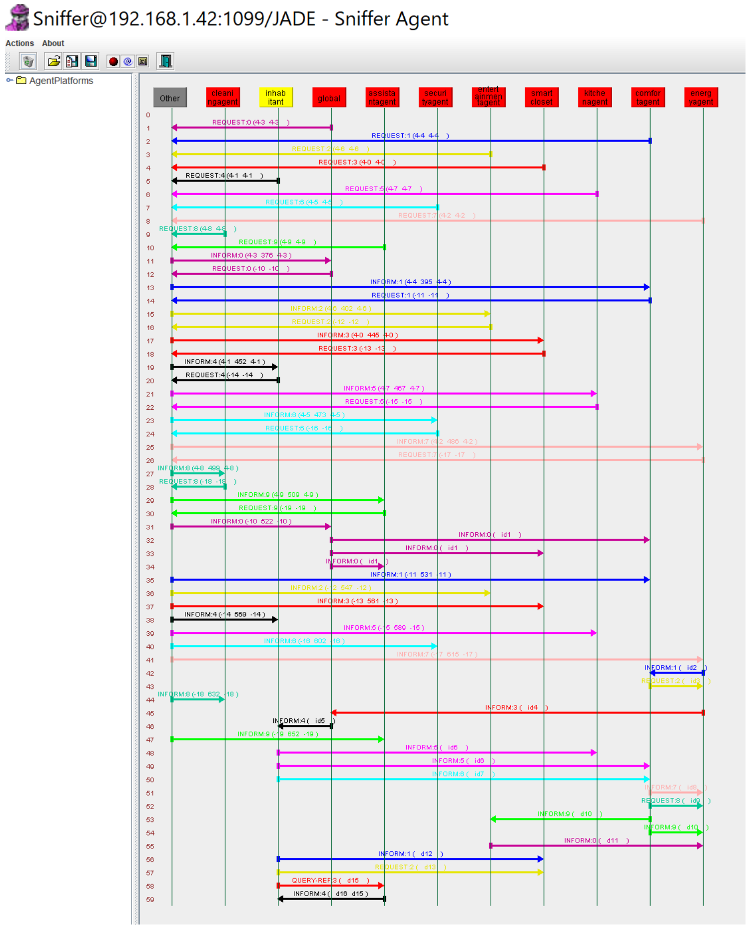
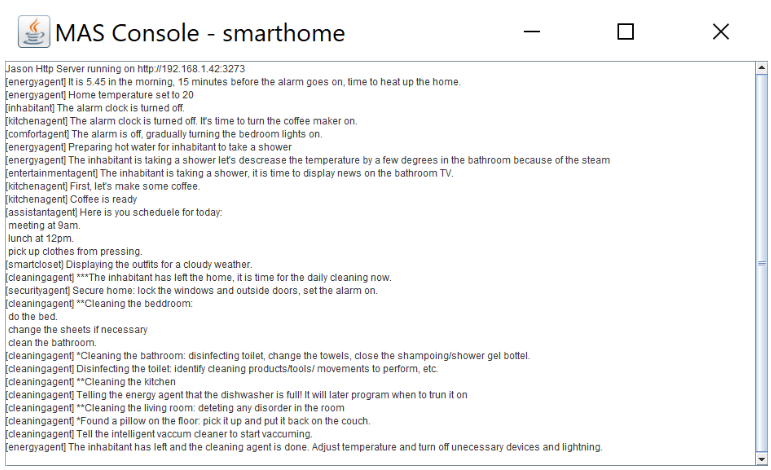


Figure 10 Jason multi-agent system console (see online version for colours)



Agents communicate through messages that have annotation of beliefs with information sources. Annotation is a degree of trust that the agent has on the agent (information sources) that sent the message. The message usually consists into a new belief that the receiving agent adds to his belief base. These communications help the agents coordinate their actions and not interfere with each other roles.

The implemented system works in a sequential way as we are only dealing with one inhabitant. The built multi-agent system gives a perfect illustration of the online knowledge processing module that was described in Section 4, where the knowledge bases are queried and reasoned on in order to achieve a specific task or respond to a given query from the user.

7 Conclusions

In this paper, we introduced the knowledge warehousing paradigm as a solution to the storage and analyses of massive amounts of knowledge. The proposed original framework describes how knowledge is stored into knowledge bases that can be connected using different factors such as task and profession. Each knowledge base can be consulted and queried using the online knowledge processing module, and historical records of these queries are periodically stored in the knowledge warehouse in order to run knowledge mining techniques and extract meta-knowledge.

The paradigm is applied for the case of smart housing where a smart home architecture based on knowledge warehousing is proposed. The smart home is described in terms of tasks to which knowledge bases are associated. The latter are managed by a multi-agent system where each agent is assigned a specific task. The inhabitants communicate with the agents to ask for assistance, and historical records of these exchanges are periodically sent to the warehouse for analysis in order to extract meta-knowledge that is used it to predict the inhabitants' behaviour. The experiments illustrated the implementation and execution of a multi-agent system using a detailed scenario for one inhabitant. The primary results demonstrated how the online knowledge processing module works in a smart home environment based on the knowledge warehousing paradigm.

In the near future, we plan to illustrate the application of knowledge mining techniques like clustering and frequent sequence mining on historical data of a specific smart home task such as entertainment. We would also like to apply the paradigm on other knowledge domains and further improve the proposed architecture.

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