A Tailored Smart Home For Dementia Care

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Copyright Statement

Abstract

Abstract

Dementia refers to a group of chronic conditions that cause the permanent and gradual cognitive decline. Therefore, a Person with Dementia (PwD) requires constant care from various types of caregivers (e.g., informal, social and formal). It is commonly accepted that utilising Smart Homes (SH), as an instance of Ambient Assisted Living (AAL) technologies, for dementia care could potentially facilitate the care and consequently improve the quality of PwDs' well-being. Nevertheless, most of the studies view dementia care as a straight application of standard SH technology without accommodating the specific requirements of dementia care. A consequence of this approach is the inadequacy and unacceptability of generic SH systems for the stakeholders of dementia care.

This work considers the specific requirements of PwDs and their care circle in all development steps of an SH, such as design, implementation, and evaluation. It investigates how utilising novel design and computing approaches can enhance the quality of SHs for dementia care and consequently improve healthcare and well-being of PwDs. To do so, the thesis first studies the existing SHs for healthcare and identifies their drawbacks. Then, the requirements of dementia care stakeholders will be collected, analysed and reflected on in an SH system design. Extensions and adaptation of existing frameworks and technologies will be proposed to imple-

ment a prototype based on the design. Finally, a series of thorough evaluations and validation of the prototype will be carried out.

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I would like to dedicate the thesis to the sun of my life, my mother **Khorshid**, who passed away while I was performing this research.

A poem about dementia

Do not ask me to remember, Don't try to make me understand, Let me rest and know you're with me, Kiss my cheek and hold my hand. I'm confused beyond your concept, I am sad and sick and lost.

All I know is that I need you To be with me at all cost. Do not lose your patience with me, Do not scold or curse or cry.

I can't help the way I'm acting, Can't be different though I try.

Just remember that I need you, That the best of me is gone, Please don't fail to stand beside me, Love me 'til my life is done.

– Owen Darnell

Acknowledgements

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I cannot express enough appreciation to my family who gave me the best support I could ask for. I am particularly grateful to my mum, Khorshid, who was my greatest teacher in compassion and My father, Abbas, who that any achievement in my academic and non-academic life is in debt to him.

Chapter 1

Introduction

1.1 General Context

Dementia encompasses a family of chronic diseases that gradually causes permanent damage to the human brain tissue. It comes with one or more of the following symptoms (Thies and Bleiler, 2013):

- Decrease in the ability to speak or to comprehend spoken or written language.
- Difficulties to distinguish or identify objects.
- Difficulties in performing motor activities.
- Difficulties in reasoning abstractly, making valid judgements and planning for complicated tasks.

People who are diagnosed with dementia often struggle to engage in discussions, to remember scheduled events, and to determine appropriate words for expressing situations. With the progress of dementia, they forget names, repeat words, face orientation problems, become confused about date and time, and wander around during the night times. In more advanced stages, the behaviour of People with Dementia's (PwDs) changes dramatically. Their sleeping and eating habits are negatively affected. In final stages, the PwDs face serious physical problems such as muscle weakness, clots in the lung, or heart attacks that eventually cause death (Finkel et al., 1997). The time-frame for dementia progress from early to late stages varies widely (i.e., 5 to 10 years). The most common type of late-stage dementia is Alzheimer's Disease (AD). In many cases, PwDs with Mild Cognitive Impairment (MCI) will never progress to AD and can live with an acceptable degree of independence (McKhann et al., 2011).

Dementia is more likely to occur in older age, and as the elderly population grows, the proportion of PwDs grows also. Although some medications can slow the progress of dementia, there is currently no way to stop its development altogether or reverse its impact on brain cells. Therefore, maintaining a high quality of life for PwDs is challenging. The progress of dementia is different for individuals, and sometimes the symptoms are entirely dissimilar. However, most of the existing studies agree on the following categorisation (Reisberg et al., 1982):

1. No cognitive decline
2. Very mild cognitive decline
3. Mild cognitive decline (Mild Cognitive Impairment MCI)
4. Moderate cognitive decline (Mild Dementia) (Often early AD)
5. Moderately severe cognitive decline
6. Severe cognitive decline
7. Very severe cognitive decline

It is noteworthy that categories cannot be perfectly identified as sometimes they overlap. Nonetheless, the categorisation enables researchers to specify potential targeted populations.

Expectations show that 20% people will be older than 65 by 2030 (Wild et al., 2004). Also, about 3% of people aged 65 to 74, 19% of people aged 74 to 84 and

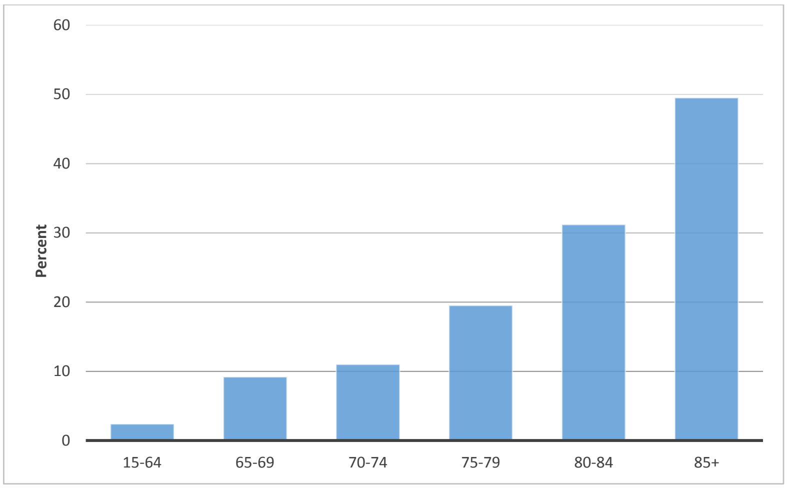


Figure 1.1: Percentage of people with care needs (Mann, 2004)

nearly half of people more than 84 suffer dementia (Umphred et al., 2013). Most of them, however, prefer to stay in their homes and communities, a phenomenon known as *age-in-place*. It has been observed that age-in-place reduces the speed of dementia progress, improves people quality of life (Cutchin, 2003) and enables them to be surrounded by their families. However, informal care at home can be excessively expensive, and in some cases, it is not possible at all (Wimo et al., 2010).

As illustrated by Figure 1.1, 31.2% of people aged 80 to 84 and 49.5% of people over 85 need constant care (Mann, 2004). Cognitive impairments such as dementia are the key causes of the elderly's need for care (Quentin et al., 2010). Taking stock of the difficulties and constraints associated with care, the use of assisted living technologies such as Smart Homes (SH) can substantially help older adults with the mild cognitive impairment to live more independently.

The SH technology aims to support people to have a better quality of life and to ensure the elderly to live comfortably and independently (Demiris and Rantz, 2004). An SH environment is usually equipped with a collection of inter-related software and hardware components to monitor the residents' behaviours and to understand their activities. By doing so, the SH system can inform about risky situations and take actions on behalf of the residents to their satisfaction (Amiribesheli et al., 2015). The SH technology can be used for different types of care: *informal* by family members, *formal* by geriatric physician and dementia nurses and *social* by non-medical caregivers. The concept of adapting assistive technologies such as SHs to support independent life for the PwDs is not new. A variety of assistive technologies has been employed for dementia care. Commonly, they provide support applications for memory aid, executive functions, visuospatial functions, social interactions, activities of daily living support, personal safety, behavioural monitoring, and mood monitoring (Bharucha et al., 2009).

It is widely accepted that SHs cannot help unless they are designed by considering the typical requirements of their users (Amiribesheli and Bouchachia, 2016; Green et al., 2004). This suggests that SHs for dementia care should address requirements of different user groups including PwDs, informal caregivers, formal caregivers and social caregivers (Amiribesheli et al., 2015; Hawkey et al., 2005). A few design initiatives that actively involve users in the design process (e.g., User Centred Design, Participatory Design, Universal Design, Design for All and Inclusive Design) are often considered as the most viable approaches to understand and capture user requirements, and to assure the ability of the final system to satisfy the requirements (John and Salvucci, 2005; Zimmermann and Grötzbach, 2007). However, given the peculiarities (e.g., memory restraints and mobility difficulties), and the evolving nature of dementia, there are challenges involved such as:

- PwDs are unique individuals who are often not aware of their needs, or unable to express them, which might lead to inaccurate requirements (Orpwood et al., 2005). Furthermore, dementia stakeholders (e.g., caregivers and PwD) needs can dramatically change with the dementia progress.

- Caregivers are not aware of all the PwD's needs, and often their experience and expertise are restricted to supporting a particular group of PwDs. Therefore, caregivers cannot be the only source for collecting PwDs' requirements.
- Other stakeholders of the system (e.g., care home managers, insurance companies) have various needs and preferences depending upon their interests and responsibilities. It means there is a much wider socio-technical aspect of the SH system. The system should be designed in a manner that can accommodate all stakeholders needs.
- Depends on the needs and preferences of a PwD and their care circle, a unique set of hardware devices and software systems are required for individual SHs. Also, the requirements are evolving by gradual progress of the PwD's disease. Therefore, the SH should be designed in a way that could be easily personalised by non-technical users.

The challenges suggest that the SH should be developed to dynamically accommodate stakeholders' needs rather than specific solutions that can only address users' needs for a period/stage within a fixed setting. Besides the unique requirements of dementia care, there are some general characteristics that all SHs should poses (Marzano and Aarts, 2003):

1. Non-obtrusiveness: An SH should not interfere with resident's lifestyle. This feature is crucial for SHs for dementia care, as adding any unnecessary equipment or interfaces inside the home can cause extra stress for PwDs, or reduces their sense of control (Orpwood et al., 2005).
2. Context-Awareness: An SH should distinguish different contexts and comprehend the evolving contexts. This feature is notably important for the SHs

for dementia care, as requirements of PwDs' requirements changes in different stages of dementia. In another word, the SH should be able to reflect the stakeholders' current contexts not only during its design phase but also during system run-time. It should be able to support PwDs as the new situation occur.

3. Personalisation: An SH should be personalised according to the residents' needs and preferences. Considering the differences in the symptoms of individual PwDs, and their preferences, personalisation should be a fundamental element of the SH.

4. Adaptivity: an SH should be able to adapt to the changes in the environment and residents' lifestyle. This capability involves the SH ability to add or remove hardware device or software components.

5. Anticipation: Ideally, an SH should predict and anticipate the changes in the environment or residents' contexts, and react to them. For instance, a PwD's decreased level of activity during the day, and insufficient sleep at nights can lead to health issues such as depression. Therefore, the SH should inform the members of care circle about the elevated risks of depression.

This PhD research looks at the specific PwD's requirements and care circle in all development steps of an SH (i.e., design, implementation, and evaluation). Also, the requirements of dementia care stakeholders are collected, analysed and reflected on a system design. The design is employed to implement a prototype. Finally, a number of thorough evaluation and validation studies are carried out using the prototype.

1.2 Research Question

In this work, a set of studies are conducted to address the key question of *How SHs should be designed to meet the requirements of dementia care stakeholders?* Also, we look at the impact of using a tailored SH prototype on the quality of the caregivers' experiences.

1.3 Research Objectives

1. Investigating the components of SH systems and understanding the challenges involved in using them for developing healthcare SHs. An literature review is conducted to achieve this objective. (Chapter 2).

2. Identifying the dementia symptoms, characteristics and effects on a PwD's life from the medical and care research literature (Chapter 3).

3. Identifying and eliciting the requirements of PwDs, studying the information collected from the previous stages and adopting adequate user-centred design tools for their validation (Chapter 3).

4. Designing an SH prototype that satisfies both functional and non-functional requirements of the dementia care stakeholders (Chapter 3).

5. Developing an SH prototype based upon the outcomes of the previous stages (Chapter 4).

6. Extending the SH prototype with components that enable it to be personalised (Chapter 5).

1.4 Research Methodology

The thesis relies on a mixed methodology to achieve the research objective. Due to the extensibility of research goals and the diversity of the influential factors, different methods were used.

In the first phase *(exploratory)*, a literature survey was performed. The survey explored the studies in the area of SHs for healthcare. A consolidated method was adopted in the second phase *(exploratory)* where the dementia symptoms were collected from the existing literature. These symptoms were presented in the form of scenarios adopting user-centred design tools. The scenarios were validated by caregivers through a series of informal interviews.

In the third phase *(experimental setup)*, a prototype was implemented using existing technologies and techniques. The phase produced an SH which satisfied the fundamental requirements of stakeholders in the dementia care.

The fourth phase *(experimental setup expansion)* extended the prototype to accommodate the dynamically evolving aspects of dementia care. To do that, the prototype was extended with software components that allows the users to personalise it.

In the fifth phase *(evaluation)*, the prototype was evaluated using multiple evaluation methods. The system functionality was assessed based on its capabilities to reduce dementia care *difficulty* and improve the care *effectiveness*. Also, the usability was evaluated by measuring the amount of task load added to the users using NASA-TLX test.

1.5 Contribution of the Thesis

A study of the existing SH solutions for dementia care reveals that very few studies investigated the unique requirements of dementia care. Most of the studies view dementia as a straight application of standard SH technology without accommodating the specific needs of dementia. A consequence of this approach is the inadequacy and unacceptability of generic SH systems to PwDs, as well as, other stakeholders of dementia care. This thesis attempts to address this challenge by introducing a tailored SH system for dementia care through utilising novel design and system implementation approaches. More precisely, the contributions of this thesis are:

1. *Requirements collection from dementia care stakeholders:* Functional and non-functional requirements of an SH dedicated to dementia care were elicited applying UCD tools and were validated by the stakeholders. The functional requirements were presented in the form of use cases. The non-functional requirements were introduced, and the common approaches for implementing them were presented.

2. *An intervention approach for SH systems in dementia care:* Existing SHs are often developed to perform the activities of daily living instead of the residents; this approach reduces the residents' sense of independence. Therefore, it makes them inadequate for the healthcare. In a dementia care circle, the caregivers avoid unnecessary interventions by utilising various levels of intervention depending on particular care circumstances. In this thesis, a five-level approach was introduced that enables the SHs to emulate the dementia caregivers for the interventions to PwDs' lives. The steps are 1) inviting awareness, 2) suggesting, 3) prompting, 4) urging, and 5) performing. They are arranged in a way that the system intervenes more as levels are increased

from 1 to 5. They assist the caregivers in setting the system reactions according to the PwDs' needs.

3. *The Prototype:* In the thesis, an innovative, functional SH prototype was introduced based on the requirements of dementia care stakeholders. It was designed to satisfy fundamental requirements of dementia care, as well as, providing the caregivers with tools to personalise the system. The common needs of stakeholders were identified by utilising UCD tools. To make the SH system personalisable, the SH was equipped with a reasoning engine that allowed the system to understand care instructions provided by the users. Moreover, the prototype enabled the users to provide the instructions through a rule management interface.

1.6 Structure of the Thesis

The thesis is structured as follows:

- **Chapter 2** (*State of the Art*): It includes a review of all components of an SH for healthcare. It discusses existing methods and technologies to implement the component and describes some of the well-known studies. Towards the end of chapter, the scientific challenges relevant to each component are highlighted.

- **Chapter 3** (*Designing a tailored SH prototype for dementia care*): It introduces a user-centred approach for designing and developing SHs for dementia care. A group of user-centred design tools are employed to collect the *functional requirements* of the stakeholders. The *non-functional requirements* are collected relying upon scenarios, literature, and interviews with caregivers.

The requirements are then exploited to design an SH system utilising standard software modelling approaches.

- **Chapter 4** (*Developing the tailored SH*): It introduces the SH components and develop a functional prototype adopting the components. The prototype addresses the common needs of dementia care stakeholders. In the end, it provides the prototype evaluation with a group of caregivers.

- **Chapter 5** (*SH Personalisation*): It introduces a reasoning engine and an interface that allow the caregivers to personalise the prototype and define customised care reactions. This is needed because PwDs have a variety of unique care requirements and preferences. Finally, it evaluates the SH prototype as a whole by the caregivers.

- **Chapter 6** (Conclusion): It concludes the thesis and sheds light on some open problems.

1.7 Publications

- Mohsen Amiribesheli, Asma Benmansour and Hamid Bouchachia *A review of smart homes in healthcare*. Journal of Ambient Intelligence and Humanized Computing, Vol 6, 4, pages 495 to 517, 2015, Springer
URL: http://goo.gl/Eo4D5v DOI: 10.1007/s12652-015-0270-2

- Mohsen Amiribesheli, and Hamid Bouchachia *Smart Home design for people with dementia*. Intelligent Environments (IE), 2015 International Conference on, Prague, 2015, pp. 156-159.
URL: http://goo.gl/4Hlhhl DOI 10.1109/IE.2015.33. July 2015

- Mohsen Amiribesheli, Mahmood Hosseini, and Abdelhamid Bouchachia *A*

User-Centred Principle-Based Transparency Approach for Intelligent Environments. To appear in British HCI 2016 proceedings

- Mohsen Amiribesheli, and Hamid Bouchachia *Towards Dementia-friendly Smart Homes*. Computer Society International Conference on Computers, Software & Applications (COMPSAC), 2016 International Conference on, Atlanta, 2016, pp. 638-647.
  URL: https://goo.gl/4tEKjQ DOI 10.1109/COMPSAC.2016.211. June 2016

Chapter 2

State of the Art

2.1 Introduction

In this chapter, we describe tools and techniques that are used for developing SHs for healthcare. The tools and techniques are employed for eliciting *users' requirements*, implementing *sensors and communication platforms*, reasoning using *artificial intelligence* techniques, developing *user interfaces* based on the Human-Computer Interaction (HCI) concepts. Finally, we highlight the challenges and research trends within the area.

SH technologies for healthcare aim to support people to have a better quality of life and to ensure elderly to live comfortably and independently (Demiris and Rantz, 2004). They are considered as ways to reduce living and care costs and to improve the quality of life for people with care needs (e.g., dementia and stroke). They have been used for many purposes (Miskelly, 2001) such as fall detection, in-home light management, smoke, fire detection and patients' kitchen monitoring adopting video monitoring, alarms, smart planners, calendars, and reminders. Equipped with sensors, actuators and eventually cameras to collect different types of data about the home and the residents, SHs enable automatic systems or caregivers to control the environment on behalf of the residents, predict their actions and track their health condition.

An SH system consists of different components structured in a layered architecture as illustrated in Figure 2.1. Each layer of the system has its function and comes with its challenges to be dealt with. Data is collected as the physical layer by sensors, transmitted through the communication layer to the processing unit in the processing layer where it is analysed for activity recognition and behavioural patterns discovery. The outcome of the analysis in the form of specific information, alerts or warnings can be communicated through the interface layer to various stakeholders (e.g., informal, formal, social caregivers, insurance policy makers). We used the layers as the classification reference for surveying literature. In the rest of the chapter, a majority of adequate studies which gained significant attention in the intelligent environment community are cited. It is worthy to mention that many of the cited studies offer solutions that can be utilised and applied in a variety of SH layers. Thus, their findings are distributed all throughout the chapter.

This chapter surveys the state of the art of SH systems in the healthcare considering the *infrastructure and communication*, *data processing* and *HCI*and discusses the challenges facing SH technology before becoming mature for successful deployment in real-world settings.

In the following, we review each layer to highlight the respective recent developments.

2.2 Sensing and Networking Technologies

An SH system consists of two types of components: hardware components and software components. The former integrates sensors and associated equipment like controllers and gateway equipment into a single network. Sensors are often seam-

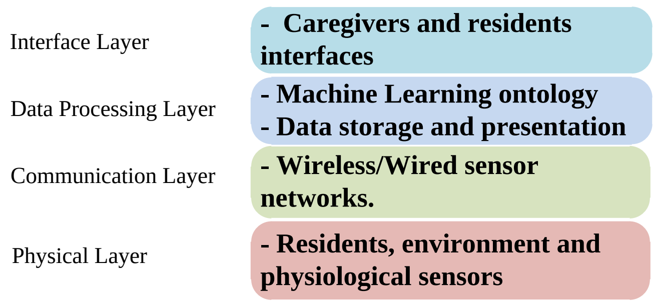


Figure 2.1: Layered architecture of an SH

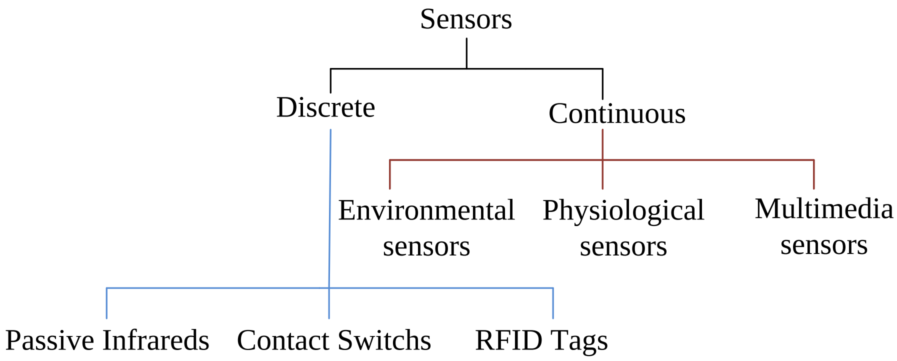


Figure 2.2: Taxonomic classification of sensors discussed in this paper

lessly integrated into the living space and are attached to the network using either wired or wireless connection. Ultimately, sensors can be remotely monitored and controlled via the Internet. Many communication technologies and protocols such as Bluetooth, ZigBee and Power Line Communication (PLC) have been used in SHs. In this section, we review the sensor technologies as well as the communication networks deployed in SHs.

2.2.1 Sensors

Sensors are physical devices for detecting changes in the environment including the residents. There is a large variety of sensors used to monitor SHs and the residents. Sensors are used to collect various types of data related to (Orwat et al., 2008):

- residents' activities
- objects states
- environment states

Sensors capture the following data (Ding et al., 2011; Ye et al., 2012):

- strain and pressure
- position, direction, distance and motion
- light, radiation, temperature and humidity
- type of material (e.g., solid, liquid and gas)
- sound
- image and video
- state of the object (e.g., present, not present)
- physiological measurements (e.g., blood sugar, blood pressure)

Sensors can be classified according to different characteristics. In the following we will categorise them based on the type of data they produce (see Fig. 2.2): discrete state sensors (also called "binary"), and continuous state sensors. Sensors usually form the building blocks of sensor networks. They can be either wireless or wired.

Discrete State Sensors

The output of state discrete state sensors is binary {0, 1}, hence the name "binary" sensors. Many studies have used binary sensors for detecting the state of objects or residents (i.e. open door/closed door, light on/off, person movement/stillness). Due to the simple nature of the data captured and the unobtrusiveness of binary sensors, many researchers have used them to collect data about residents' activities of daily living.

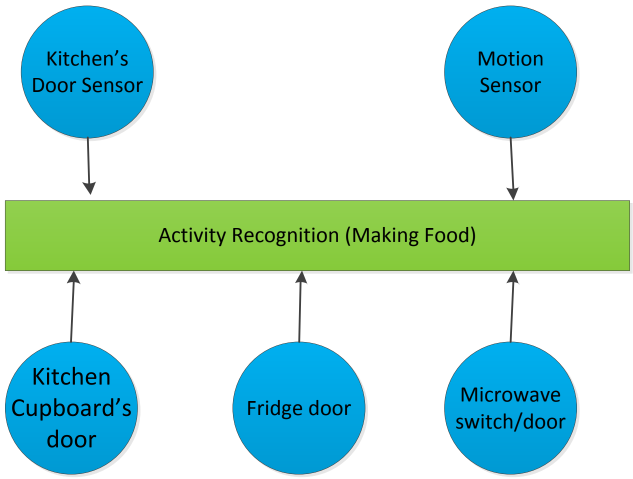


Figure 2.3: Binary sensors for capturing the activity of "making food".

The most commonly used state sensors in SHs in healthcare are the *Passive Infrared Sensors* (PIRs) (Farella et al., 2005; Lotfi et al., 2012). According to Reeder et al. (2013), all of the "effective" or promising research studies on SH have involved PIR sensors for data collection. The AILISA platform (Le et al., 2008) utilised PIR sensors to monitor the activities of elderly people. SH systems collect PIR's readings and store them in a database using the following format:

Detection [Date] [Hour] [Sensor Number]. Such data is then analysed in order to recognise abnormalities. In a study related to dementia patients, the authors in Diaz-Ramirez et al. (2013) used PIRs to collect data about the residents' movements in the home to make sure that they are safe.

Another group of commonly used state sensors is *Contact Switch Sensors* (CSSs). They are used to detect the state of objects, e.g. cupboard doors and fridge doors. A typical application of CSSs to track activities can be found in Brownsell et al. (2008). *Pressure sensors* as part of CSS family are used to detect the presence or occupancy of spaces like a bed, a chair, and a floor.

Radio-Frequency Identification (RFID) can be considered as a state technology as it serves to identify objects and people (Juels, 2006) using tags standing for identifiers and which are in general binary or hexadecimal sequences.

Figure 2.3 shows how binary sensors can be used to collect data about activities. While processing the binary data is moderately straightforward, the interpretation and presentation of binary data often require extra knowledge of the environment in order to capture the full activity. For instance, it is difficult to understand if a resident truly took his medication only by checking the captured data from the CSS attached to a drug cabinet door. To address this challenge, many sensors are required to capture the context and hence efficiently track the person.

Departing from this idea, Wilson and Atkeson (2004) tried to capture the activity context by associating the resident's location and activities. Binary sensors were used including motion detectors, break-beam sensors, pressure mats, contact switches and RFID. The goal of the study was to identify the residents and track their activities to detect abnormal behaviour.

Continuous State Sensors

In contrast to binary sensors, the output of continuous state sensors can take simple or complex forms like real numbers, images and sound. Popular sensors in this class are *environmental sensors* that are used to capture environmental data such as temperature, humidity, light, pressure, and noise. Such sensors are used to monitor all sorts of environments for different applications. *Physiological sensors* are used to monitor the resident's health condition. They capture different physiological data, such as blood glucose, blood pressure, ECG, EEG, EMG, pulse and body temperature. Commonly, physiological sensors are worn by patients forming the so-called Body Area Network (BAN).

Continuous state sensors have been used to monitor SHs. For instance, Wood et al. (2008) developed a system called AlarmNet for assisted living and monitoring. It is based on body area networks to collect physiological data from residents. AlarmNet supports different types of wireless sensors (e.g., heart rate, ECG pulse oximeter, weight, motion, dust, light, optical tripwires, CSSs) and interfaces to perform activity recognition. mPHASiS (Kulkarni and Ozturk, 2011) is a healthcare information system that uses BAN to collect physiological data. mPHASiS monitors ECG, blood pressure, acceleration and temperature. It was designed as an end to end healthcare monitoring solution. In particular, it triggers alert messages to inform the caregivers about specific health situations. The caregivers have access to the data of residents through a smartphone Tia et al. (2007) used lightweight BANs for patient triage in hospitals. Each patient wears a BAN that consists of a pulse oximeter, an electrocardiogram, blood pressure meter and a cough monitoring device to collect data. This study targets accident and disaster situations, but could be extended to care emergency in general.

The last type of continuous sensors is *multimedia sensors* that correspond to video cameras and microphones. Video cameras have been used to monitor certain situations, for instance, when the patient needs close monitoring by the caregivers. However, their use in SHs has often been criticised and rejected due to privacy constraints (Caine et al., 2005). People do not accept being watched, yet many researchers believe that video and audio sensors can considerably increase the accuracy of SH systems and should be used regardless of the privacy issues (Yamazaki, 2006).

Riedel et al. (2005) proposed an activity recognition system based on audiovisual data. They investigated activities such as having snacks while watching TV and reading the newspaper. The data was collected from six single healthy adults using multiple cameras in the home. The study achieved in average more than 90% activity recognition accuracy. De Silva (2008) developed another system using multimedia sensors to recognise activities like falling, walking, standing and shouting. The activity data was collected through simulation in a lab. For processing, two activity recognition models were applied, a model for processing obtained audio data and another for processing captured video data. The overall accuracies for activity recognition models were 94.44% for video data and 83.35% for audio data.

Another system, called COACH, was proposed in Mihailidis et al. (2008) for assisting elderly with dementia through the process of washing hands. COACH uses video frames to discover the hand position relying on the Partially Observable Markov Decision Processing Model (POMDP). The system also provides multimedia guides and alerts the caregivers when the person is facing a risky situation (e.g., when the person is not moving, the sink is full).

Table 2.1 shows some of the research studies where various types of sensors for different tasks were deployed.

2.2.2 Communication

The communication layer (see Fig. 2.1) in SHs plays the vital role of connecting all of the components such as sensors, actuators, gateway and storage hardware to each other. The following communication technologies can be distinguished:

1. Low Powered Wireless (LPW) networks (e.g., ZigBee, Bluetooth, RFID)
2. Power Line Communication (PLC) and heterogeneous PLC standard (e.g., X10)
3. Personal computer networking protocols (e.g., WIFI)
4. Universal Mobile Telecommunications System (UMTS) (e.g., ZigBee, Bluetooth, RFID)

In the following, a brief presentation of these technologies is reported.

Table 2.1: Some of SHs research studies and their sensor technologies.

Refrence	Sensors	Activities	Purpose
(Yamazaki, 2007)	Video cameras, Microphones, Floor pressure, Motion, RFIDs	Watching TV, Cooking, Tracking personal items	Behaviour monitoring, Tracking personal items
(Patel et al., 2008)	Air pressure	Not mentioned	Residents' location
(Rantz et al., 2008)	Video cameras, Bed pressure, Stove door CSS, Motion	Cooking, Sleeping, Walking in the house	Resting hours, Behaviour monitoring
(Viani et al., 2013)	Signal strength of wireless devices	Not mentioned	Resident's location
(Wilson and Atkeson, 2005)	Motion detectors, Pressure mats, CSSs, RFIDs	Eating, Bathing, Dressing, Toileting, Cooking, Watching TV	Resident's location, Behaviour monitoring and prediction
(Baker et al., 2007)	Accelerometer, Blood pressure readings, Microphones, Heart rate, Temperature	Movement, Blood pressure changes, Speech, Sound	healthcare Monitoring
(Intille and Larson, 2005)	Infra-red cameras, Microphones, Pressure mats, Motion, Water and gas flow,Light switches	Cooking, Socialising, Sleeping, Cleaning, Relaxing, Working	Behaviour monitoring
(Noury and Hadidi, 2012)	Motion	Not Applicable	Producing elderly's life scenario
(Riedel et al., 2005)	Video Cameras	Getting home and watching TV, Eating while watching TV, Reading	Behaviour monitoring
(Le et al., 2008)	Motion, CSSs	Bathing, Dressing, Toileting, Eating	Behaviour monitoring
(Wood et al., 2008)	Heart rate, Movements, ECG, Pulse oximeter, Weight, Pulse monitoring	Toileting, Sleeping, Showering, Eating and drinking, Walking,	healthcare Monitoring, Behaviour Monitoring
(Cook et al., 2013)	Motion, CSSs	Bathing, Walking, Cooking, Eating, Relaxing, Personal hygiene, Sleeping, Taking medicine	Behaviour monitoring
(van Kasteren et al., 2008)	Motion, CSSs	Toileting, Showering, Eating and drinking, Walking,	Behaviour monitoring

Low-Powered Wireless Networks

Low-Powered Wireless (LPW) or low energy wireless standards have been designed in a way to allow energy consuming devices such as sensors to function with minimum low consumption of energy (Smith, 2011) by staying in the power saving mode as long as possible. Many studies suggest that LPW technologies will shape the future of SH networking, particularly in the context of heal thcare (Dagtas et al., 2007; Patel and Jianfeng, 2010). The most common LPW standards are described in the following.

Currently, *ZigBee* is the mostly used standard among the LPW family. It is a small, low-cost, low-power, short-range wireless technology. It operates on a signal range of 2.4 GHz with the data rate of 250 Kbps (Baronti et al., 2007). Its transmission distance can spread up to 75 meters depending on the environment and the type of sensors deployed. Many SHs projects have adopted Zigbee technologies. For instance, Cavallo et al. (2009) used ZigBee to develop a system called "Pervasive Intelligence System for Rehabilitation and Assistance" (PISRA) dedicated to PwDs. The system serves to track people activities within SHs such as sleep, movement, fall, social communication and taking drugs. Moreover, the PISRA system offers help and guidance to the residents for conducting their daily activities. Van Hoof et al. (2011) developed a ZigBee-based system, called "Unattended Autonomous Surveillance (UAS)", to monitor the security and safety of PwDs. UAS consists of a number of wireless sensors located in the living room, bedroom and the kitchen which communicate through ZigBee. UAS detects incidents such as falling and inactivity and triggers adequate alarms when the person is in a risky situation.

U-Health (Lee et al., 2009) is a ZigBee-based system designed for monitoring elderly health using 12 different types of *wireless sensors for capturing heartbeat, blood pressure, body temperature, motion, location, blood sugar, cholesterol, SpO2,* *dehydration, camera, humidity, smoke, and temperature*. In the evaluation, authors only tested two of U-health sensors (the glucometer blood sensors, the ECG monitoring system) on 29 patients. They provided 20 patients with a ZigBee-based blood glucometer sensors that transmit the readings through a mobile phone to the web, and caregivers were instructed on using a web service which could illustrate the readings. The other nine have participated in ECG monitoring system, with a ZigBee-based ECG attached to their chest that transmits the readings via a mobile phone to the web, and caregivers who could see the reading through the web. The result showed the satisfaction scores of 8.59 and 9.01 out of ten points for blood glucometer sensors and web service, respectively. The mean satisfaction scores for ECG sensor and ECG monitoring services were 5.79 and 7.29, respectively.

Likewise, in Suryadevara and Mukhopadhyay (2012) a monitoring system relying on ZigBee was developed to track the activities of people in an SH designed for healthcare. Authors employed a variety of sensors including pressure and contact switches attached to household appliances like microwave, kettle, toaster, heater, TV and dishwasher. The system was used to estimate the well-being of the residents based on usage frequency of the appliances. The proposed system experimented on 4 SHs inhabited by single older adults. The system outcome showed the type appliance used by the elderly at their houses and also its collected data could be used to predict risky situations early.

Bluetooth is a low-cost wireless communication protocol that has been originally manufactured to connect mobile and handheld devices at a maximum data rate of 1Mbps within up to 10 meters of distance (Bisdikian, 2001). It employs the standard 2.4GHz signal band for communication. Some authors (Dengler et al., 2007) claimed that Bluetooth is better as it enables users to interact with the SH via conventional handheld devices such as mobile phones and tablets.

In Lee et al. (2007), it was illustrated that Bluetooth supports fewer cell nodes compared to ZigBee and Wi-Fi. Moreover, it has lower data rate compared to Wi-Fi. For these reasons and because also of the predominance of Wi-Fi-enabled handheld devices Bluetooth is less preferred for SHs.

It has not escaped our notice that the newer versions of Bluetooth (i.e. Version 5) are considerably more reliable. They got rid of Bluetooth current major deficiencies (e.g., battery life and coverage area). Thus, in future, they might gain a place as a favourable communication platform for the SHs in healthcare.

RFID is a technology for automatic identification of the objects and people by computer-based systems. RFID tags and readers use a variety of frequency ranges that can be categorised as low (124-135 kHz), high (13.56 MHz) and ultra-high (860-950 MHz). As the frequency range increases the reading range increase too. The number of SH projects for health that utilised the RFID technology have increased significantly in the past few years. RFID was particularly used for identifying people in a multi-occupant SH (see Section 2.5). For instance, in Yamazaki (2006) the authors used two separate RFID systems, an active RFID for environment monitoring and a passive one for resident identification (also known as data association problem).

Power Line Communication:

Power line communication (PLC) technologies allow SHs to adopt universally available electrical communication terminals as the communication infrastructure. In the following, some of the most common PLC technologies are presented.

X10 is an international networking protocol that enables home appliances to transmit digital data through an electrical power line. X10 is commonly recognised as a low-cost data transmission protocol with no installation requirements as it is uses existing wiring. Although the implementation of PLC is not as flexible as the wireless technologies (Ahmed et al., 2006), many researchers considered X10 as a cheap and available option to control appliances. They advise that a mix of wired and wireless technologies can offer the best of the two worlds to meet the requirements of SH systems (Cook and Das, 2007).

In Rantz et al. (2008), an X10 sensor network for monitoring PwDs living in a retirement community was applied. Motion sensors and pressures sensors were attached to rooms and beds. The research investigated the correlation between resident's daily activities and health problems such as falling or emergency medical needs. The study illustrated that the residents go into a period of restlessness before facing a problem.

Other Power Line Communication Technologies

A number of different PLC-based protocols for home automation have been proposed. Among others, these include European Installation Bus (EIB), Home Plug and Lonworks. Often these PLC protocols are enhanced versions of X10 (Hazen, 2008). The Home Plug Power Line Alliance introduced a PLC network protocol which connects nodes with a significant bandwidth of 200Mbps in an indoor distance of up to 350 meters using existing electric line (Yousuf et al., 2008). In Yu-Ju et al. (2002), the authors, discussed some reliability measures to ensure that Home Plug protocol is secure when handling sensitive data such as healthcare data. They compared home plug against some other more conventional wired and wireless protocols like 100BaseT and 802.11b. The comparison studied the network reliability factors such as the number of supported simultaneous connections, packet drops, data jitters and delays. The study stated that the PLC network successfully delivered low, medium and high bit rate data without any packet drops.

Despite the significant improvement of service in the new PLC protocols, the number of wired SH studies is limited compared to SHs that employ wireless and computer network technologies (Acampora et al., 2013). The characteristics of wireless systems like mobility, accessibility and compatibility push most of the research studies to use wireless protocols or a mix of wireless and wired protocols.

Heterogeneous networking protocols for intelligent buildings Diversity in sensor types and communication protocols have led to the development of hybrid protocols. One of the most successful heterogeneous protocols used for smart buildings is KNX (Tompros et al., 2009). KNX is a modern standard which has incorporated three European standards (BatiBUS, EIB, KNX-RF) and internet protocol to offer one package solution to SH networking. KNX allows designers to use various types of media such as radio frequency, power line and twisted pairs and the IP protocol. Heterogeneous protocols are not only limited to combining wired and wireless technologies but also protocols from the same family such as home wireless (e.g. Wi-Fi) and low powered wireless technologies (e.g. ZigBee) (Viani et al., 2013).

Personal computer networking protocols

Single-board advance computing units (e.g. Raspberry Pi, Arduino) are cheap and broadly available nowadays. Many studies tend to use computer networking protocols for SHs. *Wi-Fi* (Wireless Fidelity) is a computer networking protocol that is known as the IEEE 802.11 networking standard. Designers initially built it for the wireless local area networking, and it works on 2.4, 3.6 and 5 GHz frequency bands. Until recently Wi-Fi was considered not suitable for sensor networks and exclusive for PC networking (Ferrari et al., 2006). Nowadays, there is a variety of Wi-Fi enabled devices with sensors (e.g., smartphones, smart TVs, etc.) and houses are equipped with Wi-Fi access points for internet sharing. Hence, the creation of a Wi-Fi based sensor networks for SHs will be easy as illustrated with the CareNet

(Jiang et al., 2008).

Mobile Telecommunications System

Mobile Telecommunications Systems (MTSs) are capable of transmitting different types of data such as text, digitised voice, images, and video. MTS can be used in SH applications. For instance studies (Foo Siang Fook et al., 2006; Trumler et al., 2003; Zhaohui et al., 2011) adopted the SMS as an instrument for interacting with SHs' monitoring and remote control applications. In Al-Ali et al. (2004), the authors proposed a control system for SHs that allows the users to manage home appliances (e.g. air conditioner, light) by SMSs. The same platform could be applied to SH in healthcare. Airmed-cardio (Salvador et al., 2005) is an MTS-based monitoring system for cardiac patients follow-up in their home. Each patient has a portable monitoring equipment and cellular phone that supports data transmission. The collected data is transmitted to a base station which is monitored by a human operator.

2.3 Data Processing and Knowledge Engineering

Following the layered architecture presented in Fig. 2.1, the data is collected and transmitted through the communication medium to a data processing unit. In this stage, data potentially undergoes a pre-processing step for cleansing and preparation before further processing is initiated. The result of the first step is a set of machine-readable information (e.g., activity). Later, the information is adopted to accumulate high-level abstractions and perceptions (e.g., events) that provide meanings and insights about activities. Finally, deduced knowledge (also known as actionable intelligence, or wisdom) is discovered that shape SH reactions.

To function, data processing methods require two types of contexts:

1. Micro-contexts to extract information (also known as activities) from the raw sensor data (e.g., PIR sensor readings). This process often includes applying activity recognition techniques.

2. Macro-context for transforming information to knowledge (e.g., PwD is wandering). To do that, the system should be equipped with methods such as a rule-based system to map an activity or a group of activities to a given event.

In the literature, some of the key functions of the data processing layer are to:

- present the sensor data in a way that caregivers can track the changes of the resident's health state and how the resident accomplishes the daily activities under observation.
- detect anomalies when carrying on activities and trigger alerts in critical situations (i.e. falling, forgetting to turn off the cooker).
- identify the progress of chronic diseases and conditions (e.g. case of PwDs).
- remind the resident about scheduled activities (e.g. taking pills).
- predict activities by the resident and assist him in their accomplishment.

A variety of knowledge engineering and data processing methods can be used to analyse the collected data. In the following, we will focus on the main problem in SHs which is context modelling and recognition from sensor readings. The common computational models used for context analysis in SHs will be highlighted, and related studies will be summarised. The models considered are *Decision Trees, Fuzzy Logic, Artificial Neural Networks, Support Vector Machines, Naive Bayes Classifier, Hidden Markov Models, Emerging Patterns, and Ontology*.

Table 2.2 shows some of the SH research studies including the data source, the algorithms, and the performance of such algorithms.

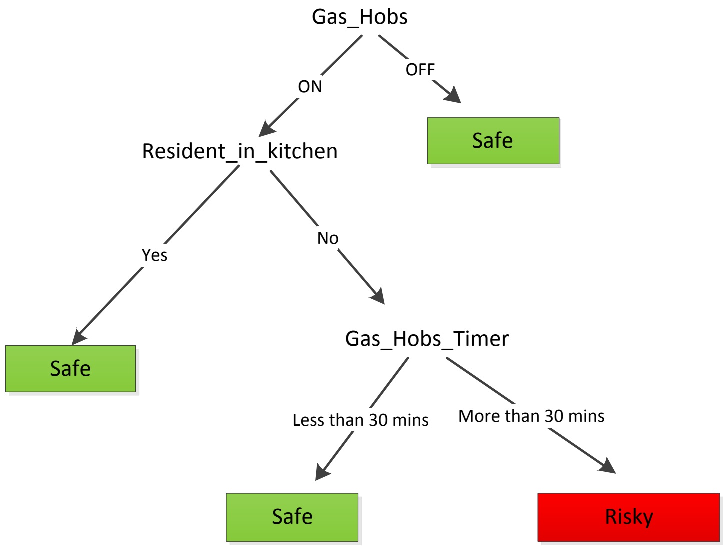


Figure 2.4: Structure of a Decision Tree.

2.3.1 Decision Trees

A Decision Tree (DT) is used to model the relation between input data and the corresponding output. A decision tree can be used for either classification if the output is discrete indicating class labels or regression if the output is continuous. A classification tree consists of nodes that represent features and branches that represent the values of the features. The leaf nodes represent the class labels.

Figure 2.4 shows a classification tree with 2 classes: *safe* and *risky*. A tree can be rewritten as a set of IF-THEN rules. For instance the rule:

IF Resident-in-kitchen=NO and Gas-Hobs-Timer > 30 *THEN Class=Risky* can be derived from the tree in Fig. 2.4. DTs are built through an induction process using a training dataset. Many induction algorithms have been devised such as TDIDT/ID3, C4.5, CART, MARS, and CHAID. Some algorithms like C4.5 and CART execute two phases: growing and pruning of the tree, while others only grow the tree (Rokach and Maimon, 2005).

In Isoda et al. (2004), C4.5 was used to generate a DT for classifying the actions of the resident that is a combination of the resident location and the object touched. The training dataset was collected from pressure sensors on the floor for locating the resident and RFID tags on the objects (e.g. gas hobs, cupboard). The evaluation of the classifier on kitchen activities achieved an accuracy of 90% to 100% depending on the size of learning data used.

C4.5 was also applied in Ravi et al. (2005) to recognise activities using data from a wearable triaxial accelerometer. The activities considered were: standing, walking, running, climbing stairs, climbing down stairs, sit ups, vacuuming and brushing teeth. C4.5 was used among other classifiers such as K-nearest neighbour, SVM and Naive Bayes. The results showed that C4.5 achieved 97.29% when trained and tested on data from the same user over many days. An accuracy of 98.53% was achieved when C4.5 was trained and tested on data stemming from many users and over many days and 77.95% when trained and tested on data not from the same day.

In Manley and Deogun (2007), the authors applied ID3, the Perceptron and k-NN to determine the location of the resident based on the wireless signal strength. Two datasets were used: Peter Kiewit Institute dataset (PKI) and Maxwell Working (MD) dataset (Quinlan, 1986). The results showed that for ID3, the mean error was 4.9 m and 2.5 m for PKI and MD respectively. The mean error of k-NN was 4.9 m and 2.4m, while that of the Perceptron was 7m and 2.4 m respectively.

In Prossegger and Bouchachia (2014), the authors applied decision trees to model activities of daily living in a multi-resident context. An extension of ID5R, called *E-ID5R*, was proposed where the leaf nodes are multi-labeled. E-ID5R induces a decision tree incrementally to accommodate new instances and new activities as they become available over time. To evaluate the proposed algorithm, the ARAS dataset which is a real-world multi-resident dataset stemming from two houses was used. E-ID5R performs differently on activities of both houses: for

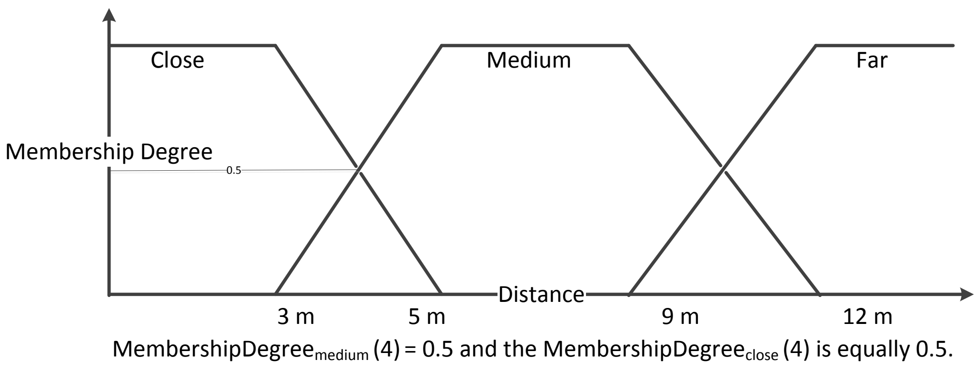


Figure 2.5: Fuzzy set represented as a fuzzy membership function.

house A whose data is quite challenging, the classification rate was modest (40%), while for house B the rate approached 82%.

2.3.2 Fuzzy Logic

As an extension of the classical set theory, Zadeh (1965) defined a fuzzy set as "a class of objects with a continuum grades of membership. Such a set is characterised by a membership (characteristic) function which assigns each object to a grade of membership ranging between zero and one." Fuzzy sets have been used to develop fuzzy logic systems. Many SH studies have applied fuzzy logic to build monitoring and prediction systems.

To explain what is a fuzzy set, the primary step is to understand the membership function. This function maps each input data to a membership degree $\in [0,1]$. For instance, Fig. 2.5 illustrates membership value of the distance value 4 to three to three fuzzy sets corresponding to the linguistic concepts:"close", "medium" and "far".

Using fuzzy sets, Rule-Based Systems (RBS)can be extended to include fuzzy "IF-THEN" rules of the form: *IF sink_water_level is High then stop_tap*. As shown in Fig. 2.6, a fuzzy RBS has the same components as a traditional RBS but the input is fuzzified at the beginning, and the output is defuzzified at the end. The inference system maps the input data to the rule base and aggregate fuzzy output of the system according to an inference method. The defuzzification converts the fuzzy output of the system to crisp output.

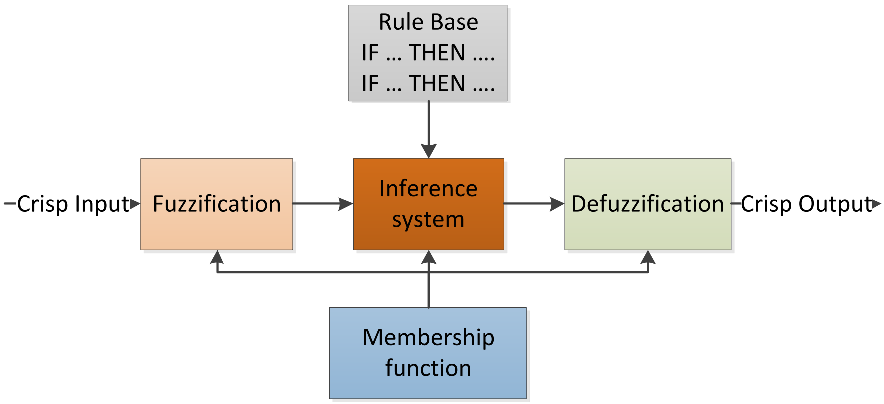


Figure 2.6: Structure of a fuzzy rule-based system

The Fuzzy Rule-based Systems (FRS) are used in the form of fuzzy rule-based classifiers. For instance, a fuzzy rule looks as follows: *IF Resident_stay_in_bed for Long and bedroom_TV=OFF then Class_risky*. Rules can be associated with confidence level which may be obtained in different ways. The structure of a fuzzy rule-based classifier is similar to the Figure 2.6 however since the outputs are classes the defuzzification step is often not necessary. A good overview of fuzzy classifiers can be found in Bouchachia (2015).

In Hagras et al. (2004), the authors used a fuzzy rule-based controller where the output of the rules is not a class but a function in order to monitor a smart environment, called “iDorm", based on preferences of the occupants. The data was generated over two months by recording two student activities in a dormitory flat which is equipped with 11 sensors: internal light level, external light level, internal temperature, external temperature, chair pressure, bed pressure, occupancy and time etc. The output is provided by six actuators: variable intensity spot lights, the desk and bed side lamps, the window blinds, the heater and PC-based applications comprising of a word processing program and a media playing program. The induction process led to a rule base consisting of 280 rules based on 132 hours of collected data.

Bouchachia (2011) introduced a fuzzy rule-based classifier, called IFS that stands for the incremental fuzzy classification system, which is capable of dealing with the dynamic nature of SHs. The classifier is based on Generalised Fuzzy Min–Max Neural Networks (GFMMNN). It is designed to learn and self-adjust in a flexible manner to react to dynamic changes such as the occurrence of new events, inputs' change, seasonal changes, etc. The study demonstrated how fuzzy rules can be continuously generated on-line to meet the requirements of a dynamic environment. The author used the iDorm data (Hagras et al., 2004). The data was split into two subsets: the training set contains 75% samples for the first month, and The testing set contains 25% of the first month and all samples of the second month. The evaluation of IFS shows that the adaptation is essential for on-line tracking of people's activities. The current error rate continuously decreases reaching 0.01. Compared with fuzzy ARTMAP and nearest generalised exemplary, IFS produces a lower current error.

In Ordonez et al. (2013) some fuzzy classifiers such as Class0, eClass1, k-NN, NB and HMM were used to recognise activities. The following activities were considered: leaving the house, using the toilet, showering, sleeping, eating breakfast, eating dinner and drinking. Using data collected from 3 smart homes, it was found that on average the evolving classifiers, eClass0 and eClass1 achieve an f-measure value of 0.6 and 0.7 respectively outperforming the other classifiers, especially when the size of the training data increases.

Bouchachia and Vanaret (2014) developed an online type 2 fuzzy self-learning classifier, called GT2FC standing for "Growing Type-2 Fuzzy Classifier". For the rule learning from data streams. They suggested that the classifier is suitable for ambient intelligence (e.g. SHs) where the goal is to use sensed data to monitor the living space on behalf of the residents. The research tackled three challenges of online learning, the complexity of the rule-based classifiers and accommodation of labelled and unlabeled data during rule learning. To illustrate the model's performance, they conducted experiments using an ambient intelligence which iDorm dataset (Hagras et al., 2004). The paper investigates the effect of labelled and unlabelled on the classification accuracy. It also compares the outcome of GT2FC against other online classifiers such as IFCS (Bouchachia, 2011), Nearest Generalized Exemplar, Growing Type-1 Fuzzy Classifier with 70% of data being labelled, the accuracy of GT2FC classifier was 81.65% while the GT1FC was 81.42; Nearest Generalized Exemplar was 75.54%, and IFCS was 75.24%.

2.3.3 Artificial Neural Networks

Artificial Neural Networks (ANN) is a computing model made up of some simple, highly interconnected processing elements, which process information by their dynamic state response to external inputs (Caudill, 1987). The fundamental processing elements of an ANN are artificial neurones (or nodes) which are interconnected by weighted links forming layers as shown in Fig. 2.7. Typically in an ANN there is one input layer and one output layer and a number of hidden layers that varies depending on the complexity of the problem at hand (Murata et al., 1994). Neurones transform the weighted input into output using an activation function which can take different forms (linear and non-linear). The process by which the weights are adjusted is called learning. A number of non-linear ANNs are known to perform as function approximators. There are various parameters that define the architecture of a neural network: the connection type (e.g. feed-forward networks

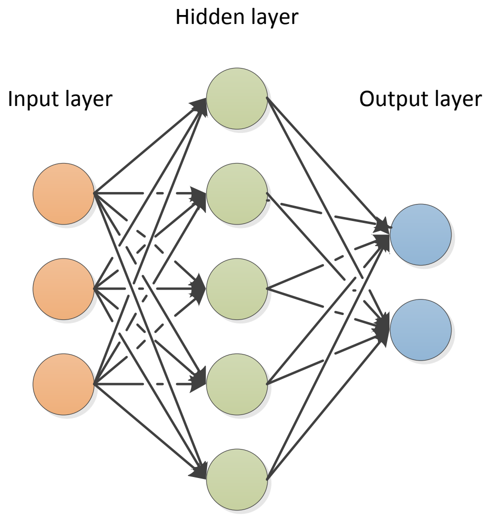


Figure 2.7: Architecture of a 3-layer feed-forward network.

recurrent neural networks etc.), learning rule (e.g. Hebbian rule, perceptron learning, back-propagation, etc.), and activation functions (e.g. sigmoidal, hyperbolic tangent, etc.). Because of these shaping parameters, there are different types of ANNs (e.g. Multi-Layer Perceptron (MLP), Echo State Networks (ESN), Radial basis function networks (RBFN), Boltzmann machine, etc.).

ANNs can be applied to a number of SH problems such as activity classification, control of appliances, novelty and anomaly recognition and prediction of activities. About health monitoring in SHs, ANNs were used to diagnose and monitor chronic diseases as well to build medical decision support systems (Er et al., 2010; Khan et al., 2001; Lisboa and Taktak, 2006).

MLP is the most commonly used ANN models for activity recognition (Begg and Hassan, 2006). A precursory work using MLP for SHs is presented in Mozer (1998). MLP is used to control the energy consumption in accordance with the lifestyle of the residents. It is trained using the back-propagation algorithm on a dataset collected from a state of the lamps, intensity level of the lamps, speed of the fans, temperature, illumination, sound level, motion and state of the doors and windows. By predicting the future activities of the resident using this MLP, energy consumption of appliances in the home can be monitored.

In the MavHome project (Cook et al., 2003), an MLP-based framework was proposed to detect activity anomalies and identify repetitive tasks performed by residents. The sensors used in this framework are motion, light, humidity, and CSS. The empirical evaluation showed an average of 64% accuracy for activity recognition in five randomly generated resident ADL scenarios. Rivera-Illingworth et al. (2005) employed a Recurrent Neural Network (RNN) based on Evolving Connectionist System (ECoS) to recognise activities like sleeping, eating, working with the computer, and to detect abnormal behaviours. ECoS operates online, which means that new sensors can be added to the architecture, and new activities can be accommodated at any stage. The authors evaluated RNN using a dataset collected from a student dormitory in Essex using different sensors like light, temperature, pressure, etc. They achieved an average of 74.57% accuracy rate on a test dataset and 89.14% of abnormal activity detection rate.

In Li et al. (2008) a One-Pass Neural Network (OPNN) was applied to identify anomalies and to perform activity recognition. Similar to EcoS, OPNN runs online. In the study, a bedroom was used as an experimental space. The room was equipped with a set of sensors like chair and bed pressure sensors, light, table lamp, bed lamp, air condition, and window blind. To produce the dataset of simulated ADLs, the authors gave questionnaires to the students to annotate their activities (e.g. working on the table, computer use, listening to music, sleeping). OPNN was evaluated on a sample of achieving 92% accuracy. A layer was added to OPNN for deciding the type of abnormality: abnormal behaviour, abnormal sequence, and abnormal frequency. For instance, when the duration of cooking exceeds a specified upper limit or when using the toilet frequently, the system will perceive this as abnormality.

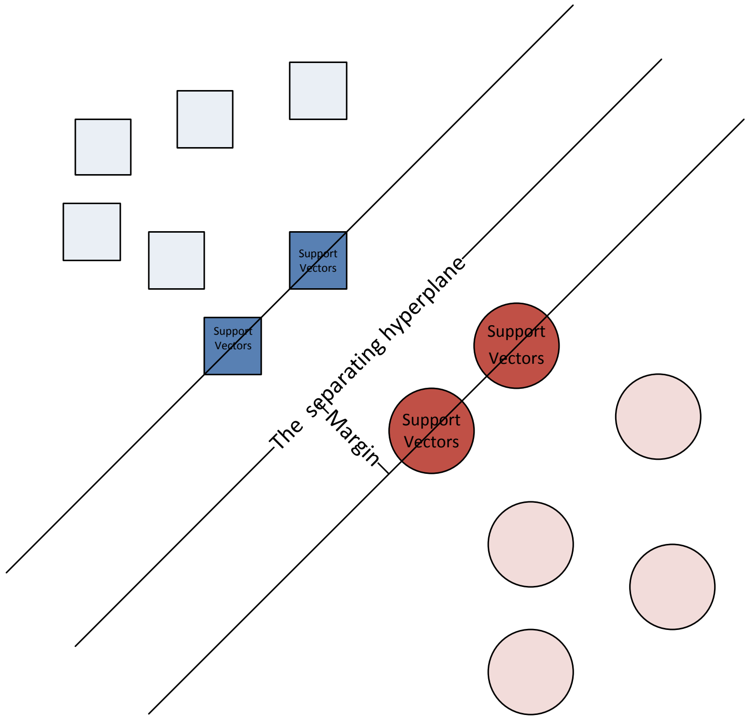


Figure 2.8: Hyperplane, margin and support vectors.

Lotfi et al. (2012) applied Echo State Networks (ESN-NN) to predict future abnormal activities for elderly with dementia. The system aims at identifying anomalies such as sleep deprivation and sending alerts or reports via e-mail or phone to the caregivers. The data used was collected from PIR and CSS sensors. The empirical evaluation produced an anomaly prediction rate of 93% to 99% for very simple activities. In this study k-means and fuzzy c-means clustering algorithms were applied to detect abnormal activities using the start time and the duration of activities. Large clusters have found to match normal activities and smaller ones to as abnormal activities.

2.3.4 Support Vector Machines

Support Vector Machines (SVMs) are quite popular classification methods and have been used various applications such as face identification, text categorisation and stock classification. SVMs have been used for activity recognition in a number of studies. Consider the linearly separable data in Figure 2.8. Classes are separated by hyperplanes. SVMs maximise the margin around the separating hyperplane. The margin is the distance from the hyperplane to the closest data points which are called support vectors. SVMs use different optimisation techniques to find the optimal hyperplane by maximising the margin. SVMs use kernel functions (e.g., radial basis kernel, polynomial kernel, etc.) to map the non-linearly separable data from the input space into a higher space where data become linearly separable.

SVMs have been used for Micro-context analysis (i.e., activity recognition) in a number of studies. For example, an application of SVMs was described in Fleury et al. (2010). The data was collected through a set of binary (e.g., PIR, CSSs, flood detectors) and non-binary (e.g., microphones, wearable kinematic sensors) sensors. An SVM-based system was applied to recognise seven activities: sleeping, resting, dressing, eating, using the toilet, hygiene activities and communications. The cross-validation test gave the results with a satisfactory classification rate of 75% for a polynomial kernel and 86% for a Gaussian kernel.

Cook et al. (2013) employed SVM and the Naive Bayesian classifier (see Sec.2.3.5) and Hidden Markov Model (see Sec.2.3.6) to deal with activity discovery and recognition. The data was obtained from 3 SHs inhabited by elderly residents using PIR and CSS on doors. The daily activities targeted included bathing, walking, cooking, eating and taking medicine. The results revealed that SVM outperformed the other models, achieving an average accuracy of 91.52% for the three homes. Moreover, an activity discovery model was introduced in order to detect novel activities and to enhance activity recognition. SVM could improve the accuracy up to 10% when using activity discovery along with activity recognition.

In Luštrek and Kaluža (2009) applied SVM among other algorithms (C4.5 DT, NBC, K-nearest neighbour, and random forest) for fall detection. The data was collected using 12 radio tag equipment attached to the shoulders, elbows, wrists, hips, knees and ankles of three people. The evaluation of the algorithms showed that SVM outperforms the rest of classifiers obtaining an accuracy of 97.7%.

In He and Jin (2009) an activity recognition technique based on the Discrete Cosine Transform (DCA) and SVM was proposed. The dataset was collected via a Bluetooth-based triaxial accelerometer from 11 people. Four activities were considered: running, staying still, jumping and walking. First, the features were extracted from the data employing DCA; then SVM was trained to recognise these activities. A high accuracy of 97.51% was obtained.

2.3.5 Naive Bayes Classifier

The Naive Bayes classifier (NBC) is one of the simplest probabilistic classifiers. It relies on Bayes' theorem to build the decision boundary making use of the assumption that all of the input features are independent. This assumption makes the classification process tractable. Given an input $X = [x_1, x_2, \cdots, x_d]^t$ and a set of classes $\{C_1, \cdots, C_J\}$, the conditional probability $P(X|C_j)$ can be written as:

$$P(x_1, x_2, \cdots, x_d | C_j) = \prod_{i=1}^{d} P(x_i | C_j)$$

The label of X is then predicted as follows:

$$C = \arg \max_{j=1 \cdots J} P(C_j) \prod_{i=1}^{d} P(x_i | C_j)$$

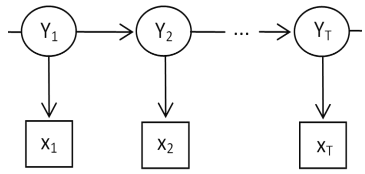


Figure 2.9: Structure of HMM

NBCs have been employed in many SH research studies. Tapia et al. (2004) used NBC to recognise daily activities such as washing hand, toileting, cooking, resting and dressing. A set of 77 binary sensors were installed on targeted objects like doors, windows, cabinets, a microwave, a stove and a dishwasher. Using accuracy (number of times the activities were correctly recognised) and whether the activities were detected with or without delays, NBC has produced the best accuracy of 89% considering different settings. Using the same dataset, van Kasteren and Krose (2007) applied dynamic NBC (DNBC) for activity recognition. The experimental results showed that DNBC outperformed NBC.

NBC was also evaluated on a video data in Messing et al. (2009). In this study activity like ”working with the phone", ’drinking water" and ”eating snacks" were targeted. The experimental evaluation showed that NBC could perform well on video data achieving an accuracy of 89%.

2.3.6 Hidden Markov Model and its Variants

Hidden Markov Model (HMM) is a special case of Bayesian Networks which model joint probabilities of states and observations.

It used to estimate hidden state sequence $(y_1, y_2, \cdots, y_T)$ given the input sequence $(x_1, x_2, \cdots, x_T)$ as illustrated in Fig 2.9.

HMM is one of the most common computational models applied to activity recognition. As shown in Fig 2.10, the activities represented as ovals are modelled as hidden states, while observations (called also observed states) represented as

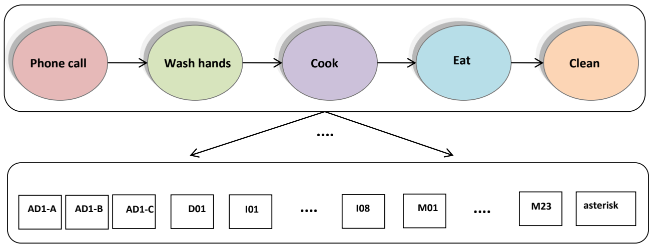


Figure 2.10: Activity modeling using HMM

rectangles indicate the data emitted by the sensors. The horizontal edges represent transition probabilities and downwards edges represent the emission probabilities of the corresponding observed state.

This encoding was reflected on in van Kasteren et al. (2008) where HMM was applied to recognise some target activities: leaving the house, toileting, showering, sleeping, preparing breakfast, preparing dinner and preparing a beverage. Using a set of 14 CSSs located on doors, cupboards, refrigerator and toilet flush were used to collect data, the study investigated three aspects: data representation, the size of the training data and difference between on-line and off-line inference. The experimental results showed that a better data representation through preprocessing improves the recognition ability of HMM, while a minimum of 12 days of data is required for an efficient training. The experiments also showed that off-line inference is more effective than on-line.

In another study (Chua et al., 2009) HMM was applied on the MIT PlaceLab (Tapia et al., 2004). Compared to many similar studies, this study focuses on tracking a whole behaviour as a sequence of activities that occur close to one another in time, in one location. Thus, the activities are seen as a data stream giving room to consider variable and fixed sized windows of observations. Two accuracy measures were used: behavior-level recognition and observation-level recognition. In the first, the HMM output is compared against the ground truth whenever the behaviour changes, while in the second the output is compared against the label of the observation. Using different splits of data, the experiments showed that variable sized windows provided very good recognition rate using both types of measures. However, the values of the observation-level measure were always higher than those of the behavior-level measure.

Despite its popularity, HMM suffers from several limitations. HMM cannot capture long-range or transitive dependencies of the observations due to the strict independence assumptions on the observations. Furthermore, without significant training, HMM may not be able to recognise all of the possible observation sequences that lead to a particular activity (Kim et al., 2010). Moreover, HMM does not take temporal considerations into account, meaning that the duration of an action is not explicitly modelled and the interaction cannot be encoded directly. To overcome these limitations, Hidden Semi-Markov Model (HSMM) was proposed to explicitly model the duration of activities.

HSMM was compared against HMM in van Kasteren et al. (2010). In this study, binary CSS sensors were used to collect 3 datasets related to two different individuals who are 26 and 57 years old. Activities that were targeted include eating main meals, using a dishwasher, drinking and eating snacks. To evaluate the accuracy of HSMM and HMM, the f-measure was used. The experimental evaluation showed that HSMM (65.5%) outperformed HMM (54.1%). This means that considering duration improved the classification, specifically when the sensor data does not provide enough information for activities to be distinguished.

Another variation of HMM is the Hierarchical Hidden Markov Model (HHMM). HHMM was devised to cope complex activities that can be split into smaller units (actions) with a hierarchical structure. It extends the traditional HMM in a hierarchic manner to include a hierarchy of hidden states. Each state SHMM is generalised recursively as another sub-HMM with special terminal states. Thus, HHMM

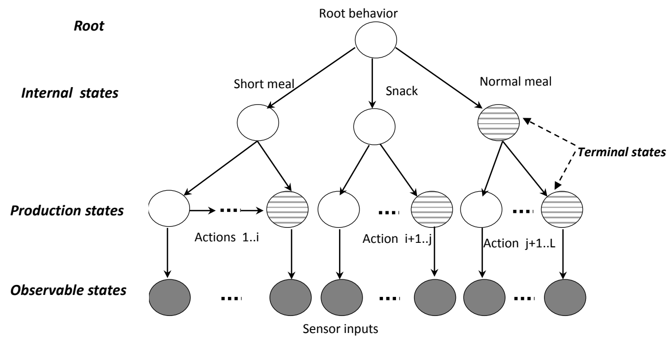


Figure 2.11: HHMM representation

contains three types of states (see Fig. 2.11): root, internal and production states. The root state is the starting node at the top of the hierarchy. The production state is the leaf node which emits the observable output, and the internal state is the composite node which is composed of several internal sub-states or production sub-states and does not emit observable output directly.

van Kasteren et al. (2011) investigated the application of HHMM in activity recognition following the model shown in Fig. 2.12. A set of sensors were used to collect the data from three houses: CSSs, pressure mats, PIRs, and toilet float sensors. It was found that when the actions are allocated separately for each HHMM outperform the other models like HMM and HSMM using the F-measure. For the first house HHMM, HMM and HSMM achieved 79%, 72% for HMM and HSMM. About 56% for HHMM, 51% for HMM and 52% for the second house, while 52% for HHMM and 45% for HMM and HSMM for the third one were obtained.

2.3.7 Conditional Random Field

Conditional Random Field (CRF) is a discriminative graphical model in contrast to HMM and its variants which are generative. CRF is the most popular discriminative model and can be applied to find a hidden state transition from observation sequences. However, instead of finding a joint probability distribution p(x; y) As

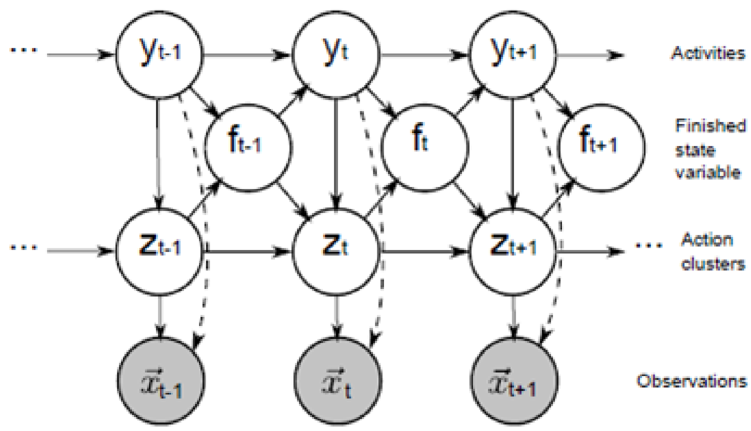


Figure 2.12: HHMM representation as proposed in van Kasteren et al. (2011)

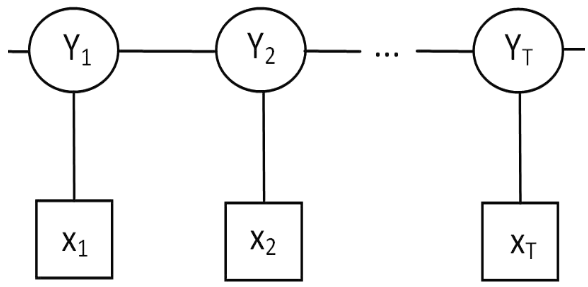


Figure 2.13: Structure of CRF.

HMM does, CRF attempts to find only the conditional probability p(x|y). Moreover, it allows arbitrary, non-independent relationships among the observations. Hence, it is more flexible. Another significant difference is the relaxation of the independence assumptions, in which the hidden state probabilities may depend on the past and even future observations (Sutton and McCallum, 2006). A CRF is modelled as an undirected acyclic graph, flexible for capturing any relation between an observation variable, and a hidden state see Fig. 2.13.

Studies presented in Kasabov (2007); van Kasteren et al. (2010) have demonstrated that CRF commonly gives a better accuracy than other probabilistic models in the context of activity recognition. In the first study (Kasabov, 2007) CRF and HMM were compared using different activity data representations to show that CRF outperforms HMM. In the second study (van Kasteren, 2011) CRF was compared against NB, HMM, and HSMM and CRF scored again better.

2.3.8 Emerging Patterns

Emerging Patterns (EPs) (Gu et al., 2009) were used to model and discriminate the activities. Thus, an EP of an activity consists of the most discriminating set of features. For instance, {location = kitchen, object = stove} is an EP for the activity ”cooking", while {object = cleanser, object = plate, location = kitchen} is an EP for ”cleaning the kitchen". The set of EPs of an activity constitutes the corresponding activity model. Often the features in an EP can be found simply by frequency counting.

Gu et al. (2009) showed how activity models could be built from sensor readings using EPs. To evaluate this technique, a real-world data set was collected from wearable sensors (RFID wristband readers and iMote2 sets) by four people. In all 26 common ADLs such as coffee making, tea making, oatmeal making, shaving, toileting, etc. have been considered. EPs were then generated for each activity. Using time-slice accuracy to recognise activities through intervals of time, an average accuracy of 85.84% was achieved for different activities.

2.3.9 Ontological modelling

Used to model, encode, and represent knowledge of a given domain, an ontology is a conceptual model consisting of a set of representational concepts. The concepts are typically classes, attributes, and relationships (Gruber, 2009). Activity ontologies describe the hierarchy of activities, activity types and their relationships. Relationships can be of different types: ”is-a" or ”part-of". For instance, ”MakeTea" is a subclass of MakeHotDrink. Properties are used to establish the interrelations between concepts. For instance, ”hasDrinkType" is a property of the ”MakeHotDrink" activity that links the DrinkType concept (e.g., tea, coffee, chocolate) to the “MakeHotDrink" concept. The ontological approach to activity modelling defines the formal semantics of human activities using some ontological language like OWL and RDF.

The ontological reasoning is used to recognise activities by identifying contextual information such as sensor reading, the location of persons and objects, properties of objects, etc. Chen and Nugent (2009) described an algorithm for recognising activities using ontologies which can be illustrated by the following scenario. For example, the activation of the contact sensors on a “cup" and “milk bottle" can link the “cup" and “milk" to the unknown activity through a concept “hasContainer" and “hasAddings" properties. By aggregating sensor observations along a timeline, a specific situation that corresponds to an unknown activity could be reached. For instance the situation can be described by “hasTime(10am)", “hasLocation(kitchen)", “hasContainer(cup)" and “hasAddings (milk)". By matching this situation against activity ontologies, the activity class that mostly overlap with the situation (e.g.,“MakeDrink") is considered to be the actual activity.

Riboni et al. (2011) followed a similar idea using activity ontologies to recognise the daily activities. In particular, they evaluated the effectiveness of the ontological approach based on dataset described in van Kasteren et al. (2008). This study showed that ontological techniques underperform the data-driven techniques like HMM in the absence of temporal reasoning. However, when ontological techniques were extended with temporal information, their effectiveness (80.3% accuracy) becomes comparable to HMM (79.4% accuracy).

2.3.10 Context-Aware Reasoning

Context awareness refers to the exploitation of various kinds of information to recognise the environmental conditions within the living space to help make the smart home system intelligently interactive and self-adaptive. Information can be temporal, spatial, and related to the resident and objects in the environment (Abowd et al., 1999). Context awareness enhances the usability of a system by enabling it to react suitably and offers optimised interfaces for different contexts. There exists a number of approaches for modelling and reasoning about the context such as Unified Modelling Language, Object-oriented Models, key-Value models, and domain/web ontologies. The latter enable the system to define contexts semantically and share common knowledge of the structure of context among users, devices, and services (Gu et al., 2004).

In Helal et al. (2005), a reference model for healthcare context-aware SHs, was introduced. The context was generated by a set of sensors and actuators that were managed through OSGi (Open Service Gateway initiative) service bundles. System objects represented the sensors and actuators in the environment and were modelled along with contexts using ontologies. Authors presented two mere applications of “Smart Floor" and “Smart Plug" to prove the effectiveness of the system.

Wongpatikaseree et al. (2012) introduced a context-aware activity recognition system. An ontology was exploited to model the context which is obtained through a set of sensors. To handle various activities of daily living, especially in ambiguous situations, the context is augmented with information obtained through the ontology which consists of various classes. To illustrate how the system works, some simple activities such as watching TV, relaxing and sleeping and were simulated.

Fenza et al. (2012) proposed a hybrid context-aware healthcare system consisting of a web service Ontology (OWL-S) and a fuzzy rule base. The residents’ health context is obtained using sensed health data such as heartbeat, blood pressure, blood sugar, blood oxygen, height, weight, age, and temperature. The data is used to run a fuzzy rule-based clustering. Given an input, the fired rule indicates the cluster in its consequent part. The premise of the rule, corresponding to the context, is matched against the description of the service required in the current context of the person. To evaluate the approach, a simple rule was studied using recall and precision to measure to which extent the context is well identified through the matched services. The results obtained were moderate.

Authors in Riboni and Bettini (2011) introduced a hybrid ontology and statistic context-aware activity recognition system adopting the Android platform. Activities such as walking, brushing teeth, writing on a blackboard and hiking were considered. The data was collected via a phone GPS and Accelerometer, and an accelerometer wristband. The activity recognizer relied on an ontological reasoning which is combined with statistical classification to recognise activities that are not identifiable by the classifier only. The experiments showed an activity recognition accuracy of the 93.44%.

2.4 Human-Computer Interaction

Interfaces of an SH must be designed in a way that empowers the users (also known as stakeholders) to interact effectively and effortlessly with the SH system. In the case of SHs for healthcare, we can distinguish four groups of main users:

- *Residents* (e.g., dementia patients, disabled people, elderly people, etc.)
- *Informal caregivers* (e.g., family members of older adults)
- *Social caregivers* (e.g., the care homes professionals)
- *Formal caregivers* (e.g., geriatric physician, nurses)

Table 2.2: Excerpt of SHs research studies

Reference	Dataset Type	Algorithm	Target	Evaluation metrics	Results
(Mozer, 1998)	private	ANN (MLP)	ADL(General)	Not mentioned	-
(Cook et al., 2003)	private	ANN (MLP)	ADL(General)	Accuracy	Activity recognition: 64%
(Rivera-Illingworth et al., 2005)	private	ANN (EcoS)	ADL(healthcare)	Accuracy	Anomaly detection: 74.57%, Activity recognition: 89.14%
(Li et al., 2008)	private	ANN (OPNN)	ADL(healthcare)	Accuracy	Activity recognition: 92%
(Lotfi et al., 2012)	private	ANN (ESN)	ADL(healthcare)	Accuracy	Abnormally detection: 93%-99%
(Isoda et al., 2004)	private	DT (C4.5)	ADL(General)	Accuracy	Activity recognition: 90 %-100%
(Ravi et al., 2005)	private	DT (C4.5)	ADL(General)	Accuracy	Activity recognition: 57 %-97.29%
(Manley and Deogun, 2007)	private	DT (ID3)	Resident's Location	Mean error of location prediction in Meters	The Mean error: 4.9 meters on the first dataset and 2.5 meters on the second dataset.
(Hagras et al., 2004)	private	ISL (Fuzzy)	ADL(General)	Number of the generated rules by the algorithm	280 rules in 72 hours.
(Hagras et al., 2007)	private	Fuzzy type-2	ADL(General)	RMSE	0.229
(Bouchachia, 2011)	private	GFMMNN (Fuzzy+ANN)	ADL(General)	Current error (Missed / No Presentations)	Adapted: 0.01 for 220 online presentations
(Andreu and Angelov, 2013)	private	Evolving fuzzy classifiers	ADL(General)	F-measure	60% - 70%
(Bouchachia and Vanaret, 2014)	private	GT2FC(Fuzzy)	ADL(General)	Accuracy	For 70% labelled data accuracy is 81.65%
(Chua et al., 2009)	public	HMM	ADL(healthcare)	Accuracy	90.75% behaviour-level recognition accuracy, 98.45% observation-level recognition accuracy
(van Kasteren et al., 2010)	private	HSMM	ADL(General)	F-measure	65.5%
(Gu et al., 2009)	private	EPs	ADL(General)	Time-slice accuracy	85.84%
(Riboni et al., 2011)	public	Ontological approach	ADL(General)	Accuracy	80.3%

Accordingly, the design requirements of the interface must be specific for these user groups. For instance, a formal caregiver is interested in receiving updates on the progress of the resident's disorder by capturing physiological signs such as blood pressure, blood sugar and body temperature. However, such information is not necessarily relevant to the informal caregivers. Moreover, choosing an adequate interaction medium for a stakeholder needs particular considerations. As an instance, people with dementia might not be able to learn how to operate a new equipment; thus, SHs for people with dementia should be capable of operating regardless of the residents' capacity.

A detailed design methodology is required to acknowledge unique requirements and specifications of SHs for healthcare. The design methodology of SH interfaces follows the standards of general user interface design that consist of requirement analysis, design, and evaluation. Sommerville (2004) defined a functional user interface in a way that matches the skills, experience, and expectations of the anticipated users. Four main human factors should be taken account of during the process of designing interfaces:

- Users have limited short-term memory
- Users make mistakes
- Users are different
- Users have different interaction preferences

In many cases, the resident of an SH for healthcare has special design requirements. For example, the limitation of short-term memory is more severe for elderly people. On some occasions, it is difficult for them to learn new interaction methods. Consequently, the interface design process for SHs needs to reflect on additional human factors and use *Natural User Interfaces (NUI)* such as gesture recognition and speech recognition. Multi-modal NUI is a family of interfaces which are invisible to the users and allow them to communicate with the system.

Users of SHs for healthcare (e.g., residents, formal caregivers) have unique requirements, and in some cases, these requirements evolve over time. For instance,

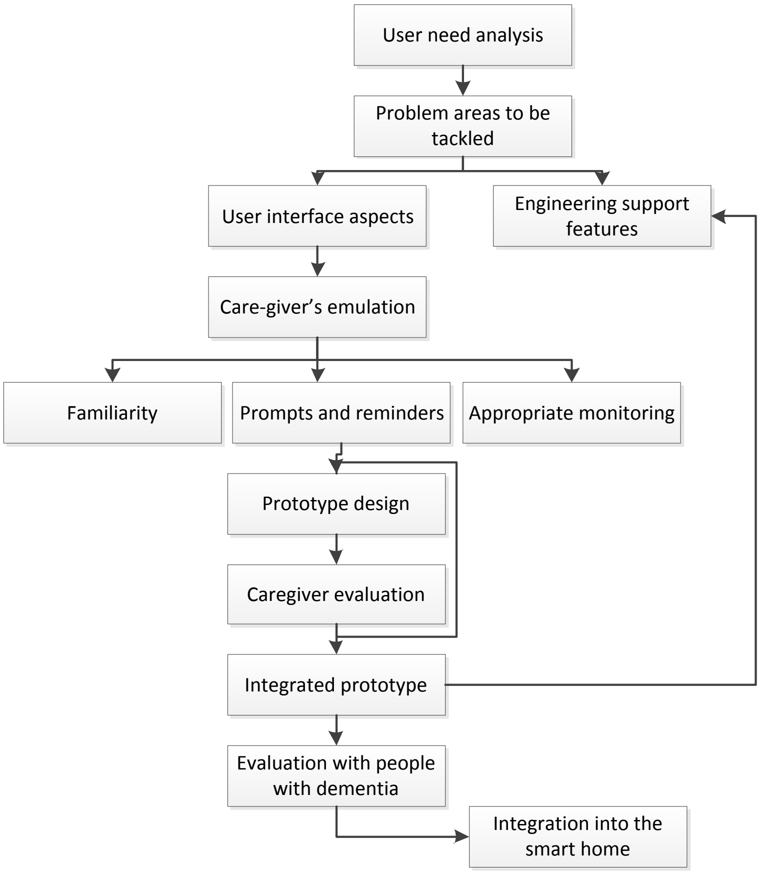


Figure 2.14: Design methodology for developing SH technologies for people with dementia (Orpwood et al., 2005)

an SH monitoring system might need to produce a more comprehensive health report, as the residents' disease progress. As a result, SH interfaces should be designed in a way that empowers the users to customise the system to their needs. The users of an SH for healthcare do not necessarily have the required expertise (i.e., a high level of computer literacy) to customise the system through intricate processes such as scripting. To address this challenge, a common approach is to design SH interfaces based on design concepts such as End-User Development (EUD). EUD is an emerging paradigm that allows non-expert end-users at some point to modify, extend and create software artefacts through a set of methods, techniques and tools (Lieberman et al., 2006).

Orpwood et al. (2005) presented an interface design methodology for people with dementia (Fig. 2.14). The study argued that the interface design will be successful only if it is human-centred and led by users themselves. Considering PwD's memory condition, just caregivers were involved during the evaluation step. Several scenarios were studied to demonstrate the effectiveness of the methodology proposed. Many considerations have resulted from this research, including caregiver emulation, the familiarity of the user with the new interface/device, prompts and reminders, and patient behaviour monitoring.

In another study by Koskela and Väänänen-Vainio-Mattila (2004), were a set of usability experiments to evaluate different interfaces for remote control of SHs. Three types of user interfaces were evaluated: a PC-based interface, a media terminal interface (attached to the TV) and a mobile phone interface. The results stated that a PC-based interface was more appropriate for a central unit to control functions that can be planned and determined in advance (i.e., turn on the kitchen light every day at 8 am). The study showed that the mobile phone interfaces are more suitable for instant control (i.e., switch off the gas hob now). In six months of trial with two people, a young couple, the mobile phone was the primary and most frequently-used interface.

The Sweet-Home project (Portet et al., 2013a) suggested a voice interface for elderly residents. The system was designed for control of windows blinds, lights, kitchen appliances, etc. The evaluation involved 18 participants consisting of eight old persons, seven informal caregivers (relatives) and three formal caregivers (professional caregivers). To assess the effectiveness of the system, a series of qualitative evaluation methods such as Wizard of OZ and interviews were used. Results revealed that old residents prefer voice interfaces over other interaction methods such as typing or touch interfaces.

Ur et al. (2014) investigated the practicality of end-user programming to customise the smart home. They evaluated numerous trigger-action programs shared on the website IFTTT ("If This Then That") and carried usability tests with more than 200 participants. They reported a learning effect in which the participants' performance improved while completing few successive tasks. Moreover, they stated that older participants performed poorer compared with the younger ones. HomeRules (De Russis and Corno, 2015) is a trigger-action interface designed for enabling the users to define rules to customise an SH system. Authors introduced the interface by developing a prototype and evaluating it. As well as developing the interface, they suggested a set of guidelines that could be followed for designing trigger-action interfaces.

Rocker et al. (2005) employed three qualitative research methods to collect the interface requirements based on scenarios, focus group and open discussion. The study resulted in a set of prioritised design guidelines:

- The residents must always remain in charge of the system
- The system must be secure, safe and protect user's privacy
- The system must provide added value over existing ones
- The system should never unnecessarily replace direct interaction between people
- The home comfort should always be a priority and not be subversive to the system

Mennicken et al. (2014) proposed a web-based interface for SHs, called Casalendar. Casalendar which visualises SH data in the form of a calendar [time, event/-task], was evaluated by 6 participants. Results illustrated that the participants were thoroughly in favour the calendar-like (temporal) interface. Huang et al. (2013) proposed a "smart space" that consist of interactive objects, e.g., glass, table, digital photo frame, or MP3 player can be interactive. For instance, an interactive table could perceive users' actions on a glass and triggers events like changing the music. The "smart space" was evaluated by some participants who provided positive feedbacks.

More interestingly, Rivero-Espinosaa et al. (2013) reported on a prototype for elderly monitoring SH. The prototype is based on service-oriented architecture (SOA) that addresses data distribution and scalability of SHs for healthcare. The prototype is equipped with web-interface that was evaluated by a certain number of people who rated it 7.8/10. The interface displays the sensor readings such as room temperature, fire sensors status and blood pressure. Also, it provided the user's ability to configure the SH based on the residents' preferences.

Monk (2008) introduced a set of requirements for SH user interfaces and relevant technologies. In particular, it is stated that a user interface for domestic home applications should be simple, social, ethical and beautiful. The simplicity in design was studied in relation to people with dementia on how to make such people not forget which knob controls which stove. For the social requirement, the author measured the enjoyment made by using services through a set of qualitative experiments. The ethical criterion in design was analysed in the telecare context. Privacy was discussed from the perspective of agreement of the people through formal consent and responsibility of telecare services. The "beauty" criterion was studied on two pieces of necklaces with monitoring sensors that could transmit signals to each other remotely. Unfortunately in this study no evaluation was done.

2.5 Discussion

Up until here, this chapter covered various technologies that are used to build SH systems for healthcare. It summarised sensing technologies, communication platforms, data processing techniques and user interfaces with some research studies that adopted them. The aim was to provide sufficient information to draw a broad picture of the state of the art technologies without intending to be exhaustive. Before, showing how such technologies are used to develop prototype SHs for dementia care, in the following, we will discuss the challenges of design and implementation of SHs in general and in healthcare in particular. It will address the challenges from three aspects of *Quality Attributes, Requirements Elicitation, System Architecture and Data Processing*.

2.5.1 Quality Attributes

Many research studies (Amiribesheli et al., 2016; Courtney, 2008) pointed out that qualitative attributes such as privacy, security, obtrusiveness, and reliability of the SHs are key concerns of their users. Regardless of SHs functions, stakeholders will not accept systems that do not retain these attributes. For instance, to investigate the importance of privacy, Demiris and Rantz (2004) ran a qualitative study with 14 older adults living in a retirement home confirming that the primary concern is the privacy, especially the use of video cameras at the home.

On the other hand, wireless technologies raise more security issues compared to wired ones. Data collected from SHs is highly sensitive, therefore, privacy measures have to be taken to meet the legal and ethical standards. Chan and Perrig (2003) identified six major issues: sensor compromise, eavesdropping, privacy of data, denial of service attacks, malicious use of the sensor network. Also, they address the limitations and advantages of the existed solutions for these issues. Kotz et al. (2009) compared different existing privacy frameworks and proposed a set of privacy policies for mobile healthcare applications and SH systems. Some of these policies are:

- People should be informed on the matters related to collection and storage of data.
- People should always be enabled to access their own data.
- Easy-to-use interfaces should be provided.
- The collection and storage of data should be restricted only for the purpose of monitoring.
- The quality of data in terms of completeness, authenticity and accuracy should be ensured.
- People's identity and personal data should be protected against unauthorised access.

In many cases, residents of the SHs for healthcare are vulnerable people with limited cognitive abilities (e.g., PwD). To support these users, some studies offer frameworks and guidelines to protect their ethical rights and needs (e.g., data protection, transparency (Amiribesheli et al., 2016)). Zwijsen et al. (2011) provide an overview of the literature on the most relevant ethical concerns in the field of SHs for PwDs. The overview states that the most common concerns of existing research studies are on areas of residents' autonomy and the system obtrusiveness.

Preserving reliability and safety is an important matter in SHs. The well-being of the occupant can be affected by the SH system itself if safety requirements are not considered during the design and development of the SH system. For instance, if a (vulnerable) occupant increases the heater temperature inadvertently to an unacceptable level, the consequence for him can be severe. To prevent critical problems, SH systems should be equipped with safety measures, especially in the case of vulnerable people (Dewsbury et al., 2001). Moreover, to develop stable SH systems, designers should use reliable components (software, hardware, communication protocols, etc.).

Wireless technologies have made developing cheap and affordable healthcare SHs possible. However, problems such as battery life and remote connectivity can reduce the reliability of SHs that use wireless as their core communication platform. Focusing on wireless healthcare SH systems in rural China, Fong and Pecht (2010) identified and reviewed the factors that can impact on the reliability of wireless SH system as physical obstacles, atmospheric absorption, inadequate fade margin, and general system failures.

A challenging aspect of SH security is that conventional security methods and components (i.e., authentication) are often complicated for stakeholders in a dialogue of care such as patients, formal, informal and social caregivers. For instance, it is rather difficult for an elderly person with the mild cognitive disorder to remember a complex password. On the other hand, most of SH data is quite sensitive and private and requires an adequate security arrangement. Many research studies attempted to address these issues by employing novel security measures such as biometric and graphical passwords.

In Flores Zuniga et al. (2010), the benefits and drawbacks of biometric technologies for authentication in healthcare environment have been presented. The outcomes suggested that the main advantages of biometric technologies are the reliability of user authentication mechanisms, restriction in the delegation of access rights as well as discouraging fraudulent access or impersonation of users. Moreover, the biometric authentication technologies facilitate the remote access to electronic health records for both patients and other stakeholders, reduce maintenance cost and provide a secure encryption of personal data. They also presented some limitations of biometric technologies such as the ability of a user can be influenced by age, skin colour, damage or lack of a biometric feature. Furthermore, biometric technologies could not be suitable for particular health settings.

Another feasible solution for authentication challenges in healthcare SH is to use video-based systems. Catuogno and Galdi (2014) presented a prototype "mean of video event recognition protocol" for authentication. Evaluation of the prototype with an initial test of usability illustrated that the authentication mechanism was well accepted by users and achieved a considerably low error rates.

Hupperich et al. (2012) proposed a security architecture for healthcare systems. The key concern that the authors attempted to address was the necessity of having an architecture that is secure while flexible. The approach relies on a modern cryptographic scheme that is not entirely based on smart cards allowing the patient to authorise other stakeholders remotely (e.g., by phone) to access their healthcare data securely.

Castiglione et al. (2013) proposed an entirely distributed peer to peer model that allows secure sharing of medical information for healthcare systems. The model enables each client-server nodes to securely and swiftly access a substantial amount of data. Thus, the model increases the clinical assessment speed. To evaluate, a group of physicians were asked to use the system that had simulated data. Later, they provided answers to the question regarding the system effectiveness compared with the conventional methods. The results illustrated a remarkable improvement in the users' experiences.

2.5.2 Requirements Elicitation

SHs for healthcare have a variety different users with unique requirements. Residents might have cognitive limitations that cause them not to be able to express their needs from the system accurately. To address this problem, a series of new requirements engineering methods should be utilised that guarantee the system is designed considering the vulnerable users' requirements (e.g., participatory design). Commonly, these methods involve alternative stakeholders (e.g., caregivers) as proxies for the vulnerable users.

COGKNOW (Meiland et al., 2007) was a cognitive prostatic device designed to support PwDs who live in an SH. To successfully elicit the requirement of PwDs, authors relied on a participatory design method in which PwDs and their caregivers were involved in a series of workshops and interviews. The results of their study showed the most vital needs identified by participants are a) activity reminders e.g. for eating meals; b) item locators; c) picture dialling to keep in contact with family and friends; c) support for pleasure activities; d) enhancement of feelings of safety.

In another study (Hwang et al., 2012), informal caregivers were involved in the requirement analysis and design of SH user interfaces as they are likely to become primary users in the future. They adopted participatory design approach for an intelligent coach system that assists with activities of daily living in the SH. The result of the study was a prototype user interface that could reduce the difficulties of dementia care.

2.5.3 System Architecture

A significant number of SH for healthcare are designed based on *server-centric* architecture (Alam et al., 2012). In such architecture, a server processes the sensor data, makes decisions and prepares the information to be presented by client interfaces. There are potential problems with adopting the server-centric approach for SHs, such as the poor fault tolerance of the system, and heavy computational load on the server. Therefore, SHs need to be designed using distributed approaches such as the Mobile Agents or the Web-services (Wu et al., 2004).

The residents of an SH for healthcare have diverse requirements. For instance, a resident might have Chronic Obstructive Pulmonary Disease (COPD) and dementia. Another resident might have dementia and Parkinson's diseases. Hence, the architecture of the SH system for healthcare should be modular to enable addition or removal of system components without making significant changes to the current configuration of the system. A very prominent modular methodology that satisfies these needs is the Service-Oriented Architecture (SOA). A system based on SOA usually consists of a set of application components. Each component offers a service that can be consumed by other components typically over a computer network. The Open Services Gateway Initiative (OSGi) is a common method to implement SOA.

There exist studies applying modular and agent-based architecture designs to improve the quality of system. In the study (Fook et al., 2006), an SOA-based architecture for a healthcare monitoring system in smart hospitals is suggested aiming at supporting applications that employ a variety of sensors and actuators. The architecture proposed a loosely-coupled system including universal plug and play, and semantic web. Lin et al. (2008) propose an SOA based SH architecture that applies OSGi in a way that the components can communicate with other primary non-OSGi platforms through different types of networks.

2.5.4 Activity recognition

Data-driven algorithms have been predominantly applied in the context of activity recognition for SHs in healthcare (Cook et al., 2013; Sarkar et al., 2010; van Kasteren et al., 2010). That said, in contrast to their proven capabilities, knowledge-driven techniques seem not to be very popular. Only a few authors have attempted to use logic and ontologies (Riboni et al., 2011) for SHs. Some studies mixed probabilistic models with knowledge-based techniques as In (Hong and Nugent, 2011, 2013) where the evidential theory and ontologies are combined to handle uncertainty attached to activity recognition.

The challenges and open questions in the area of activity recognition.

- *Recognising interweaved and concurrent activities:* This is a challenging and active area of research. As an example, a study (Gu et al., 2009) adopted an EP-based approach to recognise these types of activities in addition to sequential ones. Some authors advised that CRF and HMM can be the most efficient approaches to model these types of activities (Benmansour et al., 2016; Kim et al., 2010).

- *Imbalanced data:* The amount of data recorded for each activity in datasets by the sensors is often imbalanced van Kasteren et al. (2008). For instance, in an SH the activity of ‘going to bed’ can be more frequent than other activities which can cause inaccuracy for the micro-context detection.

- *Multi-resident activities:* Most of the work on smart homes has been concerned with single-occupancy. However, in general, a home is occupied by more than one person. In the simplest situation, a person lives alone but could have a pet and receive visitors such as family members, caregivers, friends, neighbours, etc. In the presence of more than one occupant, many of the daily activities can be performed in parallel or together. The modelling and recognition of such activities require a different approach from the ones used for single-occupancy activities. A few studies have recently focused on multi-occupancy (Benmansour et al., 2016; Gu et al., 2009; Prossegger and Bouchachia, 2014), but the area is still to grow as it comes with is own scientific challenges and application potential.

- *Online activity learning:* In comparison to offline activity recognition, online activity recognition has not been much investigated by the researchers. In fact, most of the methods used by the researchers in the field are based on offline supervised learning. An interesting comparison study of online and offline inference using fuzzy rule based systems is presented in Bouchachia and Vanaret (2014) showing that online learning performs equally well as offline learning. in van Kasteren et al. (2008) also a comparison between offline and online settings using HMM and CRF has been presented. However, the online setting considered is not the usual setting used in online learning where only part of the data, ideally only the new sample(s) is used. The authors pointed out that the offline inference performed better for both models. Because of the relevance of online learning in this context of activity monitoring, it is important that more effort should be devoted to it.

- *Applicability and adaptability of the activity model:* Existing activity recognition systems were trained either on private datasets or publicly available datasets. The fundamental problem with these systems is that they require real-world data. Often such systems are trained on particular data stemming from a particular setting and therefore the activity recognition models are tightly tailored to the characteristics of the living space from which data has been collected, to a particular user's habits, and to the types of activities monitored at home. As a consequence, an activity recognition system trained in an environment would not be applicable to other environments. To overcome this problem, the authors in Sarkar et al. (2010) suggested the use of an alternative source of activity data, such as web data, to train the activity model. However, this solution does not reflect on the real-world situations.

- *Scalability of the activity model:* Scalability of the activity model is an important issue and can be discussed regarding:

  a- `New activities`: Considering scalability of activity models presented in section 2.3, some of them present the advantage of having a separate model for each activity. As in (Gu et al., 2009) the authors extracted a set of EPs for each activity. In the same context, the authors of the study (Hong and Nugent, 2011, 2013) constructed an evidential ontology network for each activity. Hence, adding a new activity in the environment only implies constructing the corresponding model for the later. Also, it would be easier to achieve high recognition rate with a separate model for individual activities rather than with a global model for all activities.

  b- `New residents`: Naively, all the methods discussed in the chapter have focused on scenarios with a single occupant. Dealing with scalability in SHs should consider not only new activities but also new occupants. Obviously, the scalability of the models on the number of residents is a vital issue. Thus, models capabilities should be evaluated with more than one residents. However, this important matter is often ignored by the SH studies focused on the activity recognition.

Chapter 3

Designing a Tailored SH Prototype for Dementia Care

3.1 Introduction

A crucial goal of the Requirements Engineering (RE) process for the SHs is to specify PwDs' needs. A compelling way to elicit users' requirements is to employ a User Centred Design (UCD) approach which involves users of the system in the specification of their requirements (John and Salvucci, 2005). However, given the peculiarities of dementia (e.g., memory restraints and mobility difficulties), it is considerably challenging to involve PwDs in the requirements elicitation steps. Moreover, the information collected from PwDs might not be accurate (Amiribesheli and Bouchachia, 2016; Orpwood et al., 2005). On the contrary, informal and formal caregivers are usually well-informed about PwDs' needs and preferences. Therefore, the requirements elicitation and evaluation could only be driven by the caregivers. Having said that, caregivers are not aware of all the PwD's needs and often their experience and expertise are restricted to supporting a particular group or type of PwDs (e.g., people with mild cognitive impairments, vascular dementia). Hence, caregivers cannot be the sole source of insight into the dementia care requirements. Also, when it comes to designing an SH for PwDs, there is no *'one size fits all'* solution. Nevertheless, a holistic approach to the SH functions should be recognised that includes common needs of all the members of a dementia care circle. During the requirement elicitation process, we need to consider that the SH environment should be more than a mere combination of tools to assist PwDs. It should maximise PwDs' *independence, autonomy and well-being* and ultimately secure their psychosocial, as well as, their physical needs (Black et al., 2012).

Despite the clear importance of adequate RE process for SHs and its challenges, the existing literature does not emphasise enough the problem of requirements elicitation and evaluation (Amiribesheli et al., 2015; Amiribesheli and Bouchachia, 2016; Shinohara and Wobbrock, 2011). Existing studies have mainly focused on certain care scenarios instead of covering the analysis of all stakeholders. Most of such scenarios selected scenarios are designed for particular lab environments and user settings (Intille and Larson, 2005). In contrast to most of the existing SH systems proposed for dementia care, in this chapter, a tailored SH architecture is presented that is designed based on a UCD methodology and intends to address all of the stakeholders' needs.

In an effort to overcome the challenges of the requirements elicitation, Lindsay et al. (2012) applied a participatory design method to create a digital aid tool for safe walking. In (Wherton and Monk, 2008), PwDs and their caregivers were involved in requirements definition of AAL. It was found that PwDs need support for dressing, taking medicine, maintaining personal hygiene, preparing food and socialising. van Kasteren et al. (2011) investigated the effectiveness of SHs for *age-in-place* using interviews and observation. In that study, an SH prototype was developed and used to analyse a group of old people. The prototype was equipped with various functions such as movement monitoring, fire detection, wandering detection and fall detection. It was found that PwDs appreciate safety and security, especially fall detection. Mihailidis et al. (2008) studied the application of SHs for the purpose of assisting people with moderate dementia in the accomplishment of their daily living activities. Authors evaluated an audio-visual system dedicated to the task of hand-washing in a bathroom. Also, the system uses video processing techniques to perceive how the washing activity is done. The system can remind the person or call the caregiver if the person does not follow wash instructions.

Kaye (2008) suggested that monitoring dementia progress via *sensor data* reveals new information which can be adopted to develop more efficient prevention treatments. To establish the point, the author compared data collected by the sensors and conventional assessment approaches and concluded that sensor data illustrates meaningful change over time. Morris et al. (2005) reviewed health technology advances in monitoring, compensation, and prevention. Results related to ethnography and feedback suggested that adoption of health technologies will increase if monitoring is woven into preventive and compensatory health applications.

Numerous studies highlight the fact that any trivial mistakes in the design and developing phases of an SH for dementia care could be costly and could prevent stakeholders from adopting SH technologies in real-world settings (Amiribesheli and Bouchachia, 2015). Additionally, lack of prior evaluation could put SH residents' safety at risk (Acampora et al., 2013). Therefore, a series of precise evaluations should be conducted to ensure the effectiveness and harmlessness of the SH.

In this chapter, a methodology is introduced and applied to perform the RE process. The methodology is developed to elicit the stakeholders' requirements and validate them through iterative rounds of user-centred evaluation.

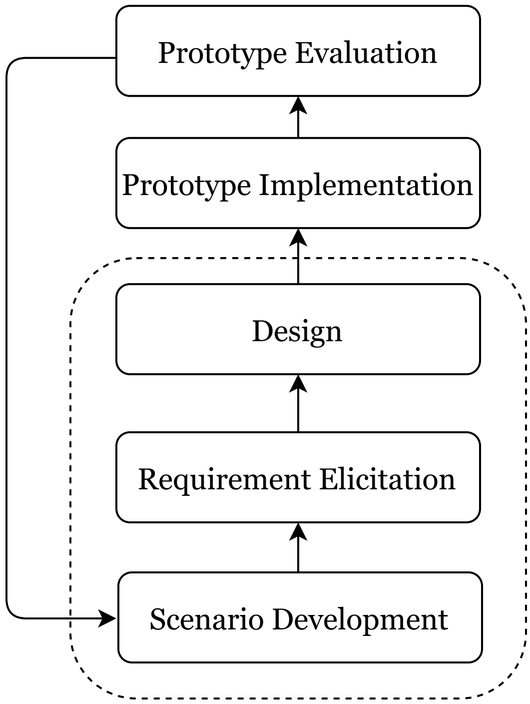


Figure 3.1: Development Steps

3.2 Methodology

Various caregivers (i.e., informal, formal, and social) participate in forming a dementia care circle, each with a particular skill set and responsibilities. For instance, formal caregivers are expected to be familiar with PwDs' medical care needs. However, they do not have the knowledge and expertise of how to support the PwDs to perform ADLs. To ensure all requirements are elicited, all classes of caregivers were involved in this research study. It is worthy to mention that recognising PwDs cognitive limitations, the only viable approach to involve them in the SH design process is to observe their interaction with a fully-developed system installed in a real-world setting. Figure 3.1 presents the methodology adopted throughout this work. In this chapter, the first three phases are presented.

3.2.1 Scenario Development

The first phase consists of developing a set of scenarios that portray most common needs of PwDs. In the following, details of the scenario development process are specified.

A- Gathering Dementia Symptoms

Designing a software system begins by approaching stakeholders to collect their requirements. Then, the system functions will be outlined and implemented addressing the collected requirements. A variety techniques such as free-format brainstorming, focus groups and interviews can be adopted to gather requirements. As stated earlier, these common approaches might not lead to full coverage of PwDs' need in the context of dementia care. Moreover, considering the large number of dementia symptoms, it is quite unlikely for one caregiver or a few caregivers to have experienced all of them. Therefore, comprehensive PwDs' needs cannot be captured just relying on the caregivers' feedback. A way to cope with this challenge is to study and collect dementia symptoms from the existing body of literature. Thus, the scenario development stage begins by collecting PwDs' symptoms. As an instance, PwDs with MCI might frequently ask about the date time and their location. The caregiver should provide them with that information in a friendly manner. Moreover, ideally, the caregivers could record the numbers of incidents and symptoms manifestations to calculate a health index for the PwD. These symptoms are then presented in scenario format that can be efficiently evaluated by the stakeholders.

In the first step of scenario development, we were compelled to *identify stakeholders* for each scenario. It includes a list of people who benefit from the SH functions, or their expertise and knowledge were needed during the system development.

- PwDs: The principle users of the SH system. Dementia is an umbrella term including different types and stages. To make the development process more efficient, in this study, the prototype SH was designed for PwDs who have dementia stage 4 (i.e., Mild Dementia) or less (See Section 1.1). People with more severe dementia are unlikely to be able to maintain an independent life with the help of the SH. The common requirements suggested by the study are valid for all stages of dementia. However, people with more severe dementia have additional care needs that are not covered here.

- Informal caregivers: Family or acquaintances of PwDs with no or very little healthcare education. Ultimately, the SH should provide them with monitoring information that increases their peace of mind.

- Social caregivers: Non-medical caregivers who support PwDs in their homes or care homes. Mainly, the SH system should provide them with customised care guidelines and inform them of the emergency changes in the PwDs' health or well-being conditions.

- Formal caregivers: Medical caregivers who support PwDs such as dementia nurses, and geriatric physiologists. The system provides them with healthcare monitoring information. Furthermore, They should be able to customise the system reactions to the PwD's needs.

- Geriatric psychologists: The system should provide the psychologists with information (e.g., PwDs activity level) that portrait PwDs' state of well-being. Additionally, their expertise could be applied in the design process to choose appropriate intervention mechanisms for SHs when they interact with PwDs (See Sec 3.2.1).

There exist groups of other stakeholders (e.g., care home managers, insurance experts, dementia researchers) who were not included in this work.

By looking at the existing literature (Herrmann and Gauthier, 2008; Sörensen et al., 2006), a majority of PwDs experience the following symptoms that need support from the caregivers:

1. PwDs often repeat statements, questions or a word. The repetitive speech is a prevalent symptom of dementia, and increase in its occurrence has a direct correlation with dementia stage.

2. PwDs can easily be dehydrated as they forget to drink a sufficient amount of water. The signs of dehydration for PwDs are persistent fatigue and inactivity, thirst, muscle cramps, general weakness, notably decreased urination, headaches, dizziness, confusion, rapid deep breathing, increased heart rate, and severe sudden memory loss.

3. PwDs often suffer from isolation and loneliness which are common threats to PwDs' health and well-being. They can cause depression which can be identified by PwD's increased inactivity.

4. Elderly people misplace or loose personal items inside their home. However, in PwDs' case, it occurs much more often. This can cause an increase anxiety for PwDs and their caregivers. Also, the increase in occurrences has a direct correlation with dementia stage.

5. It is difficult for elderly people to learn how to use previously unseen devices. For PwDs, the learning process is even more complicated. The problem causes the increase in PwD's anxiety and losing the sense of control.

6. PwDs face pacing and night-time wandering incidents. Pacing incidents commonly occur when PwDs need to go to the toilet or drink water during the

night-time. It occurs because of PwDs orientation problems. The pacing incident causes them to wake up during the sleeping hours and aimlessly walk through the house. Night-time wandering incidents occur during late-stage dementia. They can be seen as advanced pacing as PwDs are very unlikely to return to bed without a caregiver's intervention.

7. Caused by developing memory difficulties, PwDs tend to be extremely forgetful. The number forgetting incidents increases with the progress of dementia. Common manifestations of this chronic symptom are PwDs' inability to remember the date, time, season, and names.

8. The vision difficulty is a common symptom of dementia, which can significantly increase the numbers of accidents (e.g., falling). It occurs in two forms of "misperception" and "misidentification" of objects, and it occurs mostly during the dark hours of a day. Proper in-home lighting can decrease the occurrence of this symptom.

B- Development of Initial Scenarios

Scenarios are defined as tangible descriptions of activities that stakeholders engage in when performing specific tasks. Such descriptions are sufficiently detailed so that the design implications can be clearly understood (Van Helvert and Fowler, 2003). A scenario is a design-specific tool, as it shows how a task would be performed if a particular approach is adopted. The scenario not only helps the designers to clearly understand the dynamics of a system function, discussing them also helps stakeholders to express creative ways of solving a specific issue. Scenarios are considered as UCD tools to collect information about possible interactions between the users and the system. In this study, scenarios are defined as what a stakeholder would have to do and what he or she would see step-by-step while interacting with

Table 3.1: Sample initial Scenarios

Learning Difficulty: **Virginia** is an elderly person with the Mild Cognitive Impairment (MCI) living in a flat with her family. She finds it difficult to use newly added house appliances. For instance, she has problems interacting with the microwave in the kitchen. She can use the microwave easier if audio instructions are given to her. It is particularly useful if the audio is recorded using an informal caregiver's voice.
Night-time wandering incidents: **Ruth** is an elderly person with MCI. She lives in a flat with her son. Some nights she encounters night-time wandering incidents in which she wakes up during the night and walks in or outside the flat. Surely, without an instant reaction from an alert caregiver, her night-time wandering incidents could be a grave threat to her health and safety.

the SH. They are used as it is easier for the stakeholders to comprehend, discuss and criticise SHs functions when they are told as real-world interactions. Their narratives are written as short stories portraying situations made by dementia symptoms through different personas. The personification enhances the process of evaluation by making the scenarios simpler to be addressed by the caregivers during the initial interviews. For instance, Table 3.1 presents two initial scenarios prepared for the learning difficulty and night-time wandering incidents.

Initial scenarios were carefully evaluated by 4 social caregivers and 2 dementia psychologists. The evaluation process included an open-ended interview session for each interviewee. The interview started by asking the caregivers to read the scenarios and see them being acted in a doll house. During the acting process, they were asked to modify the scenarios details based on their individual experiences. As a result of the interviews, the scenarios were enriched with details, and in a few cases, new scenarios were developed. For instance, the "personal grooming" scenario was not on the initial list, and it was later added after receiving a number of suggestions from social caregivers. Ultimately, the preliminary scenarios were validated and transformed into a set of 13 scenarios (See Table 3.2).

C- Intervention Levels:

In dementia care, it is essential for caregivers to allow PwDs to do things for themselves instead of *taking over* their lives. Having the sense of control increases the PwDs' well-being and helps maintain their pride, confidence and self-esteem, rather than making them feel helpless (Rodin, 1986). Looking at the literature, it is clear that an outstanding issue of existing SHs based solutions for dementia care is their inability to simulate the caregivers' intervening approaches to the PwDs' lives. They often developed to perform the activities of daily living instead of the residents. This approach reduces the residents' sense of independence. Thus, it reduces their acceptability (Portet et al., 2013b). In a care circle, the caregivers avoid unnecessary interventions by utilising various levels of intervention depending on particular care circumstances. The SH can support PwDs' independence and guarantee their sense of control by following the concept of intervention levels. In the study, the following five levels of intervention (Seligman, 1975) were adopted: *inviting awareness, suggesting, prompting, urging, and performing*.

- *Inviting Awareness:* In this level, the system does not take actions on behalf of the PwDs. It merely monitors the activities. The data is used to produce reports which serve as basis for inviting awareness about a situation.
- *Suggesting:* In this level, the system does not take actions on behalf of PwDs. It only suggests them to choose a particular action. PwDs are free to consider suggestions or take an alternative decision. The system does not need to monitor PwD's reactions to the suggestion.

- *Prompting:* In this level, the system takes actions on behalf of the PwDs only if they ignore its suggestions. The system reminds the PwD to perform an activity in a particular way. In contrast to “suggesting", PwDs should not ignore the prompts and if the they do, the system will intervene.

- *Urging:* In this level, the system performs an activity on behalf of the PwDs and prompts them to act simultaneously. This level is particularly beneficial for tasks that involve both the PwD and the system actions.

- *Performing:* In this level, the system takes actions on behalf the PwDs without any conditions. Often, this type of intervention happens as a swift reaction to a risky situation.

D- Evaluating the scenarios

In order to provide a more detailed examination of the scenarios that were developed based on the literature, each of the scenarios was presented as a ‘medical case study’ to the caregivers. The caregivers evaluated and enriched them with details and associate adequate intervention levels to them. In this stage, the main goal was to assure the genuineness of the scenarios. As the informal and social caregivers spend considerable amount of time with the PwDs, they were very familiar with the nature of PwDs’ behaviours. Accordingly, they were the primary participants for the evaluation. Occasionally, due to lack of training, the social and informal caregivers could respond in inappropriately to care situations. Thus, they could react to it in an unfit intervention level. Hence, to ensure that the associated intervention level were correct, we asked a geriatric psychologist to confirm them. As it can be seen in Table 3.2 in some cases, scenarios have more than one intervention level associated. This occurs when a care procedure has multiple purposes or it needs a higher level of intervention (e.g., performing) as the PwD is not responding to the

Table 3.2: List of the Use Cases

No	Scenario Name	Intervention Level
1	Repeating speech	Inviting awareness
2	Getting dehydrated	Inviting awareness, Suggesting
3	Communicating with acquaintances	Suggesting, Performing
4	Misplacing personal items	Inviting awareness, Urging
5	Losing personal items	Urging
6	Learning new interactions	Suggesting
7	Remembering time and date	Suggesting
8	Experiencing pacing patterns	Inviting awareness, Suggesting, Prompting
9	Experiencing night-time wandering incidents	Urging, Performing
10	Forgetting names	Suggesting, Prompting
11	Seeing in dark	Performing
12	Performing the personal grooming	Inviting awareness, Suggesting
13	Monitoring vital signs	Urging, Performing

lower levels (e.g., suggestion).

For participants to envision their expectations of an SH and for the developers to illustrate the SH capabilities, the concept of ‘creativity triggers’ (Pommeranz et al., 2012) was adopted in the project. A dollhouse equipped with the PIR sensors was used as a *creativity trigger* during the scenario development process. In the initial evaluation of the scenarios, they were acted in the dollhouse. Simultaneously, the participants were asked to verify or alter them. 13 scenarios (See Table 3.2) were prepared and evaluated at the end of this phase which later used for the requirements elicitation. They provided information regarding "who", "what" and "why" aspects of requirements.

3.2.2 Requirements Elicitation

In this step, we attempted to elicit *functional* and *non-functional* requirements of the users. Following a waterfall methodology, this step was deemed to be the first practical step towards the prototype development. It is necessary to perform this step accurately, as its outcomes will be analysed, modelled and specified to shape the SH prototype. The system efficiency is defined by both its functional and its non-functional characteristics (i.e., quality attributes), such as usability, flexibility, performance, interoperability and reliability. Notwithstanding, in the SH literature, there has been a disproportionate emphasis on the functionality of the system, even though the SH functions is not useful or usable without the necessary non-functional characteristics (Memon et al., 2014).

The functional requirements were determined by reformulating the scenarios as use cases. Each table incorporated necessary software and hardware components for an SH to address the stakeholders needs. The non-functional requirements were acquired from analysing the literature and the participants' concerns raised during the initial interviews. In the following, the method is explained.

A- Functional Requirements

Functional requirements are collected in the form of documents that describe system operations and activities. They were elicited by extracting elements of the scenarios and manifesting them as use cases. The process of analysing the use cases led to the gradual emergence of the necessary software and hardware components of the system. Use cases enabled us to clearly look at each scenario and find the necessary components for its implementation. For instance, Table 3.3, and Table 3.4 present two use cases produced at this stage. The rest of scenarios can be found in Appendix A. Each table incorporates four sections: concept, the rationale of the system behaviour, scenario, and the required components. The concept section includes the justifications on the necessity of having a particular use case. The rationale section includes descriptions of the SH intervention types and levels. The scenario section gives a brief overview of the scenario that the use case is based on. The required component section introduces the essential hardware and software components for implementing the use case.

Some stakeholder's requirements change with the PwD's dementia progress. As an example, a formal caregiver might require a constant update on the number of PwD's repetitive speech incidents to diagnose the disease progress from MCI to AD (See Chapter 1). However, the numbers are not as useful for monitoring a PwD that is already diagnosed with AD. Furthermore, individuals in the care circle have different preferences. This section does not intend to cover these unique and evolving requirements. Here, the most common requirements of dementia care are collected. In Chapter 5, the prototype will be extended with components to empower caregivers to personalise it.

B- Non-functional Requirements

Besides the explicit features and functions that should the SH offer to the stakeholders, there exists another group of requirements that affect the overall operation of the system, rather than its specific behaviours. These requirements are described as *'non-functional requirements'* or *'quality attributes'*. For instance, being reliable is not a feature for SHs, yet, it is a required characteristic. The non-functional requirements emerge from the entire system architecture rather than any specific component. They play a significant role in the system *acceptability* amongst the users. A suitable method for obtaining the non-functional requirements is to investigate the concerns and issues raised by the caregivers.

Table 3.3: Use case 1: Repeating Speech

Title	#1 Repeating Speech
Concept	The repetitive speech is a prevalent symptom of dementia. Its progress has a direct correlation with dementia stage. Its tracking helps show the disease progress.
The rationale of system reactions	The system *invites awareness*. It detects the event by analysing the data collected from sensors (Nemes et al., 2012). The frequency of repetitive speech outlines the disease stage. Particularly it shows the transition from Mild MCI stage to early stage of AD*.
Scenario	**Robert** is an elderly person with MCI. He lives in his home with his family. He repeats his questions and statements inattentively. His GP stated that the progress of dementia could increase the number of speech repetitions. Also, very little can be done by the caregivers to prevent him from repeating his speech.
Required components	• A set of *microphones* to collect the PwD's speech. • A *database* system to save the logs and recordings. • A *reasoning engine* to perform the voice recognition and to prepare reports on the changes. • An *interface* to present the reports.

Note:* Although there are no fixed thresholds for the repetitive speech, it sudden increase is often a sign of the dementia progress.

Table 3.4: Use case 2: Learning new interactions

Title	#6 Learning new interactions
Concept	It is difficult for elderly people to learn how to use previously unseen devices. For PwDs, the process of learning how to manage the devices (e.g., home appliances) is even more complicated. Therefore, the system should guide the users interactively.
The rationale of system reactions	The system *suggests*. It gets activated by analysing the sensors readings. As the PwD begins to use the newly added device, the system prompts him/her the operation instructions through the available interfaces (e.g., radio speaker) (Mihailidis et al., 2008).
Scenario	**Virginia** is an elderly person with mild dementia living in her home with her family. She encounters difficulties to cope with new equipment. For instance, she has problems interacting with the newly added microwave in the kitchen.
Required components	• A set of *PIR motion* and *contact switches* (sensors) to recognise the activity of using the device. • A *database* system to save the logs. • A *reasoning engine* to perform the activity recognition and play the necessary instructions. • An *interface* to be used for playing the instructions.

The system should have a group of quality attributes to adequately address the concerns. For instance, during the interviews, some stakeholders had concerns regarding the possible increase of PwDs' anxiety resulted by simply putting unfamiliar devices (e.g., sensors) in the home environments. To address this concern, the system hardware should be installed in a *seamless* manner. In the following, necessary quality attributes of the SH are provided. The *modularity, reliability, personalisation, seamless integration and transparency* were considered as main non-functional requirements of SHs for dementia care.

Modularity

As well as the common requirements of dementia, individual stakeholders have unique needs, which might change as dementia progresses over time. Furthermore, the stakeholders should be able to choose their preferred care approach and technology (e.g., sensing devices, and alerting systems). Thus, an SH should be modular.

The modularisation concept can be applied to a system in *composition* and *decomposition* ways. In the composition (bottom-up) method, modules are put together to form a larger system. In this approach, all the components are built as separate units and then connected to form the system. An alternative is to take a larger system and decompose it into smaller modules. This approach is described as the decomposition or top-down method. It is applied to analysing and improving an already existing system. For instance, for an existing SH system, the interface can be designed using two separate sub-modules of administration and users' interfaces.

The coupling is the process of inter-module connection. Both modularisation approaches can be used in developing SH system. The Service-Oriented Architecture (SOA) (See Section 2.5.3) is a common development approach for a modular system. The SOA-based SHs can provide services that are platform-independent and reusable. Moreover, an SOA SH is extensible, which implies stakeholders can add or remove services at any given time.

Reliability

The SOA architecture can address the modularity requirements of the SH. However, this architecture often utilises a client-server model. It means all processes run on a computing unit (gateway), that puts all the load on a single machine. This causes the SH system to suffer from a single point of failure, which leads to issues with the SH system, particularly reliability. The SH reliability can be defined as its ability to operate as failure-free as possible. A high-reliability SH can be developed by incorporating a variety of solutions that affect the system continuous operational maintenance. For the SH a key solution is to make it distributable.

The client-server design, the gateway failure causes all the SH services to be unavailable. Client-centric distributed design methods prevent these problems by allowing the processing load to be divided into different hosts. A client-centric SH can be designed adopting a group of multi-node architectural patterns (e.g., peer-to-peer computing, mobile computing, cloud computing, and virtualisation). In a client-centric SH, the process is distributed over individual nodes, and the collected data can be stored on a single or distributed database. Hence, a client-centric SH can run on multiple physical devices simultaneously.

Personalisation

Dementia care stakeholders adopt distinct approaches for attending a care situation. PwDs are individuals with different needs that change over time. Therefore, the system should be personalised by its users. For instance, for the night-time wandering scenario, a geriatric physiologist might ask the system to provide the PwD with instructions to take a sleeping pill to going back to bed; while another geriatric might only request the system to provide the PwD with instructions to return to the bed without taking pills. In Chapter 5, the SH personalisation for dementia care is further discussed.

Seamless Integration

When a new piece of assistive technology is introduced for dementia care, often it is not accepted by users because of design issues rather than the functionality-related ones. A common problem is when unfamiliar devices (e.g., sensors and actuators) in are introduced to the PwD's living environment as they can cause them anxiety. To prevent this from happening, all the in-home physical components of an SH system must be seamlessly integrated into the environment. For instance, the communication between PwD and the SH should occur through natural user interfaces or familiar devices such as radio and TV.

Transparency

It is defined as the clear flow of information amongst stakeholders and the system. An SH is transparent if the users are capable of answering questions such as what are the types of data collected by the SH? Who have the right to access the collected data? Caregivers and PwDs repeatedly raised concerns regarding transparency of the SH system (Lê et al., 2012). Lack of transparency can damage the users trust in the system and decrease its acceptability.

To address the issue, we developed a dedicated framework (Amiribesheli et al., 2016) for transparency in intelligent environments. During the prototype design development, we ensured that SH only collects necessary data from PwDs, and it discloses the data to the relevant stakeholders with the PwDs or their legal guardians' consent.

3.2.3 System Design

It is the process of defining a structure for the system that can satisfy the stakeholder's requirements. To that aim, the design process produces a group of system diagrams that depict the system architecture by describing the components, relations among them, and properties of both components and the relations. In this study, the Unified Modelling Language (UML) is adopted for expressing the diagrams that later will be employed during the system development.

The UML offers two categories of diagrams (Holt, 2004):

- *Static* (or structural) modelling diagrams: they indicate the static structure of the system using objects, attributes, operations and relationships. It includes diagrams such as class component and deployment.
- *Dynamic* (or behavioural) modelling diagrams: they emphasise the dynamic behaviour of the system via illustrating collaborations among its components. This view includes diagrams such as use case, sequence and activity.

For this study, both static and dynamic UML diagrams are employed. First, the SH functions and their primary users are visually represented by the use case diagram. Then, the behaviour of each components is introduced in more details through the sequence diagram. Next, a blueprint of the system components is illustrated through component diagram. Finally, a deployment approach for the SH is depicted using the deployment diagrams.

Use Case Diagram

The use case diagram provides an easily comprehensible view of system functions and their targeted users. Figure 3.2 presents an the SH prototype use case diagram. Apart from the 'monitoring vital signs', 'repeating speech' and 'losing personal items', the other use cases are primarily focused on SH interaction with the PwD, and their functions are extended by an incident monitoring interface to provide information for caregivers. For instance, the principal function of the 'dehydration risk' use case is to make sure that the PwD drinks enough water through reminding them. Additionally, the use case can gather the number of times that the PwD forgets to drink enough water and present it to the formal caregivers as an indication of the disease progress.

The 'general health care monitoring' functions of the system (e.g., Blood sugar monitoring) are mainly used by formal caregivers. The 'forgetting names' use case requires the caregivers to provide and update information of the PwD's acquaintances. The 'losing personal items' and 'repeating speech' use cases are defining monitoring functions that do not interact with PwDs. By contrast, the 'seeing in dark' and 'performing personal grooming' do not provide any monitoring information to the caregivers.

A use case diagram represents the primary actors of the system and the use cases interacting with them. For the diagram, use cases are illustrated as ovals, and actors are drawn as skeletons. The objects can have the following relationships with each other:

- Extending: it means that behaviours of extending use case are added to the behaviours of the 'extended use case'. Both use cases function individually.

- Including: it means that the behaviours of including use case are added to the behaviours of the included use case. The ‘including use case’ is incomplete without the included use case.

- Generalising: it means that one actor (e.g., informal caregiver) can inherit the role of the parent actor (e.g., caregiver).
- Associating: it indicates that the actor and the use case directly interact or communicate with each other.

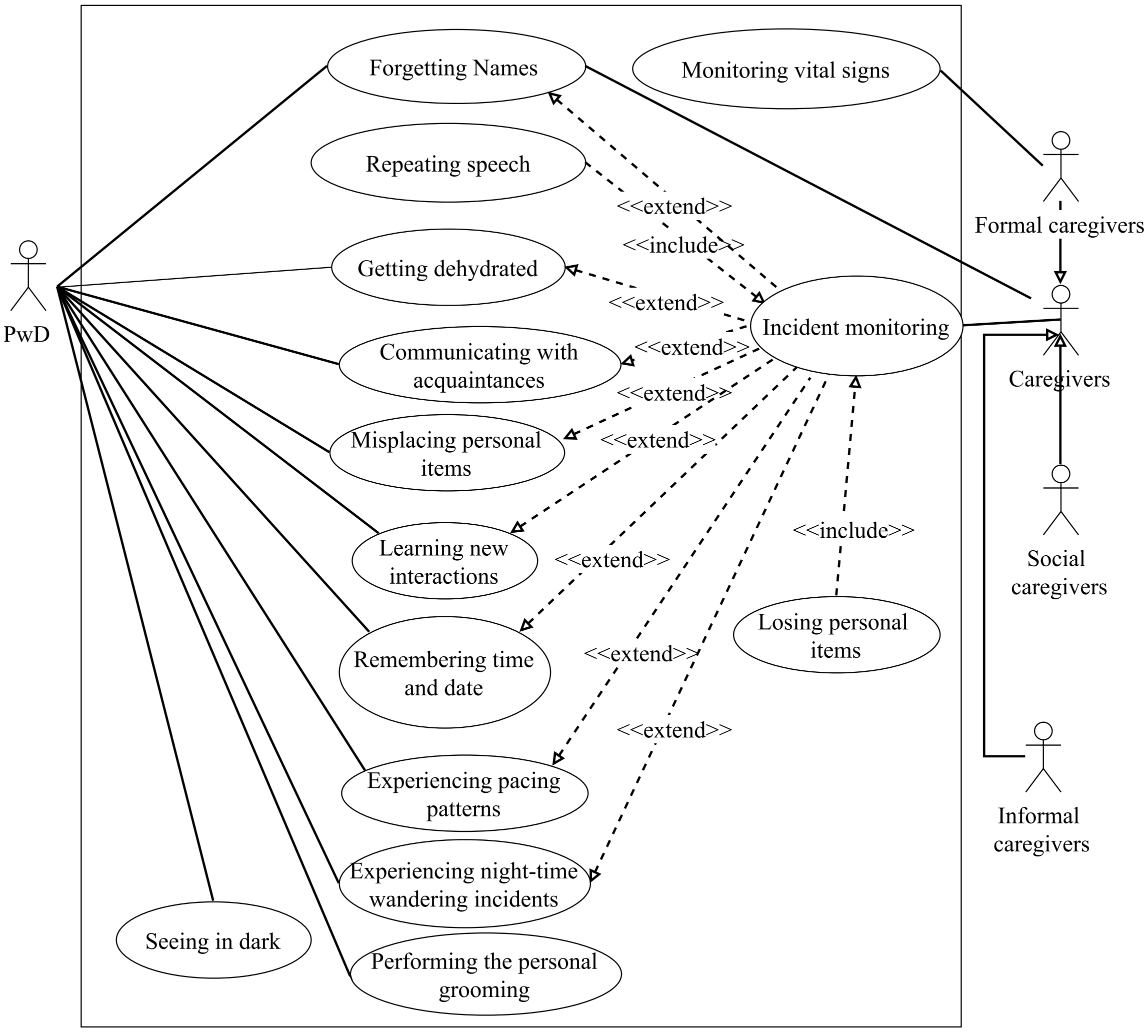


Figure 3.2: SH use case diagram.

Sequence Diagram

The UML sequence diagram is adopted to illustrate the interconnection and the behaviours of system components. It consists of a set of vertical lines (also known as lifelines) and connects them with a group of horizontal arrows that shows the exchanged messages in the order of their occurrences.

To provide a comprehensive picture, the system components are not introduced following a specific programming paradigm (e.g., object-oriented, modular). They are the essential elements that shape system functions and can be implemented as classes or modules. In the requirements elicitation phase, the following components were identified: *a communication protocols, a middleware component, a reasoning engine, managing and monitoring interfaces, a database management system.*

The SH has components in each of the layers mentioned in Fig 2.1. The communication interface and the middle-ware component are in the communication layer. The reasoning engine and database management system are in the data processing layer. The managing and monitoring interface are in the interface layer.

- Communication interface: The SH system requires a number of communication devices and protocols to enable in-home and remote communication amongst the components and users. The communication protocols are in charge of providing and maintaining the link between the system and the outside world.

- Middleware component: The role of the middleware is to bridge physical devices (e.g., sensors) with rest of the system. Also, it should include the necessary abilities for discovering, adding and configuring new hardware devices to the SH. Ideally, the processes should occur without the need for restarting or reconfiguration of the system.

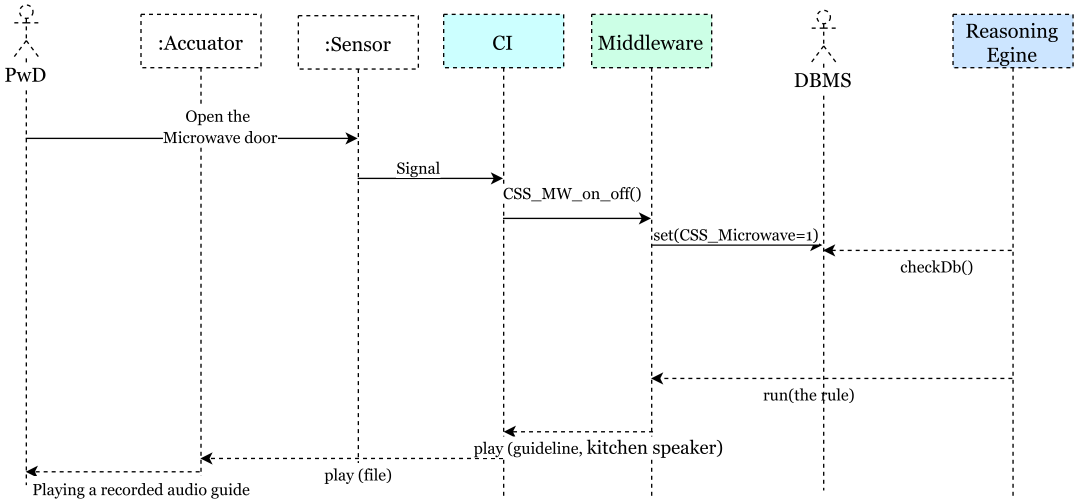


Figure 3.3: *Learning difficulties* sequence diagram.

- Reasoning engine: The role of the reasoning engine is to infer knowledge from the collected data and decides the SH reactions. The reasoning engine enables the SH system to change its behaviours (e.g., reactions) in reaction to the changes in the users' and the environment contexts (See Section 2.5.4).
- Managing and monitoring interfaces: The interfaces enable the stakeholders to change the SH configuration and to monitor the PwDs situation (e.g., incidents monitoring). Considering the users' diversity, it is necessary to develop cross-platform interfaces that are available on a variety of devices (e.g., mobile phone, tablet and PC).
- Database management system: As an SH uses and generates a high volume of data, a set of databases are required to store them. Therefore, the SH needs a database management system.

Figure 3.3 presents the sequence diagram for "learning new interactions" use case. It shows the following actions: (1) Opening the microwave door activates a contact switch sensor. (3) The sensor triggers a signal that communication interface receives. (4) Communication interface sends a message to the middleware using a supported protocols (e.g., a simple text of **CSS_MW_on_off**). (5) The middleware records the event by manipulating the relevant database using the DataBase Management Services (DBMS). (6) The reasoning engine reads the database and triggers the associated rules for the event. For instance, "the rule is to play an audio instruction in the kitchen using the digital radio as an actuator". (7) The communication interface transmits the order to the digital radio located in the kitchen that plays the guides for using the microwave.

Component Diagram and Component Tiers

In the previous step, the SH components and their exchanged messages were formally presented. Here, all the components are presented together in a UML component diagram. The component diagram portrays the system as a whole by exposing the components interconnections. Considering the nature of the design phase, this diagram might be modified and updated during prototype implementation. Figure 3.4 presents the components that are architecturally significant for the deployment of the prototype. Furthermore, it presents the services provided and used by the components within the system. As an instance, the reasoning engine uses the DBMS service to perceive changes in the PwD's situation or the environment. The engine uses the middleware services to react to the changes. Furthermore, if a new device is connected to the SH, the middleware can employ the reasoning engine service updating feature to improve the SH functions accordingly. As shown in the component diagram, the reasoning engine and the middleware are connected using two separate channels. They are connected through DBMS and the REST API. Having said that, there are more advanced approaches such as the publisher/subscriber and the complex event processing. They are not utilised in this thesis to make the overall architecture and consequently the prototype implementation less resource

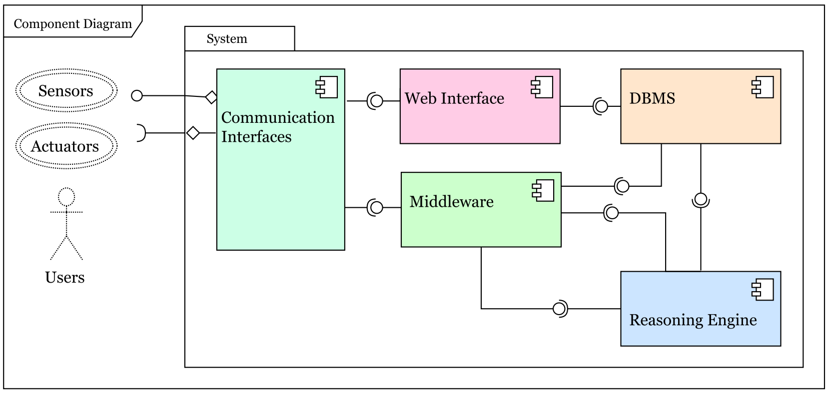


Figure 3.4: SH components

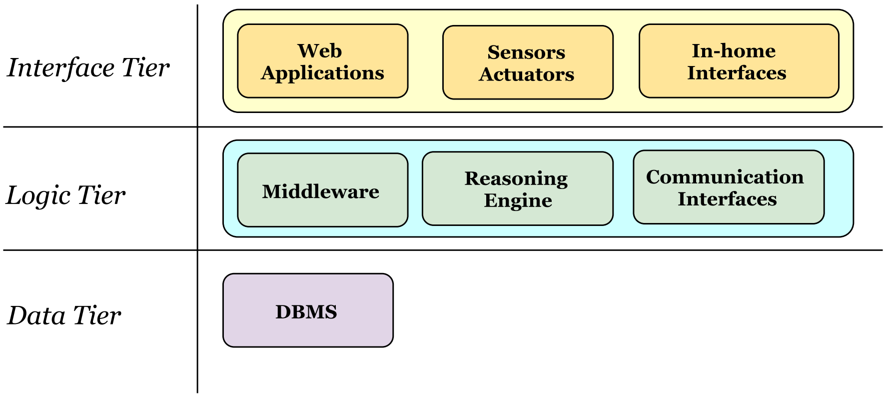


Figure 3.5: Components tiers.

intensive.

The system can be structured in 3 layers:

- Interface tier: it incorporates components that are responsible for collecting data from the environment and the stakeholders, presenting information to the stakeholders, and altering the environment.
- Logic tier: it incorporates components that are responsible for processing and transferring the data and making decisions.
- Data tier: it incorporates components that are responsible for storing and man-

aging the system data.

The classification of the components into various tiers makes it simpler to address them throughout the thesis. Figure 3.5 presents the SH tiers and their components. Ideally, the system should be deployed in a way that the logic and data tiers components can be modified with requiring very little changes for the rest of tiers. In Chapter 4, a prototype is introduced that has this capability.

Deployment Diagram

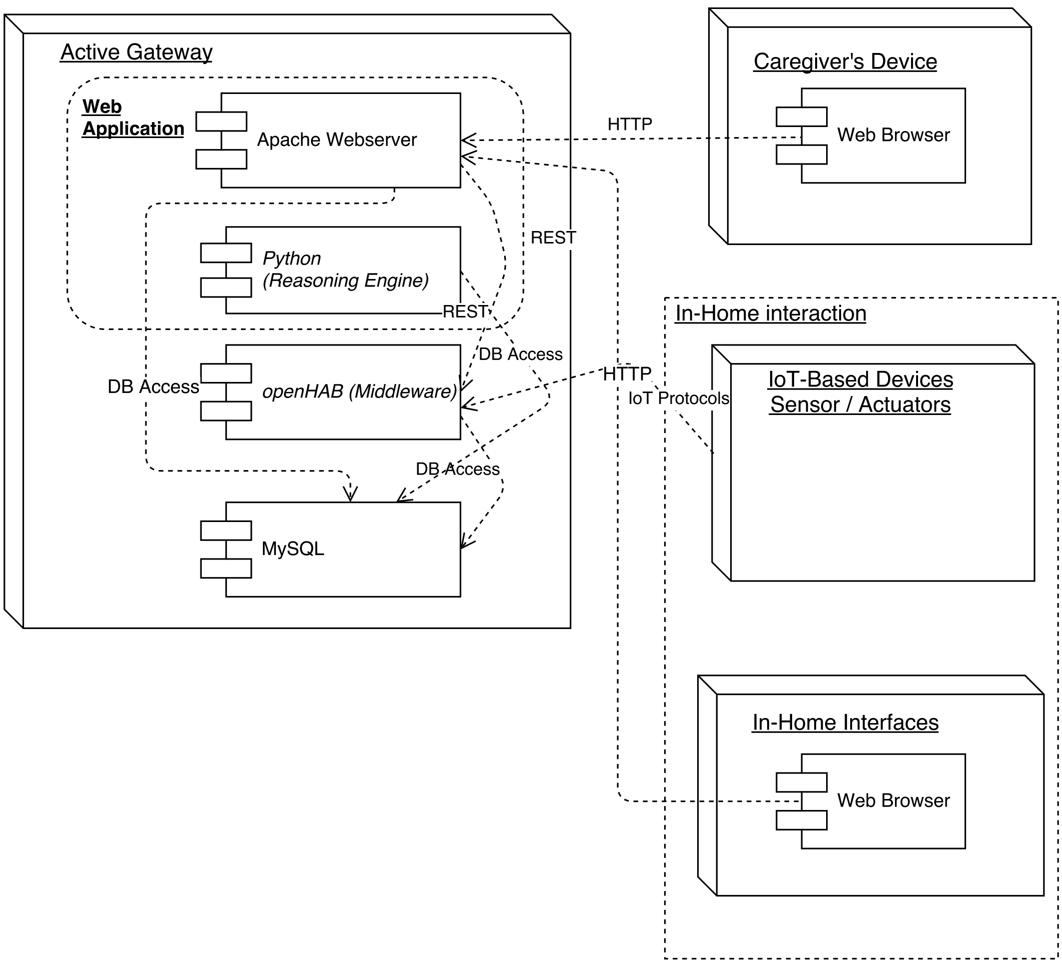


Figure 3.6: The deployment diagram.

Up until here, the SH components and their relationships were presented. Here, details of physical deployment of the prototype are introduced. The UML deployment diagram depicts the run-time architecture of the system. It incorporates system platforms and software modules that run on top of them. In the diagram, the platforms are either hardware devices or software execution environments. Figure 3.6 illustrate the system deployment diagram.

The diagram includes four key platforms:

- Gateways: they are physical devices that host primary interface, logical and data tier components. For providing basic functions, the SH requires at least one functional gateway device. Considering the reliability requirement (See Sec 3.2.2) of the SH, the modules should be able to run on a group of separate gateways as well. It means the system should be deployed in a way that supports several gateways. For the prototype implementation, multiple gateways were used (See section 4.2.2).

- Caregiver devices: to access the SH interfaces, caregivers will use a variety of devices (e.g., PC, mobile). Ideally, the interfaces should be easily accessible across all the commonly used devices. To address that, the SH prototype interfaces are developed as web applications accessible through standard web browsers.

- Sensors and actuators: these platforms include devices that can collect data from residents and the environment, and change the state of the environment. These platforms include a diverse set of physical devices such as binary sensors, vital signs monitoring kits, and switches for controlling in-home power plugs remotely.

- In-home interfaces: these platforms are advanced interactive or non-interactive displays conveying information between the system and the SH residents.

They include devices such as tablets placed on a surface, smart radios and smart TVs. They are equipped with standard web browsers modules.

3.3 Discussion

Initiating the requirements elicitation by directly interviewing the stakeholders was our preferred approach at the beginning of the study. However, from early stages in the process, two fundamental flaws were discovered with this approach. First, PwDs might not be able to express all of their needs in detail. Second, caregivers often have not dealt with all of the dementia symptoms, and considering the vast number of symptoms, they could easily forget to mention some of them during interview sessions.

To overcome these shortcomings, a novel approach using UCD tools was undertaken. All the symptoms were gathered from the literature, and they were transformed into the scenarios. Consequently, a better participation and richer feedback from the caregivers were obtained. Eventually, we had a comprehensive collection of care scenarios that were accepted by all the participants of the design and prototype evaluation sessions.

The standard requirements engineering tools (e.g., use cases) were applied to obtain the SH components. Also, the outcomes of analysing the information collected from the literature and the interviews with caregivers were used to introduce the non-functional requirements of the SH such as transparency, and seamless integration. The non-functional requirement plays a significant role in the acceptability of the SH by its stakeholders. These considerations could not be reflected simply by introducing a group of components, but they affected the whole system. The modularity, reliability, seamless integration, personalisability and transparency were considered as non-functional requirements to be considered during the system design. We believe that ignoring any of these considerations will negatively affect its acceptability.

This chapter also incorporated details of the system design process which resulted in an architecture that satisfies the collected users' requirements. To introduce the system architecture the UML use care, component, sequence, and deployment diagrams were used.

Chapter 4

Developing a tailored SH for common needs of dementia care

4.1 Introduction

Prototyping refers to the process of producing an incomplete version of a system for the purpose of early evaluation. As a standard practice, prototypes only simulate most essential functions of the final system. That way they can be developed *quickly* and with less cost. In the context of the SH, a flawed design process could produce a system that put PwDs' health and safety at risk. Thus, a prototype should be developed and evaluated rigorously before setting up a trial SH in the real-world setting. The prototyping process enables users to experience system functions and comment on them. Moreover, the user interaction with the prototype could reveal new requirements that should be considered in its next versions.

In this chapter, the prototype is introduced based on the presented designs (See Chapter 3). We follow an evolutionary development approach. The approach begins by developing a robust initial prototype and refines it through iterative evaluations. The iteration continues until the prototype is deemed as adequate and safe by the stakeholders.

The majority of SH solutions for dementia care primarily focus on supporting one or a few numbers of PwDs' care needs. On the contrast, the prototype introduced in this chapter incorporates the necessary tools to react to all PwDs' basic care requirements that were elicited during the design phase. In Chapter 5, the prototype will be extended with components to provide personalised responses for PwDs' and the caregivers' unique care and preferences. In the following, the implementation steps of the prototype are introduced and the outcomes are evaluated by the users.

4.2 Hardware Components

Studying, optimising and evaluating hardware components of an SH are not considered in the thesis. However, the prototype capabilities cannot be fully illustrated and evaluated without running them on adequate hardware devices. In our implementation, **two** groups of hardware devices were used: ***1) sensor, actuators and in-home interfaces*** and ***2) gateways***. These are described in the following section.

4.2.1 Sensor, Actuators and In-home Interfaces

Hardware manufacturers are in a constant competition over producing more affordable and more customisable SH technologies (e.g., temperature sensors, vital sign monitoring technologies). Naturally, an SH function can be developed utilising a variety of hardware devices coming from different providers. For instance, to check the PwD's location, employing both passive infrared sensors and cameras could be equally effective. Therefore, the prototype should be developed in a way that can function using different available technologies. This gives the SH users the ability to choose their preferable SH hardware technologies. Ideally, the SH should be an open system where devices join and leave while offering a particular service to the users. Such a design would improve the SH abilities to be personalised and modular which is aligned with the elicited non-functional requirements.

Although the SH system ideally should be developed as an open system, for this implementation, the prototype is set up to utilise only binary sensors and vital sign reading. This approach complies more with PwDs' privacy (Demiris and Rantz, 2004) and transparency requirements. Additionally, it prevents the prototype from being resource-intensive (Lifton et al., 2007)

For generating the necessary data for the prototype, CSS sensors, PIR (motion) sensors, and pressure sensors are used. PIR sensors are used to simulate data that shows the PwDs' presence in different *in-home locations*. CSS sensors are used to simulate data gathered from the room doors and cabinets for identifying the PwD's interaction with these objects. Furthermore, pressure sensors are used to simulate the collected data from sofas, beds, chairs and floors. Also, to generate health monitoring data, we employ an e-health sensor kit that included sensors for vital signs monitoring such as SPO2, airflow, body temperature, and blood pressure.

As mentioned earlier, the SH *in-home interfaces* are a group of interactive and non-interactive devices (e.g., tablets, smart radios and smart TVs) that convey information between SH and the residents (i.e., caregivers and the PwD). For the prototype, a tablet with Android OS is used as a digital frame mounted on the home wall. Also, a digital wireless radio is used to test the SH capability for playing sounds (e.g., guides and instruction).

4.2.2 Gateways

As stated in Chapter 3, the gateway is a device responsible for running logical and data tier software modules. The prototype gateway device should be light, cheap, easily replaceable and fault tolerant. Principally, several single board computers can satisfy these needs. In this work, the Raspberry Pi (model B) is chosen as it is affordable and widely available. It has a 700 MHz processor, 512 MegaBytes of RAM, and communication ports including USB and General-Purpose Input/Output (GPIO).

The power source of a gateway is one of the key challenges that affect its reliability. It is important for gateways to function even during an unexpected event such as electrical disturbance at home. The Raspberry Pi addresses this issue by accepting the following alternative power sources:

- Solar chargers that are available for mobile phones.
- Universal Serial Bus (USB) ports, powered USB banks.
- Alkaline batteries.

In our prototype, a non-graphical version of Linux operating system, an Apache web server, the middleware, a PHP service, a Python compiler, Java virtual machine, and an instance of MySQL DBMS are installed on the gateway. For the fault tolerance, the gateway is configured in a way that the settings and collected data are backed up automatically on another identical machine utilising file transfer protocol. The backup machine (also known as the passive gateway) is always ready to function as the prototype gateway at any given time.

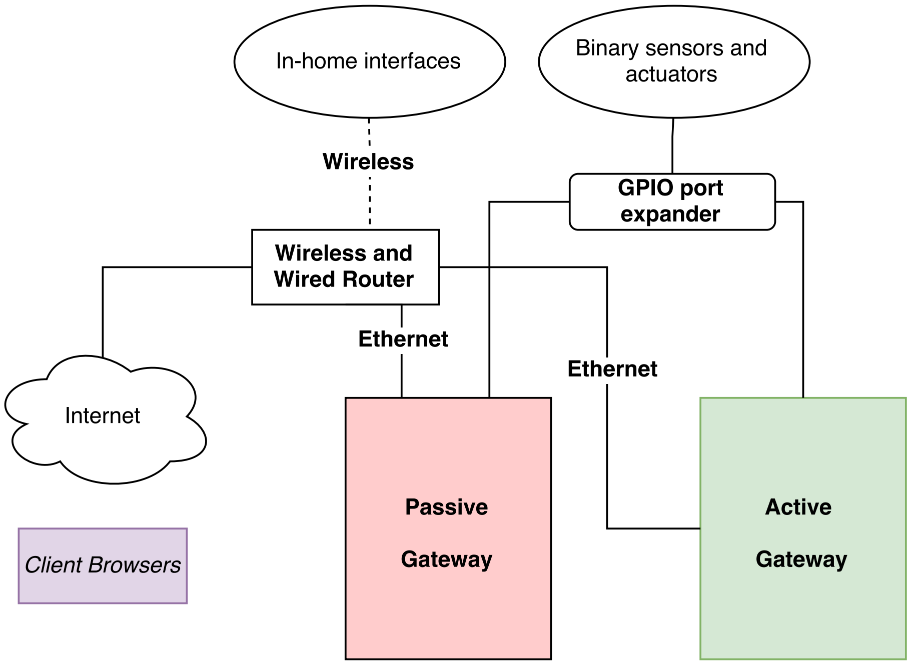


Figure 4.1: Prototype communication interfaces.

4.3 Software Components

The following describe the 4 key software components that are used in the prototype: *Communication Interfaces*, *Middleware*, *Reasoning Engine*, and *Managing and Monitoring Interfaces*.

4.3.1 Communication interfaces

Physical communication ports are required for connecting the interface, logic and data tier components. Figure 4.1 illustrates the prototype communication ports. To use the ports, the components require communication interfaces (i.e., computer networking and proprietary protocol) running on the gateway device.

The Raspberry Pi wired Ethernet networking card is utilised to connect the system to the Internet through a router. To secure the SH inner-communications, the gateway is equipped with a functioning Linux-based firewall (i.e., the uncomplicated firewall package). Furthermore, all the network traffic between the active and passive gateways goes through a secure VPN connection (OpenVPN package).

There exists a variety of sensor networking protocols for in-home communication as sensors and actuators might require a proprietary network protocols. By default, the gateway is equipped with GPIO, Inter-Integrated Circuit (I2C), and Serial Peripheral Interface (SPI) protocols. They enable it to communicate with a broad range of binary sensors and switches (i.e., binary actuators) devices. In our implementation, the gateway is enabled to contact indoor sensors using the GPIO. As the Raspberry Pi has a limited number of GPIO ports, a GPIO port extender is used.

4.3.2 Middleware

The middleware software enables the physical devices (e.g., sensors, actuators) to communicate with rest of the system. It provides a software connectivity layer to make the devices accessible by the other software components. There exist several open source middleware systems for SHs that can be adjusted to meet the necessary requirements of the prototype (Tazari et al., 2012; Wolf et al., 2010). In this work, to save resources, we opted for this solution instead of developing a new middleware from scratch. The open Home Automation Bus (openHAB) (OpenHab, 2016) is an open-source middleware developed based on Java Open Service Gateway initiative (OSGi), which is one of the most common approaches to implement SOA (See Section 3.2.2). As the middleware is based on a Java OSGi framework, it requires a Java virtual machine to run on the gateways. Also, it allows the devices to be added and removed without causing any negative ripple effects on the system functionality.

Figure 4.2 illustrates the openHab modules that are used in the prototype. The

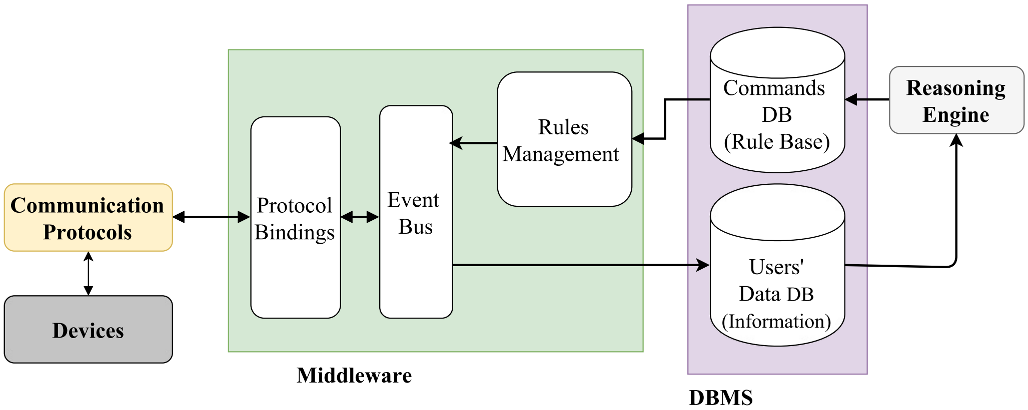


Figure 4.2: Middleware modules.

rules management module shown in the diagram accepts basic if-then statements for device reactions written in the Java Xtent programming language. The event bus module is responsible for the middleware reactions to events. It reacts to two types of events a) changing the state of a device based on the rules. b) updating the database in reaction to status changes in the devices. The binding module connects the event bus to the SH devices through the communication platforms.

Considering the dementia care requirements, the simple rule management module of the middleware is unsuitable for the SH knowledge deduction and decisions making process. For that reason, a dedicated reasoning engine is developed, which will be discussed in the next section. The middleware executes the reasoning engine commands by performing the following steps: 1) the reasoning engine changes a specific entry in the commands database. For instance, it changes the living room light entry value from 0 to 1. 2) the middleware rule management module runs the rules associated to each of the commands entries using the event bus. For instance, if the living room light entry is 1, it turns on the living room light. Furthermore, the sensor data is collected by performing the following steps: 1) a sensor changes state and it sends a signal to the middleware through the communication interfaces. 2) the event bus writes the event and its time stamp to the sensor database.

Figure 4.3: Kitchen sensors configuration page (tablet view)

4.3.3 Reasoning engine

The reasoning engine deduces knowledge from the PwD's activities, the state of the environment, and a group of rules. It utilises the knowledge to decide the SH reactions. As an example, the system automatically activates a phone call to emergency services if the PwD falls and does not move for a long time. In this chapter, the system uses a set of fixed rules. Section 5.2.1 presents comprehensive details of the reasoning engine implementation.

4.3.4 Managing and monitoring interfaces

The interfaces are responsible for enabling the stakeholders to interact with the system to monitor the PwD and to determine the SH intervention behaviours. Ultimately, adopting tools (e.g., movement monitoring) provided by the interfaces improve PwDs' quality of life through enhancing their in-home safety. Furthermore, the interfaces help formal and social caregivers to perform their tasks efficiently. Additionally, the informal caregivers' peace of mind is increased as a result of highly accurate constant online monitoring information.

The SH interfaces are developed as web applications to be readily available across a variety of platforms (e.g., computers, tablets, and mobile phones). For the prototype, the web development programming languages of PHP and Javascript are utilised. Furthermore, the middleware default interfaces are employed for enabling the stakeholders to customise the SH overall settings such as disabling a sensor on or off. Naturally, experts who initially install and configure the SH are the main users of these interfaces. As the OpenHab configuration interfaces are satisfying the SH requirements, they were not modified in this research. Figure 4.3 illustrates the prototype kitchen configuration page as seen on a tablet.

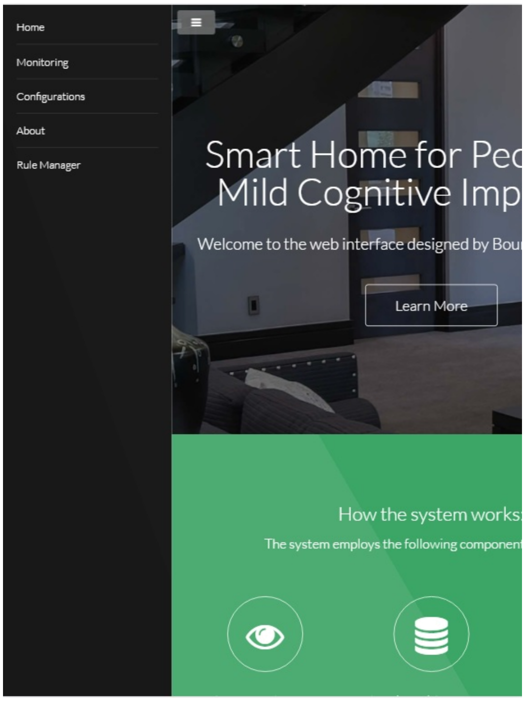


Figure 4.4: Prototype interface: The welcome page (tablet view).

Figure 4.4 shows the homepage of the web application. After selecting the monitoring option, following the authentication of the user, each caregiver will be presented with a list of PwDs whom they care for. After selecting the PwD, the facts about the activity and the health of the selected PwD are displayed. Figure 4.5 shows the default available SH monitoring functions (e.g., sleeping hours) and the

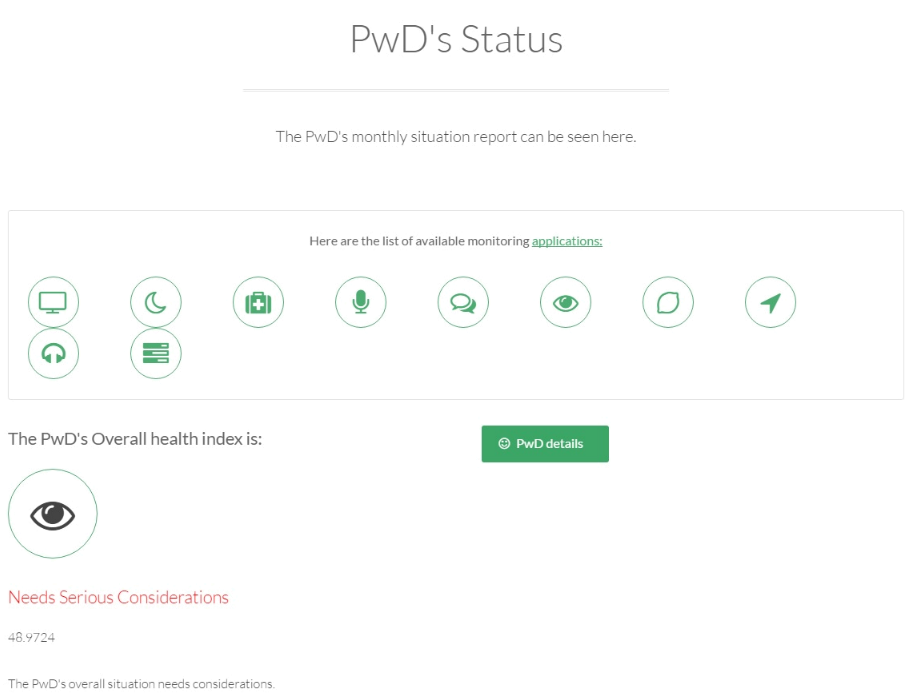


Figure 4.5: List of available monitoring functions for a PwD (PC view)

overall situation from a PC browser. Also, by clicking on the PwD details button a short form of the medical record will be presented.

On the same page, some health alerts are presented. Figure 4.6 shows the screen that allows the caregivers to adjust the intervention level for an alert. In case the type of action is not adjusted by the caregiver, the system performs the default intervention. For instance, if the geriatric set the required threshold for the daily urination times "often" and the collected data illustrated "seldom", then the system assumes that the PwD is not drinking enough water. Hence, it will play a pre-recorded audio reminder via a wireless speaker in the PwD's location. Furthermore, an email alert will be sent to the caregivers for information. By clicking on each alert, the relevant data is visualised. For instance, Figure 4.7 presents the PwDs' sleeping hours and types collected (0 = deep sleep, 4 = awake) by a mobile phone located on the bed.

The following table represents the critically risky situations detected by the system.

ID	Date	Message	Current Action
1830	09/02/15 2:42 PM	The PwD used the toilet 63 times this month which is much lower than expected (min = 90).	Suggesting Change
1831	09/02/15 2:42 PM	The PwD only used the kitchen appliances 80 times this month which is much lower than expected (min= 160).	Suggesting Change
1833	09/02/15 2:42 PM	The PwD repeated a phrase 40 times which is much more than expected threshold. Please click on the ID for more details.	Urging Change
2649	09/15/15 12:54 PM	The PwD only urinated 57 times this month which is lower than expected. He might be in Dehydration risk	Suggesting Change

Figure 4.6: Critical events detected by the system (PC view).

As an other example, Figure 4.8 shows the SH vital sign monitoring interface. It shows data collected from the e-health sensor kit.

4.4 Prototype Evaluation

To evaluate the prototype, a set of experimental tools are adopted that examined whether the system satisfies the specified requirements. Moreover, considering the general healthcare sensitivities, the evaluation process is designed to make sure that the system as a whole does not put PwDs' health and safety at risk. An SH system can be assessed from different aspects (e.g., functionality, reliability or usability). In this chapter, the prototype is thoroughly evaluated from the functionality standpoint.

The preferable method of evaluating an SH is to deploy it in real-world environments and observe the stakeholders' interactions with it for a substantial period. Observing the SH users interaction enables us to assess its impacts on the quality of the users' experiences. However, the real-world deployment of a healthcare system is not possible without speculating on its potential benefits and its effects on the residents' health and safety.

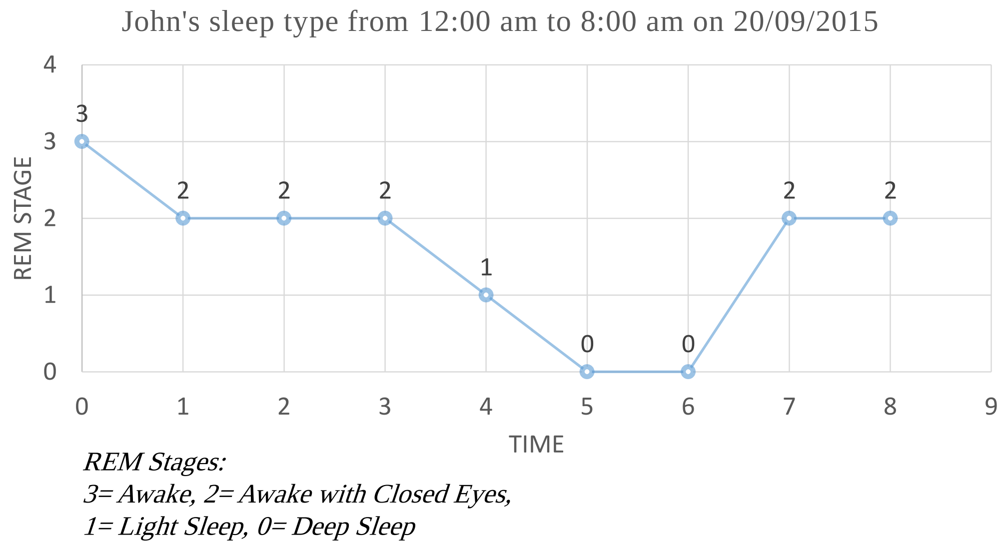
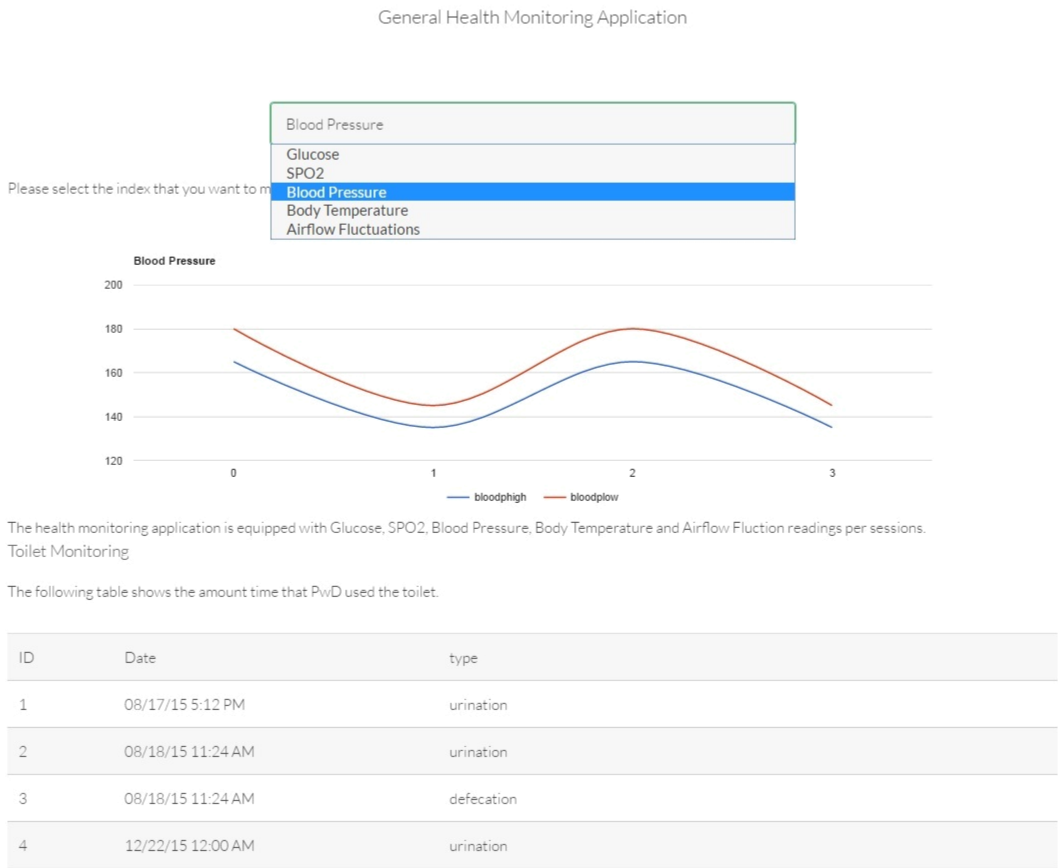


Figure 4.7: Sleep type per hours (PC view).



ID	Date	type
1	08/17/15 5:12 PM	urination
2	08/18/15 11:24 AM	urination
3	08/18/15 11:24 AM	defecation
4	12/22/15 12:00 AM	urination

Figure 4.8: General monitoring page (PC view). The drop-down list at the top part of the page illustrates all the collected vital sign data. The chart shows PwD's blood pressure over time and the table presents the PwD's toilet habits entered manually to the system.

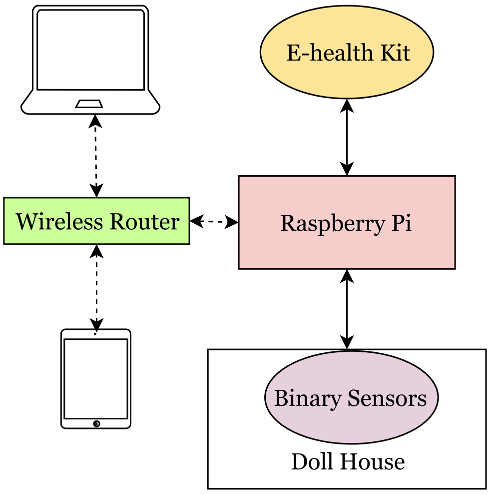


Figure 4.9: Physical setup of the evaluation prototype.

The evaluation is intended to illustrate that the SH system successfully achieves what it is designed to do (i.e., functionality), and it has the required quality attributes to be accepted and used by the users.

Figure 4.10: The Doll House.

Five geriatric specialists participated in two 45-minute-long evaluation sessions in which they were presented with the prototype (See Figure 4.9). The prototype was equipped with three sets of sensor devices including two groups of binary sensors (Passive Infra-Reds (PIRs) and Contact Switch Sensors (CSSs)) and an e-health monitoring kit that included sensors for vital signs monitoring such as SPO2, airflow, body temperature, and blood pressure. Binary sensors and the e-health sensors were used to populate the databases through the process of acting the scenarios in the doll house (See Figure 4.10). The participants could interact with the prototype using a tablet and a PC.

The key objectives of the evaluation were to answer the following questions based on the participants' feedback:

- Does the system have the adequate monitoring capability to be installed in a real-world setting?
- Can the system reduce the care difficulty?
- Does the system consider PwDs' health and safety?
- Can the system improve the quality of dementia care?

In the following, we provide the details of the evaluation process.

4.4.1 Evaluation Approach

The SH evaluation approach should be sensitive to the individual differences of the caregivers and reflect their priorities in the final results. Moreover, it should not overlook any of the prototype components and their functions. Considering these, the following evaluation approach was selected.

Two evaluation sessions were held for each caregiver. We asked them to answer the questions before and after being introduced to the prototype. In the first session, we examined the importance, the difficulty, and effect of care actions on PwDs assuming that the caregivers performed them. In the second session, we investigated the difficulty and effect of the care actions on the PwDs assuming that the system performed them.

Three measures were utilised in the questionnaires. The "importance" and the "difficulty" were adopted from the study Wessels et al. (2002), while "effect" was introduced in this study.

Importance

The measure is applied to estimate the overall importance of a care response. It allows to examine the importance from *monitoring* PwDs and *compensating* their limited capabilities. Moreover, it enables the participants to judge the relevance of all the questions. The scale of this measure ranges from 0 to 5: 0 indicates that a care response does not have any importance at all, and 5 indicates that the question topic is significantly important.

Difficulty

The measure is applied to examine the difficulty of performing a care action with or without using the SH system. Naturally, it is anticipated to observe a significant drop in the difficulty level, after the SH is introduced to the participants. The scale ranges from 1 to 5: 1 means that the care response is quite easy to be performed and 5 indicates that it is extremely difficult to perform it.

Effect

The measure is applied to investigate the effect of performing a care action of the caregivers or the SH on the well-being of PwDs. It is expected for the care responses with higher importance to have a greater effect on PwDs. Using technology may result in a novel type of care that did not exist before. Therefore, its effects on the PwDs might change. The scale ranged from 1 to 5: 1 means that the care response does not have any effect on the well-being of PwDs and 5 suggests that it has a major effect on them.

4.4.2 Results

We asked 48 questions from the five participants in the first evaluation round. The questions included three sets of 16 items regarding the importance, the difficulty, and the effect of the care responses. In the second evaluation round, after introducing the SH to the participants, 36 questions were related to the difficulty and the effect of care responses. Therefore, each participant responded to 84 questions. As an instance, Table 4.1 illustrate the study questions regarding the dehydration risk, communication difficulties, and misplacing items for PwDs. Based on the answers, a difficulty score $D_{(score)}$ and an effectiveness score $E_{(score)}$ were calculated using the following expressions (i.e., ordinal multiplication):

$$D_{(score)} = \textbf{“importance”} * \textbf{“difficulty”}$$

$$E_{(score)} = \textbf{“importance”} * \textbf{“effect”}$$

For instance, the second participant, a geriatric specialist with 20 years of experience, supposed the results of monitoring repetitive speech symptoms provided critical diagnosis information $(i = 5)$. He thought it was troublesome for the caregivers to record the change in the frequency of PwD's repetitive speech $(d_1 = 4)$. Considering the possible imperfections of the manually collected data, reviewing them could have little effect on his diagnosis and consequently, on the quality of dementia care $(e_1 = 3)$. After being presented with the prototype, he thought the difficulty of collecting the fluctuations dropped drastically $(d_2 = 1)$. Moreover, he would trust the sensor collected data more than manually collected data and the visualisation made the changes more explicit. Hence, it could have a more significant impact on his diagnosis and the quality of care $(e_2 = 4)$.

Figure 4.12 and Figure 4.11 present the median D and E scores for each participant. The median of difficulty score was 16 in the first round of evaluation. It slashed drastically to 5 in the second round. Moreover, the median of effectiveness score was 16 which increased to 20 in the second round of evaluation.

Table 4.1: Study questions regarding dehydration risk, communication difficulties and misplacing items

	#1. Getting dehydrated
Round 1	**Before being introduced to the prototype:**
1	How important is it to remind the PwD to drink enough water?
2	How difficult is it for the caregivers to remind him/her to drink enough water?
3	What kind of effects does the reminding process have on the quality of PwD's care?
Round 2	**After being introduced to the prototype:**
1	Considering the SH functions, how difficult is it for the system to remind the PwD to drink enough water?
2	What kind of effects does the reminding process have on the quality of PwD's care?
	#2. Communicating with acquaintances
Round 1	**Before being introduced to the prototype:**
1	Do you think staying connected using telecommunication applications is important for increasing the PwD's quality of life?
2	How difficult is it for the caregivers to help people to use such technologies?
3	What kind of effects does the process of helping PwDs have on the quality of PwD's care?
Round 2	**After being introduced to the prototype:**
1	How difficult is it for the system to help PwDs to use the telecommunication applications?
2	What kind of effects does it have on the quality of PwD's care?
	#3. Misplacing Items
Round 1	**Before being introduced to the prototype:**
1	Is informing PwDs on the location of the misplaced items is important for increasing the PwD's quality of life?
2	How difficult is it for the caregivers to help people to finding the misplaced items?
3	What kind of effects does the process of helping PwDs have on the quality of PwD's care?
Round 2	**After being introduced to the prototype:**
1	Considering the SH functions, how difficult is it for the system to help PwDs to find their misplaced items?
2	What kind of effects does it have on the quality of PwD's care?

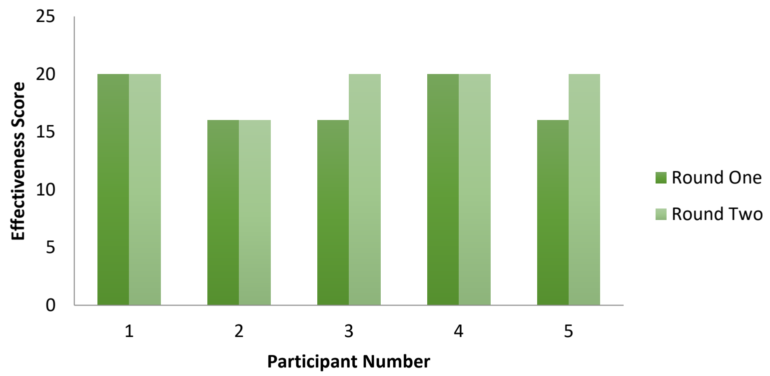


Figure 4.11: Median E scores for each participant in the two evaluation sessions

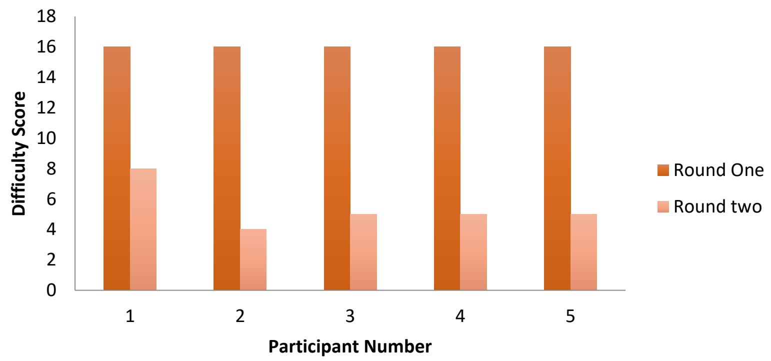


Figure 4.12: Median D scores for each participant in the two evaluation sessions

4.5 Discussion

A functional SH system prototype for the dementia care was introduced by tailoring a group of widely available hardware devices, open-source platforms and a collection of well-designed software components. The prototype was developed reflecting on an architectural model that was based on common requirements of dementia care stakeholders. It included web interfaces that empowered caregivers to monitor PwDs and determine the SH reactions in different situations that could happen to PwDs. Further, a variety of in-home interfaces and actuators were used to intervene in the PwDs' lives in ways which were prudently chosen by the caregivers.

Considering the results shown in Sec. 4.4.2, it is fair to assume that the prototype can reduce the difficulties of dementia care dramatically. It increases the caregivers' peace of mind and allows them to spend more time on tasks that improve the well-being of PwDs. Chapter 5 will provide the prototype with the ability to be personalised by caregivers and evaluates it in more details.

Chapter 5

The SH Personalisation

5.1 Introduction

In the previous chapters, we have concentrated on designing and developing SH systems that address common care needs of PwDs and their circle of care. Adopting a comprehensive design methodology, the stakeholders' requirements have been carefully gathered, and the corresponding design was introduced to develop a prototype that was evaluated by caregivers.

The personalisability enhances the acceptability of all types of AALs. Having said that, it is of particular importance for the SHs designed for dementia care, because PwDs have a variety of unique evolving needs that cannot be addressed by a set of fixed generic functions (Portet et al., 2013b). For instance, the number of PwD's weekly journey to the bookies could be a significant index of his well-being when it is presented to his children. Therefore, the SH should monitor the PwDs' weekly journey to the bookie and notifies the children if its occurrence pattern substantially changed.

The process of adding new functions to the SH system, following the approach discussed in Chapter 3, requires employing a set of software design and development tools. The process is time-consuming and potentially costly. Additionally, in a real-world setting, formal caregivers regularly revise their care and monitoring strategies based on information and feedback gathered from other stakeholders. For instance, a geriatric physician might ask a PwD's spouse to have an eye on the number of times that she has polyphagia (i.e., sudden need for eating), and informs them if the incidents occur *too often*. This information is considered as an indication of the progress of PwD's dementia or possible changes in her blood glucose level. The monitoring polyphagia incidents is not a common requirement of dementia care. However, it can be an important indication of health for PwDs with diabetes. To address these types of unique requirements, the SH should have the ability to be easily and quickly personalised by members of dementia care circle.

The personalisation is a multifaceted challenge that involves altering the software and sometimes hardware components of the system. In this chapter, it is addressed from the software-development viewpoint. The personalisation allows the users to define customise reactions to the changes in the environment and PwD's states. The variations in the states and their required reactions can be expressed in the form of rules. A rule defines a pattern of changes and specific actions that should be triggered when it occurs. To work with the rules, the SH requires 2 key software components of the *rule management interface* and the *reasoning engine*. The interface empowers relevant stakeholders to enter new rules to the system or to manage the existing ones in an effortless manner. The reasoning engine extract information, deduce knowledge, and constantly matches the rules with the collected information and deduced knowledge to set the reactions of the SH.

In the following, the reasoning engine and the interface are introduced. Then, the SH as a whole is evaluated, and the results are discussed.

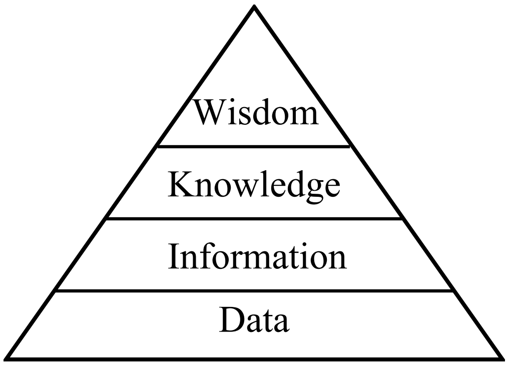


Figure 5.1: DIKW model (Frické, 2009)

5.2 Reasoning Engine

The key functionality of the engine is to extract information from sensor data, to deduce knowledge from information, and to decide the SH reactions based upon the deduced knowledge. In this work, the knowledge deduction and decision-making happen based on a set of rules. As an example, a geriatric physician creates a rule that requires the system to automatically activate a phone call to emergency services if the PwD falls and does not move for *'a long time'*. In principle, the engine enables the SH to reason and behave like a vigilant caregiver who continuously monitors the PwD and act based on formal caregivers' specific instructions.

In this work, the definition introduced in the Data Information Knowledge Wisdom (DIKW) model (Frické, 2009) (See Figure 5.1) is adopted to presents the relationship between the collected data, extracted information, deduced knowledge and gained wisdom. For the SH, the bottom layer of the model presents data (e.g., binary data) produced by the sensors and in-home interfaces. The above layer expresses conceptualised, structured and readable information (e.g., activities) that is extracted from the raw data. The knowledge level represents knowledge deduced from the information. The knowledge is a high-level abstraction and perceptions (e.g., events) that provide meanings and insights about PwD and the environment.

The top level shows a sub-group of deduced knowledge (also known as actionable intelligence, or wisdom) that the SH should react to.

To extract information and deduce knowledge, the engine adopts various levels of contexts (See Section 2.3):

1. It uses the *micro-contexts* to extract information (also known as activities) from the raw sensor data (e.g., PIR sensor readings). This process often includes applying activity recognition techniques.

2. It needs the *macro-context* for transforming information to knowledge (e.g., PwD is wandering). To do that, the system should be equipped with reasoning methods such as rule-based systems to map an activity or a group of activities to a given event.

Ultimately, to gain wisdom and react, the engine employs the rule-based system to match the occurrence of specific events with decisions.

Figure 5.2 shows the structure of the engine and its relation with rest of the SH components. The engine transforms collected raw data into knowledge and wisdom. The sensors and in-home interfaces generate raw data which, an activity recognition unit processes to recognise activities (e.g., sitting on a sofa, PwD's location) from. Following, an inference system matches the activities and direct pieces of information from the caregivers (e.g., PwD has a cold) to a group of rules to discover events (also known as situations). For instance, if the PwD is in the kitchen, and the gas hob is on, then the unit declares that "PwD is cooking". The inference engine matches gathered events to the rules to produce decisions. For instance, reminding the PwD to take his sleeping pills when he is experiencing an intermittent insomnia episode.

In Chapter 2, common methods of activity recognition and their implementation implication were briefly introduced. In this work, we do not aim to explore

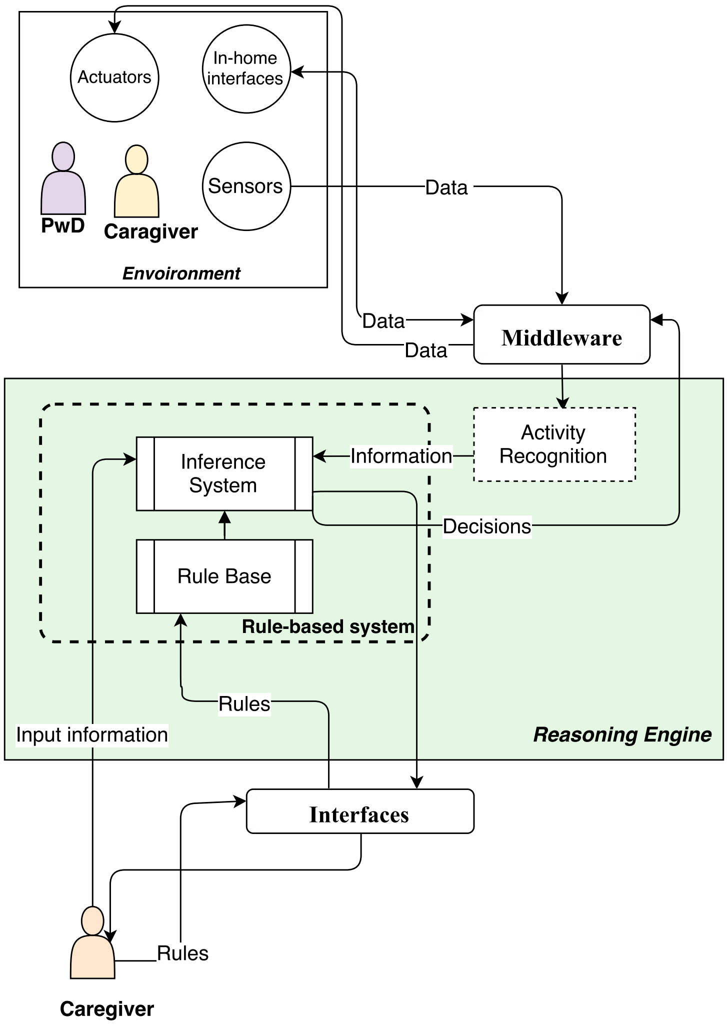


Figure 5.2: Reasoning engine structure

and improve activity recognition techniques. Therefore, it is assumed that all the required information are precisely collected and reasonably inferred. In the following, a rule-based system is introduced and develop to deduce knowledge and gain wisdom.

5.2.1 Fuzzy Rule-based System

The rule-based system is used to match the extracted information with a set of rules to deduce knowledge. It is also used to match the knowledge with rules to make decisions. Each rule is an IF-THEN statement that has antecedents (also known as premises) after the ‘if’, and consequences that come after the ‘then’. The rule-based system checks the validity of the antecedent against the information or the knowledge, and if it is validated as true, it triggers the consequences of that rule. The process is forward chaining as it begins by processing information to reach an outcome (e.g., an action).

A rule-based system is developed with either imperative (e.g., Java, Python) or domain-specific rule-based (e.g., Prolog, CLIPS) programming paradigms. In this work, the imperative paradigm is used. The paradigm considers the antecedent of a rule as a Boolean proposition with *true* or *false* value. Using the logical operators (e.g., AND, OR), it also enables the rules to have more than one antecedents. The antecedents are considered true if they meet a distinctly defined condition. For instance, assuming that the average number of night-time wandering incidents per night over a month precisely corresponds to N, to set a rule, the following statement with a threshold is needed:

IF $N \geq 10$ THEN inform a caregiver.

In the real-world, members of the care circle rarely follow the rules with precise numeric thresholds. For instance, a formal caregiver asks informal caregivers “if the PwD’s pulse rate is *slow*, inform a caregiver”. There are multiple approaches (e.g., probability theory and fuzzy logic) for a system to cope with uncertainty. The most common way is to employ fuzzy logic (Medjahed et al., 2011; Zadeh, 1965). That being said, in this thesis, the engine is developed as a proof of concept, therefore, no detailed comparison between various uncertainty handling techniques are provided. Using fuzzy logic, users can define rules that have premises with linguistic variables. Fuzzy rules are IF-THEN statements where the antecedents and consequences are fuzzy propositions that include linguistic variables (e.g., too many, too few). An antecedent is to a certain degree true or false. Considering the example of night-time wandering incidents:

A fuzzy set X is defined for "*high*" linguistic variable, let N be the average number of night-time wandering incidents per night over a month and $\mu(N)$ is a membership degree from 0 to 1. Thus, $X = \{N, \mu(N)\}$. The $\mu(N)$ is defined as:

- For $N \leq 10$: $\mu(N)$ = 1
- For $N = 0$: $\mu(N)$ = 0
- For $10 > N > 0$: $1 > \mu(N) > 0$

To create a fuzzy set, the membership degree $\mu(x)$ is calculated using a mathematical function. The function (also called a membership function) defines how an element is mapped to a membership degree. For instance, 3 membership functions are needed to map the N to linguistic variables of 'low', 'acceptable' and 'high'. There are different forms of membership functions such as triangular, trapezoidal, piecewise linear, Gaussian, and singleton.

The fuzzy rule-based system is a rule-based system that accepts fuzzy rules. It requires the following elements to function:

- *Fuzzy Rules*: In this work, they are stored in a database that is accessible by the engine.
- *Membership functions*: In this work, a group of formal caregivers (i.e., five geriatric physician) provided the necessary information (i.e., thresholds) to develop the membership functions for the common care linguistic variables. They were asked about their interpretations of vital sign and healthcare sensor readings (e.g., as blood pressure, glucose level, sleeping hours, numbers

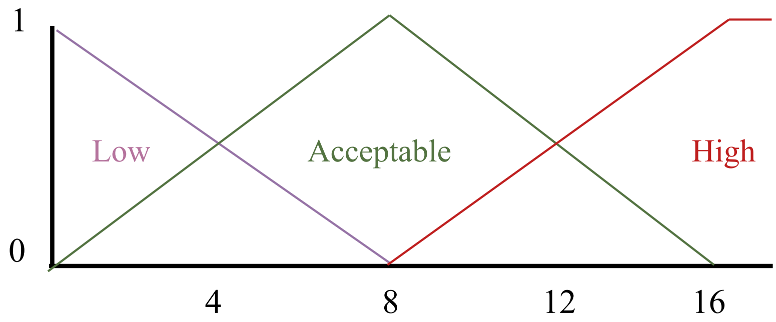


Figure 5.3: The horizontal axis shows the average number of night-time wandering incident per night over a month. The vertical axis shows the membership degree for the 'low', 'acceptable', and 'high' linguistic variable.

of night-time wandering incidents) for an elderly PwD with type two diabetes. Later, different types of membership functions (i.e., Triangular, and Trapezoidal) were used to implement them. Figure 5.3 illustrates a plot that includes membership functions for the 'low', 'acceptable', and 'high' linguistic variables for the average number of night-time wandering incident per night over a month.

- *Input information*: In this work, they are stored in a database accessible by the engine.

In addition to knowledge deduction, the rule-based system utilises specific occurrences of each symptom expressed by linguistic variables to determine a *health index*. The index indicates a PwD's overall health condition. It is calculated by incorporating the adverse outcomes of the symptoms on PwD's health. It is expressed as a number between 0 to 100 (i.e. 0 indicates that the PwD's health is critical, and the 100 indicates that he is entirely healthy). To calculate the index, the system should be informed on the relationship between the symptoms and the health index. For example, if the PwD has a 'high' average of night-time wandering incidents per night over a month the index should be reduced.

To function, the fuzzy rule-based system requires 3 types of rules:

1. **Knowledge Extraction Rules**: They are used to deduce knowledge (also known as fact) from information. Caregivers do not need to change or updated these rules for each PwD. Also, as they form the knowledge of the system, they should be fired before any other types of rules. For instance:

   R1: IF 'Current_time' IS 'Sleeping' AND 'Accelerometer_Active_Time' IS 'Too Long' THEN Signal 'NTW' AND Update 'SUM_NTW' ++

   Where: The *'Current_time'* is fuzzy set for time with 2 membership functions of *'Awake'* (e.g., 6 AM to 11 PM) and *'Sleeping'* (e.g., 10 PM to 8 AM). The 'Accelerometer_Active_Time' is a fuzzy set for accelerometer activation time with 3 membership functions of *'A short time'*, *'Acceptable'* and *'Too Long'*. The *Signal* is a programming function that changes an event status to *'True'*. The *NTW* is a variable that represents the occurrence of night-time wandering incident. The *Update* is a programming function that change the value of a variable. The *'SUM_NTW'* is sum of nigh-time wandering incidents.

   R2: IF 'Avg-in-home activity' IS 'Low' AND 'Avg-out-home activity' IS 'Low' THEN Signal 'Over-all in-active'.

   Where: The *'Avg-in-home activity'* is fuzzy set for average in-home activity over a month period collected by sensors with 3 membership functions of of *'Low'*, *'Acceptable'* and *'High'*. *'Avg-out-home activity'* is fuzzy set for average out-home activity over a month collected by sensors (e.g., mobile GPS) with 3 membership functions of *'Low'*, *'Acceptable'* and *'High'*. The 'Over-all in-active' is a variable that represent the PwD is overall inactive.

2. **Health Index Calculation Rules**: They are fired to calculate the health index. They explicitly define the relationships between the occurrence of symptoms and the health index. These rules should be tuned for each PwD. Caregivers

provide constant negative values for each symptom. The value demonstrates the negative significance of a symptom on the PwD's health. Later, in this section, the calculation process is presented.

R3: IF 'Avg_ntw' IS 'High' THEN HealthConcern.

Where: The *'Avg_ntw'* is fuzzy set for an average number of night-time wandering incidents over a month. It has 3 membership functions of *'Low'*, *'Acceptable'* and *'High'*. HealthConcern is a programming function that reduces the health index.

R4: IF 'Avg_sleeping_hours' IS 'Low' THEN HealthConcern.

Where: The *'Avg_sleeping_hours'* is fuzzy set for average of monthly sleeping hours. It has 3 membership functions of *'Low'*, *'Acceptable'* and *'High'*.

3. **Decision-making Rules**: They are fired by the inference system to make decisions. Some of these rules are built into the system, and some are written by the caregivers. Their consequences include SH actions for different situations.

   R5: IF 'Dehydration' IS 'True' THEN Inform (formal caregiver).

   Where: The *'Dehydration'* is an incident statement that is either 'true' or 'false'. The *'Inform'* is a programming function that sends a message to a / a group of people via their preferred medium.

   R6: IF 'Over-all inactive' THEN Inform (all the caregivers).

   Where: The *'Over-all inactive'* is an incident statement that is either 'true' or 'false'.

   R7: IF 'A pill is missed' THEN Play_BedroomSpeakers (reminder).

   Where: The *'A pill is missed'* is an incident that is either 'true' or 'false'. The

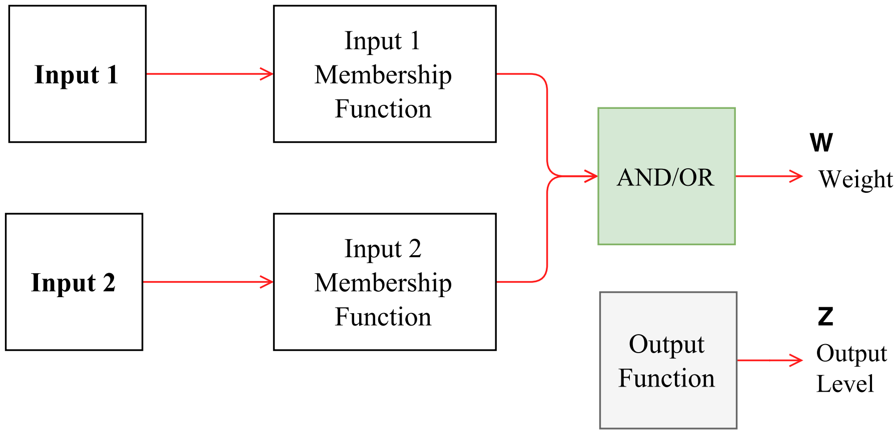


Figure 5.4: Sugeno Fuzzy Inference System

'Play_BedroomSpeakers' is a programming function that uses the bedroom speaker to play a pre-recorded audio reminder.

Figure 5.4 shows the process of the fuzzy inference of the system. The inference system uses fuzzy set theory to map inputs to outputs. In this work, the Takagi-Sugeno (also known as the TSK fuzzy model) (Sugeno, 1985) is used. TSK accepts fuzzy rules in the following format:

IF $input$ **IS** $linguistic\_variable$ **AND/OR** $input_2$ **IS** $linguistic\_variable_2$ **THEN** $Z = function$.

Where $linguistic\_variable$ and $linguistic\_variable_2$ are fuzzy sets in the antecedent, while $Z = function$ is a crisp function in the consequent that determine an output level. Commonly, the Z is a polynomial that includes the input variables (e.g., $f(input, input_2)$), however, in this work, Z is a constant, that makes the inference method a zero-order Sugeno fuzzy model.

To infer rules, TSK performs the following 5 tasks:

1. Fuzzification of the inputs.
2. Calculation of the rule weights.
3. Calling the consequence function.
4. Calculation of the health index.

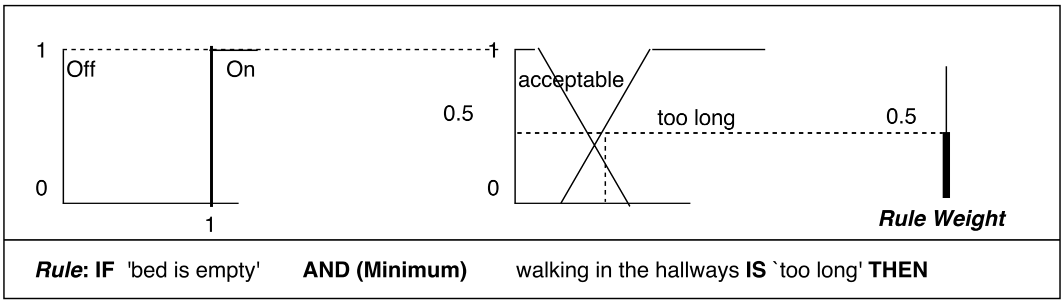


Figure 5.5: Rule weight calculation

The fuzzification is simply the process of adopting membership functions to map discrete inputs to a membership value. In this research, membership functions that are formed by straight lines such as TRiangular-shaped Membership Function (TRIMF) are used. TRIMF is defined by a lower limit a, an upper limit b, and a value m, where $a < m < b$. The function is expressed as follow:

$$\text{TRIMF}(input, [a, m, b]) = \begin{cases} 0 & \text{input} \leq a \\ \frac{input-a}{m-a} & a < \text{input} \leq m \\ \frac{b-input}{b-m} & m < \text{input} < b \\ 0 & \text{input} \geq b \end{cases}$$

For example, the following membership functions are defined: The ‘a long time’ = TRIMF (input walking minutes, [5, 10, 10]), the ‘a short time’ TRIMF (input walking minutes, [0, 0, 7]).

In the second step, the inference method applies the fuzzified inputs to antecedents of the fuzzy rules for the purpose of calculating of the rule weight. Figure 5.5 visualise the process of calculating a rule weight of w_i for a rule including a binary type and a linguistic variable in the antecedent. For the binary value, the on and the off linguistic variables are used. In a rule, when there are more than one fuzzy inputs, fuzzy logical operations are used to calculate the weight:

$\mu(A)$ AND $\mu(B) = min\{\mu(A), \mu(B)\}$

$\mu(A)$ OR $\mu(B) = max\{\mu(A), \mu(B)\}$

In the third step, the output level Z of each rule is multiplied by the weight of that rule to calculate an outcome $Outcome = w_i * Z$. For instance, if Z = 1, for the rule showed in Figure 5.5, the output is calculated as $0.5 * 1 = 0.5$. To fire a rule, the system calculate the outcome. It only fires the rule if the outcome is greater than 0.8.

The health index is calculated using the rules and a constant negative value that is associated to each symptom. To do that, all the rules weights are multiplied by their constant and the result is reduced from 100:

$health\_index = 100 - \sum_{i=1}^{n}(W_i * C_i)$

Where C_i is a constant weight that shows the adverse significance of each symptom. The constant is chosen by the caregivers in the way that $\sum_{i=1}^{n} C_i$ is not more than 100.

The effective performance of weights and membership functions thresholds utilised by the reasoning engine is largely based on its careful optimisation and personalisation. To do that, employing two approaches comes in mind. First, the weights and membership functions should be personalised, refined and tested by the stakeholders throughout system trails. Second, the engine should be equipped with a machine learning algorithm capable of self-optimisation of the parameter based on individual PwDs' needs. In this thesis, the engine was developed as a proof of concept. Thus, these approaches are not fully applied; they are further discussed as future work in Chapter 6.

Commonly an ambient intelligent system triggers actions utilising either *state-driven* or *event-driven* approaches. Using the state-driven approach, the reasoning engine continuously checks the environment state and triggers actions when there are new meaningful developments (i.e., situations). While using the event-driven approach, the reasoning engine is idle and only reacts to the occurrence of a set of predefined events (i.e., interrupts). In this thesis, the engine is developed following the state-driven approach.

To execute, the engine constantly match the rules against the knowledge and information. To avoid making wrong decisions, the rules are fired in an order. It begins by running the rules for deducing knowledge, then it runs the rules for the health index calculation, and finally, it executes the decision-making rules.

Caregivers' rules and the default system reactions might conflict. To handle this, the reasoning engine prioritises all the caregivers' defined rules to the default ones. Also, amongst caregivers defined rules the more recent ones are executed.

5.3 Rule Management Interface

In this section, a web interface is introduced that enables the caregivers to enter and manage the rules. The rules such as "IF the PwD IS inactive THEN inform a formal caregiver. In a real-world setting, the majority of high-level care decisions are made by the formal caregivers such as dementia nurses and geriatric physician. The rest of the care cycle follow the formal caregivers' instructions. Hence, the formal caregivers are the principal users of the rule management interface.

Considering formal caregivers diversity and their different computer literacy levels, the interface should be designed in a way that the interaction with it, requires minimum efforts. Moreover, the interface should provide a clear view of SH functions and capabilities to allow caregivers to create efficient rules. To do that, in this work, the interface is specifically designed as an End-User Development (EUD) tool. The EUD refers to a set of methods, techniques and tools that allow non-expert end-users to modify, extend and create software artefacts.

The interface is designed as a visual attribute programming tool. The visual attribute programming is a subcategory of EUD in which the users interacts with the system through an interface that includes modifiable visual layouts. It presents the system functions, as attributes of a visual representation (e.g., position, colour) that can be changed by users. It can be implemented by methods such as the jigsaw pattern, the form generators, and the trigger-action programming.

Some studies (De Russis and Corno, 2015; Ur et al., 2012, 2014) propose the trigger-action programming as the most suitable way of enabling the users to generate rules for an intelligent environments. In this approach, users set the SH reactions by specifying triggers (e.g., "IF the blood pressure IS too high"), and the consequence actions (e.g., "Send a message to the geriatric physician"). Also, popular web applications such as IFTTT (Tibbets, 2016) that allow users to generate rules for automation can be regarded as a successful implementation of drag and drop trigger-action interfaces. In this work, the prototype interface was developed as a drag and drop trigger-action environment.

Figure 5.6 shows the connection between the interfaces, the reasoning engine, and the middleware.

Here, the rule management interface is implemented using PHP, JavaScript language and can be accessed through tablets, mobile phones and PCs. After clicking on the link located at the home page of the SH website, the caregiver is directed to the main page of the 'rule management ' (See Figure 5.7). They are presented with the list of all the PwDs they provide care for. After clicking on the PwD's name, a new web page opens that includes the rules (See Figure 5.8). The page enables the users to modify the existing rules or add new ones. An intervention level bar indicates the level of intervention of the consequence of each care rule based on the physical devices (e.g., actuator) involved. For instance, reducing the light in the

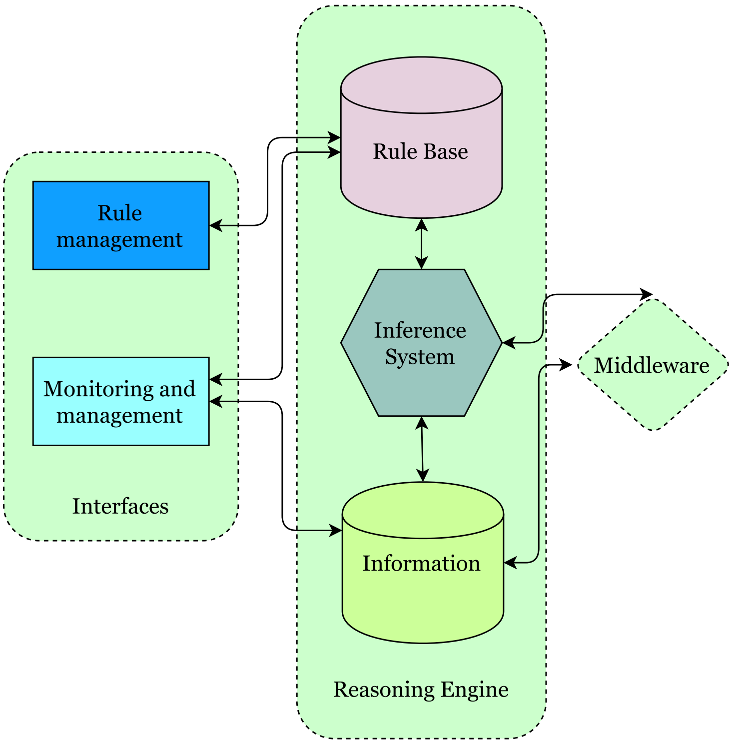


Figure 5.6: Connection between the interfaces, the reasoning engine, and the middleware

living room is classified as ‘a performing level’ intervention, and sending an email to a caregiver is ‘inviting awareness level’ (See Section 3.2.1).

Figure 5.9 shows the page that allows the caregivers to add new rules. The page displays also all the antecedents and consequences that the system supports. The caregivers can shape a rule by dragging and dropping its antecedents and consequences.

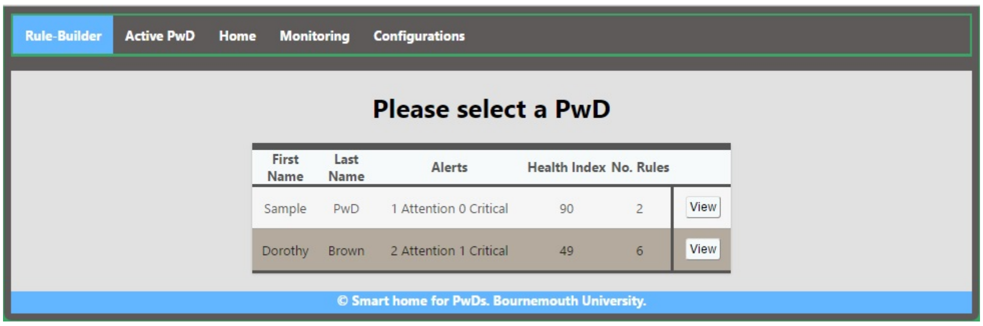


Figure 5.7: Main page of the rule management (PC view)

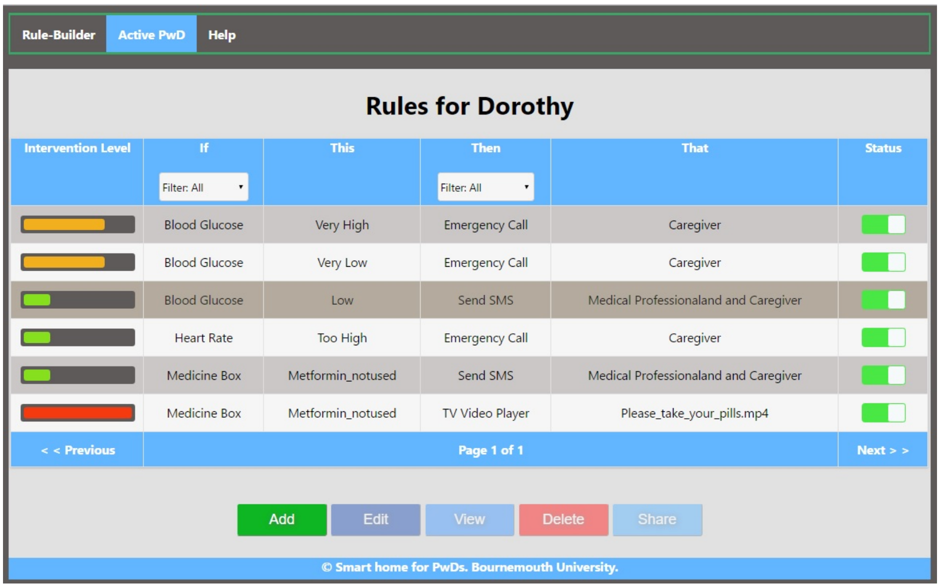


Figure 5.8: List of rules (PC view)

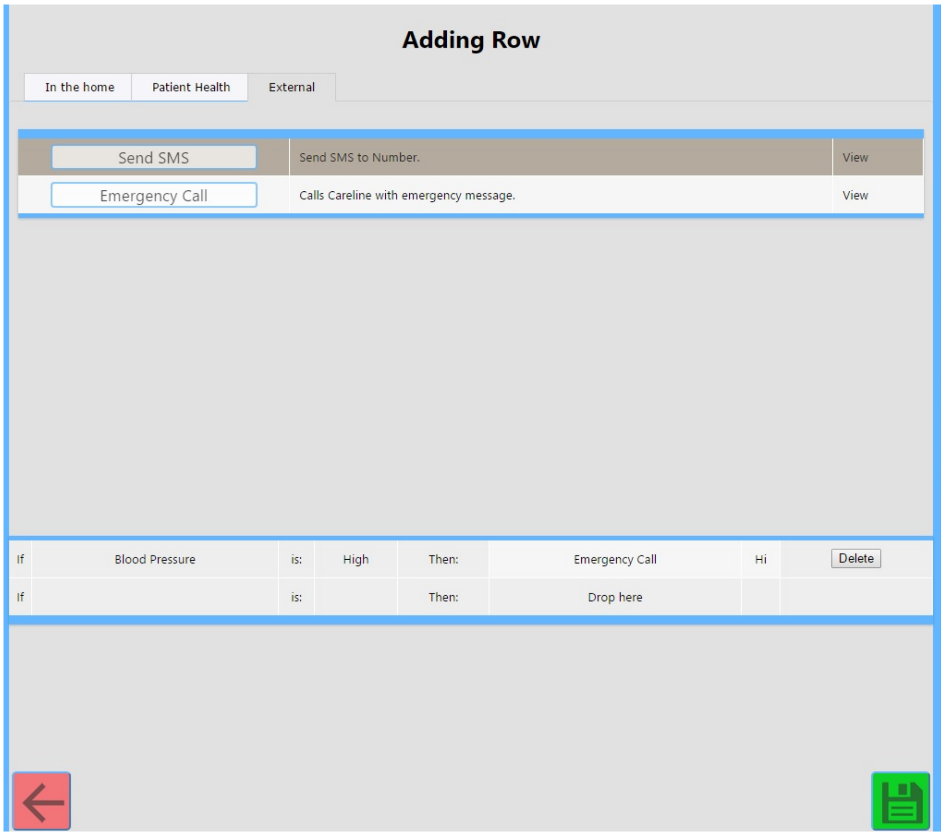


Figure 5.9: Adding a new rule (PC view)

5.4 Prototype Evaluation

Five geriatric physician participated in the prototype evaluations (See Chapter 4) that was extended with the rule management interface and the improved reasoning engine. The evaluation looked at the system functionality from three aspects of the importance of the system functions, the difficulty of utilising it, and its effectiveness in improving the quality of care. Moreover, the evaluation investigated the prototype usability through performing NASA-TLX (Hart and Staveland, 1988) assessment that measured the amount of task-load added to caregivers' routines when they use the system. During the sessions, participants were presented with a prototype that was equipped with the 'monitoring and management' (See Chapter 4), and the 'rule management' interfaces. The interfaces could be accessed by mobile phones, tablets, or personal computers. Key objectives of the evaluation were to provide answers for the followings questions based on the participants' feedback.

- Do the system functions match the needs of the users?
- Can the system reduce care difficulties for the formal caregivers?
- Does adopting the system improve the quality of delivering care?
- How much tasks-load employing the system adds to its users?
- What are the stakeholder's concerns? Is the system capable of addressing them?

5.4.1 Evaluation approach

Two rounds of evaluations per participant were held. The first round began by providing the participants with a hypothetical PwD's profile with her brief medical record. The profile was created by consulting a geriatric physician to ensure its authenticity. The participants were presented with two care scenarios: 1) Moni-

Table 5.1: Backgrounds of the participants

Participant Number	***Years of experience***	***Computer Literacy Level***
P1	Two	Proficient
P2	Three	Proficient
P3	Six	Intermediate
P4	Ten	Intermediate
P5	Twenty	Basic

toring PwD's general health, and 2) Monitoring PwD's sleeping patterns. In the first round, they answered questions on the approaches for handling situations considering the PwD's profile. They provided the concerns that they have when they attempt to gather information through conventional method (e.g., PwD's feedback). Also, they wrote necessary care instructions for other stakeholders regarding each scenario. At the end of the first round, they provided scores (see Section 4.4.1) for importance, difficulty and effectiveness of each scenario.

During the second round, the participants were introduced to the system. After choosing their preferred interaction device (e.g., tablet, laptop), they were asked to provide instructions for the two scenarios employing the system. They provided scores for the difficulty and effectiveness based on the system functions. Also, they judged if the system addressed the concerns that they mentioned in the first round. At the end of the session, their interactions task-load were gathered adopting the NASA-TLX approach.

We needed to ensure that the defined rules do not mask each other's effects. To do that, an informal interview with a geriatric physician was held where he confirmed the submitted rules effectiveness and lack of conflict. Having done that, the full extent of the rules outcomes on the PwD and environment can only be observed during PwDs' interaction with a functioning SH.

Table 5.2: Medical record

Record	***Information***
Demographics	Full Name: Dorothy Brown BOD: 3/04/1945 Marital Status: Widowed Occupation: Retired Teacher Ethnicity: White (British)
History of Present Illness (HPI)	Type 2 Diabetes, High Cholesterol
Past Medical History (PMH)	Major Depression
Medication History	Metformin, Simvastatin
Allergies	None Recorded

Participants' backgrounds

Table 5.1 presents participants' (i.e., formal caregivers) experiences in dementia care and their self-declared general computer literacy level (Maryland_Technology, 2016).

PwD's profile:

Dorothy is a 71-year-old female with Mild Cognitive Impairment (MCI) (See Chapter 1). She lives in a two-bedroom. Angela, her daughter, is her main informal caregiver. Her primary outdoor activities are spending time at a local market and meeting her friends on Sundays afternoon in a local cafe. Table 5.2 displays her brief medical record. The records only include information, that potentially affect the participants' instructions.

5.4.2 Baseline study - Round 1

Scenario 1

In the first scenario, the participants ask Angela or a social caregiver to report Dorothy's Vital Sign Readings (VSRs) (e.g., blood pressure, blood glucose, pulse) to them. Caregivers should also notify the participants if a substantial change occurs in the readings. If deemed necessary, the participant could request for additional medical tests. For instance, if the blood pressure is high, the caregiver checks the possibility that the PwD has forgotten to take the necessary medications (i.e., Simvastatin). The informal and social caregiver needs to assure that the PwD takes the pills at the correct times and if the blood pressure does not return to the normal range he or she has to inform a formal caregiver. The participants were asked to elaborately answers 2 questions and provide instruction for the social and informal caregivers. At the end of first round, they gave the importance, difficulty and effectiveness scores of the scenarios for the time the scenario is performed by the social and informal caregivers.

Scenario 1: participant 1's responds

Is it possible to perform the task?

Yes, it is possible for the social and informal caregivers to collect and interpret VSRs. They can inform medical professionals in emergency cases regarding the irregularities of VSR. However, the following matters make the process challenging.

- Social and informal caregivers might not be skilled in working with VSR technology. Therefore, it is not realistic to think they can always interpret the readings accurately and act upon them.
- Medical monitoring devices can be costly.
- VSR ranges are unique to each person. The caregivers should learn what is ordinary for the PwD. As social caregivers change over time, they might not be able to learn the normal vital sign readings for a person. To making correct decisions based on the readings, caregivers require access to historical medical records that are not available to the non-medical caregivers.

Is performing the scenario beneficial?

Yes, it is beneficial to know an older adult's VSRs. It is specially important for PwDs as they struggles to express their symptoms accurately, having regular VSR data can improve the accuracy of our diagnosis.

Write the necessary instruction for the caregivers?

If Dorothy's activities or habits has not changed, and the fasting blood glucose or the blood pressure indicator or heart rate changed to a considerably lower or higher rate than the PwD's average, inform me.

Scenario 1: participant 2's responds

Is it possible to perform the task?

Yes, the non-medical caregivers can inform medical professionals and perform basic care routines in emergency cases. The following challenges may complicate the process.

- In many cases, social and informal caregivers cannot use the standard VSR tools, especially, when the devices are analogue.
- A considerable number of people with MCI suffer from a condition known as white coat hypertension. That cause the blood pressure readings to be incorrect if the PwD is anxious. This phenomenon can occur when the caregivers are obtaining the readings.
- For caregivers to interpret the data correctly, they need to have a holistic view of the PwD's health.

Is performing the scenario beneficial?

Yes.

Write the necessary instruction for the caregivers?

Check the VSR before breakfast and compare it with the range of values which formal caregiver provided to you, if it is not within the range, contact formal caregiver.

Scenario 1: participant 3's responds

Is it possible to perform the task?

Yes, it is possible for social and informal caregivers to collect VSRs. Also, they can inform the relevant stakeholders in emergency cases. For the practice to be more effective, the informal and social caregivers should be encouraged to participate in common 65+ healthcare course provided to non-medical people. However, the following could make the task challenging.

- Some social and informal caregivers might not be able to receive the adequate training. Therefore, they cannot use the devices or interpret the VSR appropriately.
- Considering medical data privacy, the non-medical professionals cannot have access to the PwD's medical record without their/the guardians' consent.

Is performing the scenario beneficial?

Yes, it is critical to see the change in vital signs as early as possible. However, VSR is a key healthcare task that should be performed by the medical professionals.

Write the necessary instruction for the caregivers?

Inspect the vital signs including the blood glucose, *the blood pressure, and the heart rate* regularly (i.e. three times per week) and inform me as soon as seeing a noteworthy change.

Scenario 1: participant 4's responds

Is it possible to perform the task?

No, considering the abilities of social or informal caregiver, there is a chance that they read the vital signs incorrectly. Although I do not prevent caregivers from collecting VSRs, I do not rely on them for medical diagnosis.

Is performing the scenario beneficial?

Yes, it is helpful to have accurate historical VSRs.

Write the necessary instruction for the caregivers?

Not identified

Scenario 1: participant 5's responds

Is it possible to perform the task?

Yes, it is possible for Angela or a social caregiver to provide the VSRs. Also, I like to see the results of PwD's Mini-Mental State Examination (MMSE) at least every three months. The Mini–Mental State Examination (MMSE) test is a 30-point paper-based questionnaire that is used in clinical settings to measure the level of cognitive impairment.

The following points make the process of data collection and interpretation challenging.

- The social and informal caregivers' ability to use VSR devices and collect accurate readings.
- The social and informal caregivers' ability to understand and react to collected data correctly.

Is performing the scenario beneficial?

Yes.

Write the necessary instruction for the caregivers?

Take the vital signs in weekly basis and if there are any irregularities in them consult with formal caregivers. Also, if it is possible, perform mini-mental state

Table 5.3: Summary of the common concerns in relation to scenario 1

Concern	*Detail*	*Raised by Participants*
C1	The caregiver's inability to work with VSR devices.	P1, P2, P3, P5
C2	The caregiver's failure to interpret the data correctly.	P1, P2, P3, P4, P5
C3	The caregiver's lack of access to medical history.	P1, P2, P3
C4	Medical monitoring devices are expensive and have high maintenance costs.	P1
C5	Many people with MCI suffer from a condition known as white coat hypertension That makes collecting VSRs complicated.	P2

Table 5.4: Scores Scenario 1 - Round 1

Participant	*Importance*	*Difficulty*	*D Score*	*Effectiveness*	*E Score*
P1	4	5	20	2	8
P2	2	5	10	1	2
P3	5	3	15	3	15
P4	3	4	12	1	3
P5	5	5	25	2	10

examination every three months and report any significant changes to other stakeholders.

Table 5.4 provides the summary of participants' scores for the scenario 1 of the Round 1.

Scenario 2

The participants provided their feedback for a situation that they require Angela or a social caregiver to report on Dorothy's night-time activities. The caregiver collects the number of pacing and night-time wandering incidents and report them to a formal caregiver. Commonly, these information are used to perceive the PwD's dementia progress. This information is especially valuable in noticing PwD's transition from MCI stage to Alzheimer's disease. In this scenario, the participants were asked to provide the necessary guidelines for the caregivers on handling night-time wandering incidents as well as collecting the numbers of occurrences.

Scenario 2: participant 1's responds

Is it possible to perform the task?

No, it is not possible for Angela or a non-medical caregiver to collect accurate information regarding the PwDs sleeping behaviours. Considering Dorothy's age and diabetes, she is going to wake up during the night to use the toilet. Therefore, it is not possible for the caregiver to record times that she wakes up during a night. Also, access to historical data records is needed to recognise changes in the frequency of the incidents.

Is performing the scenario beneficial?

Yes, the sleep pattern analysis is beneficial for supporting the PwDs during the incidents and monitoring the disease progress.

Write the necessary instruction for the caregivers?

Contact me, if night-time wandering incidents happens too often in a month. During a night-time wandering incident talk to Dorothy and tell her where she is, and ask her to either use the toilet or go back to bed.

Scenario 2: participant 2's responds

Is it possible to perform the task?

No, I think the sleep monitoring is a difficult task. Also, the feeling of being constantly monitored increases the PwDs' anxiety. PwDs sometimes face periods of sleep irregularity that last for weeks. As these sleeping changes are very common, I prescribe sleeping pills which should be taken if the regular sleeping pattern is disturbed.

Is performing the scenario beneficial? Yes.

Write the necessary instruction for the caregivers?

If the number of night-time wandering incidents are too many or increasing steadily, contact me. If the sleeping pattern is abnormal, give the prescribed Benzodiazepines to Dorothy. If the PwD has a night-time wandering incident, guide the person back to the bed.

Scenario 2: participant 3's responds

Is it possible to perform the task?

Yes, the informal caregiver can roughly portray the PwD's night-time behaviours. It is expected to see some of the dementia symptoms to get worse such as the number of night-time wandering incidents. Also, I suppose, the number of nights that the PwDs faces sleeping difficulty (i.e. dementia-related insomnia) can be a significant indicator of the dementia progress. The information provided by caregivers are often not too accurate, and PwDs' cannot remember the incident details.

Is performing the scenario beneficial?

Yes, it is beneficial.

Write the necessary instruction for the caregivers?

Report any noticeable changes in the sleeping pattern of the PwDs to me. If a wandering incident happened, make sure that Dorothy is awake, and tell her the time of the night, and ask her to go back to bed.

Scenario 2: participant 4's responds

Is it possible to perform the task?

Yes, I ask the PwDs and their caregivers to provide a summary of PwD's sleeping patterns. It is not always accurate, but this is the only available way to collect relevant data. Very rarely, the PwD's bedroom has a baby monitoring camera that provides an acceptable insight into their sleeping patterns if analysed correctly. Normally, I ask informal caregivers to analyse the video.

Is performing the scenario beneficial?

Yes, it is beneficial.

Write the necessary instruction for the caregivers?

Notify me on in the sleeping behaviours months. In the case of the night-time wandering incidents guide the PwD back to the bedroom.

Scenario 2: participant 5's responds

Is it possible to perform the task?

No, I obtain the information through talking with the PwDs about their sleeping pattern. Also, the PwD's partner could provide insight into the matter. Caused by damages to the PwD's circadian rhythm, it is very common to see a PwD to suffer from insomnia. To control it, medications such as Tricyclic, and Benzodiazepines can be prescribed. However, taking these drugs, in the long run, could speed up the PwD's cognitive deterioration. Thus, they should only be taken if the insomnia period occurs.

Is performing the scenario beneficial?

Yes, if we have the data, it is beneficial.

Write the necessary instruction for the caregivers?

Please report the changes in the sleeping behaviours to me. If insomnia occurs regularly, provide a sleeping pill to the PwD.

In Table 5.5, the summary of participants' scores for the scenario 1 of the Round 1 are provided.

Table 5.5: Summary of the concerns in relation to scenario 2

Concern	*Detail*	*Raised by Participants*
C1	The caregiver's inability to obtain reliable information.	P1, P2, P3, P4, P5
C2	The caregivers inability to provide the PwD with pills which should only be taken if the regular sleeping pattern is disturbed.	P2, P5

Table 5.6: Scores Scenario 2 Round 1

Participant	*Importance*	*Difficulty*	*D Score*	*Effectiveness*	*E Score*
P1	4	4	16	1	4
P2	4	5	20	0	0
P3	3	3	9	1	3
P4	5	5	25	3	15
P5	5	5	25	2	10

5.4.3 System evaluation - Round 2

The round lasted 45 minutes per participant. The participants were asked to perform two care scenarios of VSR and sleeping pattern monitoring, using the prototype. In the round, we collected users' scores for the system effectiveness and employing difficulty. Also, we adopted NASA-TLX method to measure the task-load generated by using the system. Finally, the participants were asked to see if the system addressed the concerns that were mentioned in the last round. They entered their instructions in the form of rules through the trigger-action interface (See Figure 5.9). The participants were asked to enter the rules using the browser of a mobile phone, a tablet or a PC. Before using the system, the participants have been introduced to the system and its capabilities.

Scenario 1

The participants were asked to perform the Scenario one (See Section 5.4.2) using the system. Table 5.7 presents the scores of performing the first scenario using the system. Table 5.8 presents the participants feedback regarding the system ability to address the concerns. In the followings, the decision-making rules defined by the caregivers are provided.

Scenario 1: participant 1's rules

1. **IF** blood glucose (in a test) **IS** *very high* **THEN** call the formal caregivers.
2. **IF** blood glucose (in a test) **IS** *very low* **THEN** call the formal caregivers.
3. **IF** blood glucose (in a test) **IS** *low* **THEN** send a text message to the formal caregiver.
4. **IF** Metformin **IS** not taken **THEN** send a text to the informal and the social caregivers.
5. **IF** Metformin **IS** not taken **THEN** play the reminder audio file via bedroom radio.
6. **IF** heart rate (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
7. **IF** Average PwD's activity (over a week) **IS** *inactive* **THEN** email the geriatric psychologist.
8. **IF** Average PwD's activity (over a week) **IS** inactive **THEN** email Angela.
9. **IF** health index **IS** *Blow 50* **THEN** arrange an MMSE test.

Scenario 1: participant 2's rules

1. **IF** blood glucose (in a test) **IS** *very high* **THEN** call the formal caregivers.
2. **IF** blood pressure (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
3. **IF** blood glucose (in a test) **IS** *low* **THEN** send a text to the formal caregivers.
4. **IF** Metformin **IS** not taken **THEN** send a text message to Angela.

5. **IF** heart rate (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
6. **IF** breathing rate (in a test) **IS** *too slow* **THEN** call the formal caregivers.
7. **IF** Average PwD's activity (over a week) **IS** inactive (weekly average) **THEN** send an email to geriatric psychologist.
8. **IF** MMSE test **IS** 3 months old **THEN** arrange an MMSE with the formal caregivers.

Scenario 1: participant 3's rules

1. **IF** blood glucose (in a test) **IS** *very high* **THEN** call the formal caregivers.
2. **IF** blood glucose (in a test) **IS** *low* **THEN** send a text message to formal caregivers.
3. **IF** blood pressure (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
4. **IF** blood glucose (in a test) **IS** *very low* **THEN** call the emergency services.
5. **IF** PwD's weight changes **IS** *abnormal* **THEN** send a text message to Angela.
6. **IF** PwD's weight changes **IS** *abnormal* **THEN** send a text message to caregivers.
7. **IF** MMSE test **IS** 2 months old **THEN** arrange an MMSE with the formal caregivers.

Scenario 1: participant 4's rules

1. **IF** blood glucose (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
2. **IF** heart rate (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
3. **IF** Average PwD's activity in kitchen (over a month) **IS** *low* **THEN** send a text message to Angela.
4. **IF** PwD's numbers of journeys to the cafe (in a month) **IS** *too few* **THEN** send a text to formal caregivers.

Scenario 1: participant 5's rules

Table 5.7: Scores entered for Scenario 1, Round 2

Participant	*Difficulty*	*D Score*	*Effectiveness*	*E Score*	*Rules Count*
P1	1	4	5	20	9
P2	1	2	4	8	8
P3	2	10	4	20	7
P4	2	6	4	12	4
P5	3	15	3	15	6

Table 5.8: Participants feedback regarding the SH efficiency

Concern	*Detail*	**Addressed**	**Not Addressed**
C1	The caregiver's inability to work with VSR devices.	P1, P2, P3, P4, P5	
C2	The caregiver's failure to interpret the data correctly.	P1, P2, P3, P4, P5	
C3	The caregiver's lack of access to medical history.	P1, P2, P3, P4, P5	
C4	Medical monitoring devices are expensive and have high maintenance costs.	P1, P5	P2, P3, P4
C5	Many people with MCI suffer from a condition known as white coat hypertension That makes collecting VSRs complicated.	P1, P3, P4, P5	

1. **IF** blood glucose (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
2. **IF** blood glucose (in a test) **IS** *abnormal* **THEN** call Angela.
3. **IF** heart rate (in a test) **IS** *abnormal* **THEN** call the formal caregivers.
4. **IF** Average number of PwD's lost objects (over a month) **IS** *High* **THEN** send a text to the formal caregivers.
5. **IF** MMSE test **IS** 3 months old **THEN** arrange an MMSE with the formal caregivers.
6. **IF** PwD's number of journeys to the cafe (in a month) **IS** *too few* **THEN** send a text to formal caregivers.

Scenario 2

The participants were asked to enter instructions for scenario 2 (See Section 5.4.2) using the system. Table 5.9 presents the scores for scenario 1. Table 5.10 presents the participants feedback regarding the system ability to address the concerns.

Scenario 2: participant 1's rules

1. **IF** waking up (during a night) **IS** *too often* **THEN** email the formal caregivers.
2. **IF** night-time urination (during a night) **IS** *too often* **THEN** send a text message to the formal caregivers.
3. **IF** average sleep hours (over a week) **IS** *high* **THEN** send a text message to the formal caregivers.
4. **IF** awake hours in the bed (during a night) **IS** *too many* **THEN** send an email to the formal caregivers.
5. **IF** average night-time wandering incidents per night (over a month) **IS** *high* **THEN** send an email to the formal caregivers.
6. **IF** night-time wandering **IS** happening **THEN** play guidelines via bed room radio.
7. **IF** night-time wandering **IS** happening **THEN** send a text message to Angela.

Scenario 2: participant 2's rules

1. **IF** PwD waking up (during a night) **IS** *too often* **THEN** email the formal caregivers.
2. **IF** average night-time wandering incidents per night (over a month) **IS** *high* **THEN** call the formal caregivers
3. **IF** awake hours in the bed (during a night) **IS** *too many* **THEN** email formal caregivers

Scenario 2: participant 3's rules

1. **IF** night-time wandering **IS** happening **THEN** play guideline audio via bed room radio.
2. **IF** night-time wandering **IS** happening **THEN** call Angela.
3. **IF** night-time wandering **IS** happening **THEN** lock the main door.
4. **IF** average sleeping hours (over a week) **IS** *low* **THEN** send an email message to the formal caregivers.

Scenario 2: participant 4's rules

1. **IF** night-time wandering incidents per night (monthly average) **IS** *high* **THEN** send an email to the formal caregivers.
2. **IF** night-time wandering **IS** happening **THEN** call Angela.
3. **IF** night-time wandering **IS** happening **THEN** call the social caregivers.
4. **IF** awake hours in the bed (during a night) **IS** *abnormal* **THEN** send an email to the formal caregivers.
5. **IF** deep sleep hours **IS** *reduced***THEN** email to formal caregivers
6. **IF** night-time urination (during a night) **IS** *too often* **THEN** send a text message to the formal caregivers.

Scenario 2: participant 5's rules

1. **IF** night-time wandering **IS** happening **THEN** play guidelines audio via bed room radio.
2. **IF** night-time wandering **IS** happening **THEN** send a text to Angela.
3. **IF** average night-time wandering incidents per night (over a month) **IS** *high* **THEN** call the formal caregivers
4. **IF** awake hours in the bed (during a night) **IS** *abnormal* **THEN** send an email to the formal caregivers.

Table 5.9: Scores given for Scenario 2, Round 2

Participant	***Difficulty***	***D-Score***	***Effectiveness***	***E Score***	***Rules Count***
P1	1	4	5	20	7
P2	1	4	4	16	3
P3	2	6	4	12	4
P4	2	10	3	15	6
P5	3	15	3	15	4

Table 5.10: Participants feedback regarding the SH efficiency

Concern	***Detail***	***Addressed***	***Not Addressed***
C1	The caregiver's inability to obtain reliable information.	P1, P2, P3, P4, P5	
C2	The caregivers ability to provide the PwD with pills which should only be taken if the regular sleeping pattern is disturbed.	P1, P2, P3, P4, P5	

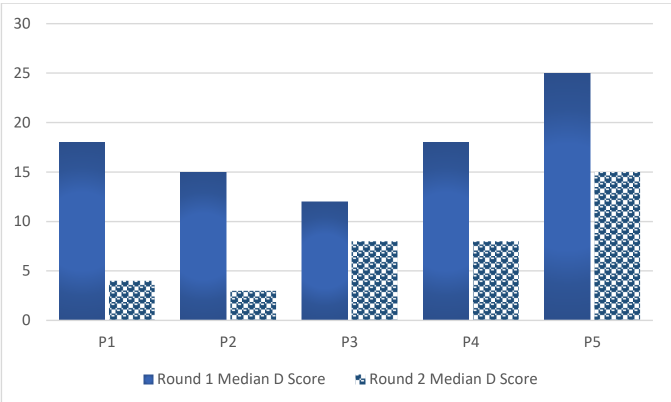


Figure 5.10: Median D Scores in the two rounds

Figures 5.10 illustrates participants' median E and D scores for in two rounds of the dynamic prototypes evaluation.

5.4.4 NASA-TLX Results

NASA-TLX is a multi-dimensional rating procedure that provides an overall task-load score based on a weighted average of ratings on 6 sub-scales of *Mental De-*

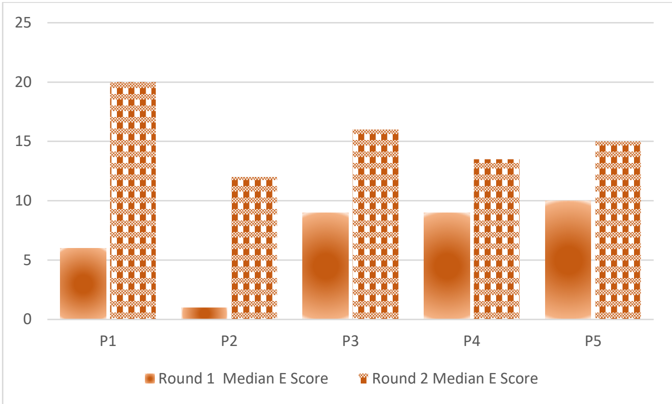


Figure 5.11: Median E Scores in the two rounds

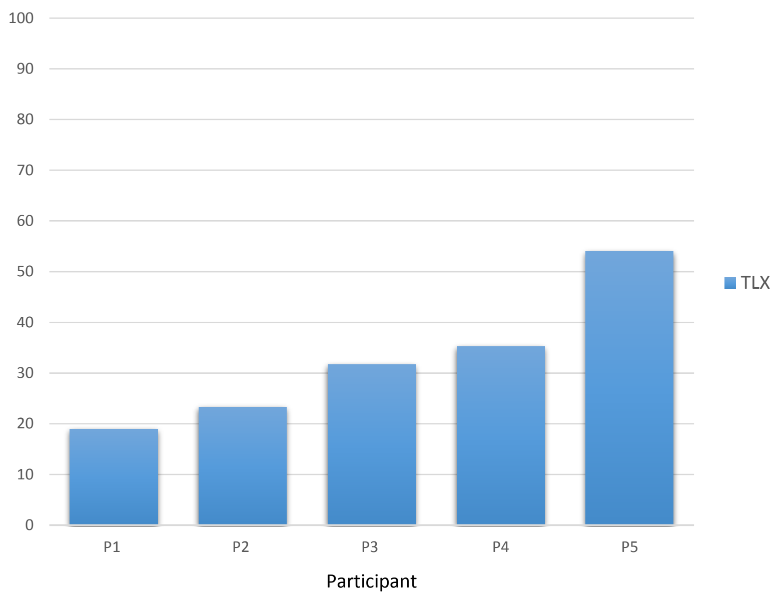


Figure 5.12: NASA-TLX Results

Table 5.11: Participants' TLX results

Participant	***TLX***
P1	19
P2	23.33333333
P3	31.66666667
P4	35.26666667
P5	54

mands, *Physical Demands*, *Temporal Demands*, *Own Performance*, *Effort* and *Frustration*. The assessment results illustrate speculated amount of task-load (from 1 to 100). Table 5.11 presents the outcome of the NASA-TLX for each participants. For details of each score see Table B.1 in Appendix B.

5.5 Discussion

Individual stakeholders' needs, as well as, the progressive nature of dementia, cause the necessity of the SH personalisation. This implies that the system should enable the caregivers to define care instructions without the need of going through exhaustive software engineering process. In the chapter, a prototype was introduced that empowers the caregivers to add their instructions to the system through an interface, and it is equipped with a reasoning engine that comprehends and acts based on the received instructions.

The prototype evaluation (See 5.4) demonstrated that employing the system reduces the caregivers' difficulty and improves the effectiveness of the delivering care. This phenomenon rooted in the fact that the personalising the SH empowers the caregivers to monitor the PwD or provide care for them in the ways that were not possible through conventional methods.

Looking at the participant answers' in the first round of evaluation, it is evident that they have different approaches to handle an incident. They also have contradicting ideas about the possibility of involving social and informal caregivers in the monitoring process, and how trustworthy the non-medical caregivers' observations are. Using the system they still had their various approaches. Nevertheless, they had far less trusting issue in regards to the collected data by the system.

Tables 5.8, and 5.10, illustrate that the majority of participants agreed that the system could address most of the concerns. The only concern that was not dealt with by the prototype was regarding to the expenses of adopting SHs for dementia care.

The participants used the interfaces to enter their instructions as rules to the system. In some cases, they added rules that have not been mentioned in their instructions to the caregivers in the first round. For instance, none of the participants asked for monitoring information regarding Dorothy's weekly journey to the cafe. However, after seeing the option in the interface, some provided it as a rule to the system.

Participants took part in a NASA-TLX assessment after interacting with the prototype. Evidently, the amount of participants' task-load score correlates with their self-declared level of computer literacy. The first participant with a low score, efficiently adopted the *drag and drop* interface while the fifth participant with a high score, found it physically and mentally demanding. Since the average computer literacy level of formal caregivers is rising globally, it is expected that the task-load for such interfaces will decrease. Ultimately, even participants with the higher TLX scores were able to successfully define rules and use the system.

5.6 Conclusion

In this Chapter, a reasoning engine capable of perceiving dementia care rules, and an interface for enabling the caregivers to manage the rules were introduced. The engine was equipped with a fuzzy rule-based system that enabled it to handle linguistic variables used in the care instructions. Also, the rule management interface was designed as an EUD tools that empower the users to manage their personalised rules. To evaluate the concept, a prototype was developed and was evaluated from functional and usability standpoints. The functional evaluation of the prototype system with the caregivers showed that the system has the potential to decrease care difficulties and improve care effectiveness. Also, a usability study on the caregivers' interaction with the system illustrated that the users did not find using the interfaces demanding.

Chapter 6

Conclusion and Future Directions

6.1 Summary of Findings

In this work, a set of studies were conducted to address the key question of *How SHs should be designed to meet the requirements of dementia care stakeholders?* Also, we looked at the impact of using a tailored prototype SH system on the quality of caregivers' experiences with regard to dementia care. The studies showed a set of findings that together address the research question. In the following, the findings are presented.

1. **The tailored solution:** Surveying the literature, it is particularly evident that a majority of studies consider dementia care as an application for the existing SH platforms. Therefore, their proposed solutions inherit some characteristics that are often inappropriate for dementia care. For instance, a majority of SH devices are manufactured and installed in a physically noticeable way. However, by nature, dementia care demands seamless integration. As another example, general purpose SH software systems (e.g., openHab) are developed to be used by tech-savvy users. Such interfaces require users to perform tasks that could be too complicated for members of a dementia care circle (See

Section 5.4). Ultimately, overlooking requirements of dementia care cause the SH to be not accepted by all stakeholders. In this work, the challenges were addressed by developing a prototype based on elicited requirements of the stakeholders. This approach does not imply that all the existing SH technologies cannot be adopted; it only suggests that they should be vetted and customised to assure satisfaction of dementia care requirements.

2. **The common care needs:** PwDs face a broad range of symptoms (See Section 1.1), and therefore, require a variety of care actions. Existing SH studies include care solutions for one or a few of the needs. By covering all the common needs, the SH acceptability can be significantly improved. In this thesis, an SH was introduced that incorporates solutions for a variety of different scenarios. An ideal SH for dementia offers solutions for personalised/individualised needs. In Chapter 3 and Chapter 4, we proposed an SH that is equipped with functions to address the common requirements of PwDs. They were collected and developed based on literature and the interviews with caregivers. In the following, the common care scenarios are presented.

    1. Repeating speech.
    2. Getting dehydrated.
    3. Communicating with acquaintances.
    4. Misplacing personal items.
    5. Losing personal items.
    6. Learning new interactions.
    7. Remembering time and date.
    8. Experiencing pacing patterns.
    9. Experiencing night-time wandering incidents.
    10. Forgetting names.

11. Seeing in dark.
12. Performing the personal grooming.
13. Monitoring PwD's health.

3. **The intervention levels:** Existing SHs are often developed to perform the activities of daily living instead of the residents. In the context of dementia care, this approach reduces PwDs' sense of control and independence. The caregivers avoid unnecessary interventions by utilising various levels of intervention depending on particular care circumstances. Following an intervention approach, increases the acceptability of the SH. In this thesis, a five-level approach was introduced that enables the SHs to emulate the dementia caregivers for the interventions to PwDs' lives. The steps are 1) inviting awareness, 2) suggesting, 3) prompting, 4) urging, and 5) performing.

4. **The UCD approach:** By using the UCD-based tools and methods, needs, preferences, and values are reflected in the final system. The tools are adopted to improve the acceptability of a system amongst its users. However, many common UCD tools (e.g., direct interview with the stakeholders) cannot be adopted in the context of SHs for dementia care. This is a consequence of PwDs' inability in expressing their needs. Moreover, caregivers often have not dealt with all of the dementia symptoms, and considering the vast number of symptoms, they could easily forget to mention some of them during interview sessions. To address the limitations, in this thesis, a novel UCD-based approach was undertaken. All the symptoms were gathered from the literature, and they were transformed into the scenarios. Consequently, a better participation and richer feedback from the caregivers were obtained. Also, we had a comprehensive collection of care scenarios that were accepted by all participants in the design and prototype evaluation sessions.

5. **The personalisation:** Caregivers adopt various approaches for providing care. The approaches are adjusted to the PwDs' circumstances. In addition, each stakeholder has unique care needs and preferences. For an SH system to effectively function in such settings, it should be personalisable by the stakeholders. In this thesis, the formal caregivers were empowered to customise the system with their care rules through an easy-to-use interface. The evaluation results (See Section 4.4.2 and Section 5.4.3) illustrated adopting a personalisable prototype improves the system effectiveness significantly. This occurs as using the personalisable prototype the caregivers can define their unique care reactions for PwDs' needs.

6. **The reasoning engine:** To provide automatic responses to various care situations, the SH should be equipped with a reasoning engine. The engine has mechanisms of perceiving events and means of reacting to them. There exist a variety of computational approaches to develop a reasoning engine for SHs. In this thesis, a fuzzy rule-based system was used. The fuzzy logic allows the caregivers to use the natural description of situations in linguistic terms, rather than in terms of precise numerical values. Ultimately, the caregivers can provide the system with care instruction in the form rules with natural descriptions.

7. **The usability:** The ability of stakeholders to effortlessly use the SH plays a vital role in its acceptability. The usability is an objective measure that estimates the easiness of users' interaction with the system. In this thesis, the formal caregivers evaluated the usability of the prototype system adopting the NASA-TLX approach. The evaluation results showed a clear correlation between formal caregivers' level of computer literacy and their' perceived complexity of performing tasks using the system. Furthermore, the results

show that the usability can be seen differently amongst various cohorts within one group of stakeholders, and it highlights the importance of training the users.

6.2 Future Directions

To precisely deduce knowledge and make decisions, the SH requires means of acquiring a set of unique information about the PwD. For instance, what is considered as a 'high' blood pressure for a PwD might be 'acceptable' for another one. In this work, we merely relied on the caregivers to provide the information. Machine learning can be used to discover and tune the information by processing the users' activities. Future studies in this area can significantly improve the performance of the reasoning process.

SH for dementia care should be accurately assessed from both functionality and usability perspectives. The functionality evaluation carefully assesses aspects such as the system robustness, its ability to reduce the difficulties associated with performing care scenarios, and its effectiveness. The usability evaluation targets aspects such as ease-of-use of interfaces, and accessibility. Further studies to create standard evaluation frameworks for SH technologies in dementia care would be of interest as they enable researchers to compare different solutions using similar measures. They could also include, ethical, clinical, economic aspects of the SH adaptation.

Assistive and companion robots are technologies that could improve dementia care. They alter the state of the environment and meaningfully interact with PwDs. Studying these technologies was not one of our research objectives. However, these technologies easily integrate with the SH architecture. For instance, PwDs' interaction with the companion robots can generate data (e.g., voice commands) that when analysed can illustrate information regarding changes in PwD's ability in abstract thinking, judgement, or the ability of speech (Mordoch et al., 2013; Shibata and Wada, 2010).

Before installing the SH technology, it is crucially important to create innovative instruction materials and approaches to introduce the SH potential benefits and drawbacks to the stakeholders. Ultimately, this enables the users to interact with the system more efficiently. There is room for further progress in determining the most effective ways to introduce stakeholders to the concept of SHs for dementia care.

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Appendix A

A: Use case tables

Table A.1: Use case 2: Getting dehydrated

Title	#2 Getting dehydrated
Concept	Dehydration is a dementia symptom that threats PwDs health. The SH should notice it and remind the resident to drink enough water.
The rationale of system reactions	The SH should provide a system for recognising the activity of drinking water. The system *invites awareness* and *suggests*. The system suggests drinking water and monitors the action. Most of the existing applications work based on the inputs by their users (e.g., Daily Water Free application by Maxwell Software). This approach is not suitable for PwDs. There exist a number of approaches for recognising the activity. The approaches such as using video cameras, or a contact switch sensor on the water cooler machine, or counting the number of times the PwD uses the toilet for urinating.
Scenario	**Dorothy** is an elderly person with mild dementia. She lives in her home with her family. She often forgets to drinking necessary daily amount of water and this causes her dehydration, which aggravates her memory symptoms (J. Wilson, Tingle, & Loveday, 2013). Reminding her to drink the required amount of water is one of her caregivers' responsibilities.
Required components	• A contacts switch (sensors) on the water cooler machine. • A *database* system to save the logs and recordings. • A *reasoning engine* to recognise the activities and events. • An *interface* to present the reports.

Table A.2: Use case 3: Communicating with acquaintances

Title	#3 Communicating with acquaintances
Concept	There are telecommunication applications (e.g., Microsoft Skype, Apple FaceTime) providing video calls for computers, tablets and mobile devices via the Internet. However, it is not easy for PwDs to use them. In that regard, The SH should adapt familiar devices (i.e., TV) or natural user interfaces to make the conventional telecommunication applications accessible for PwDs.
The rationale of system reactions	It is not easy for PwDs to use the existing telecommunication applications. The system *suggests* and *performs* to support PwDs. It enables the PwD to contact the acquaintances employing common household devices such as TV and radio. It is worthy to mention that, there are TVs that can connect to the internet and run video-conferencing applications. However, their application interfaces are not designed for PwDs.
Scenario	**Barbara** is an elderly person with mild dementia. She lives in her home with her granddaughter. She cannot stay in touch with her acquaintances as often as before because of her illness and age. Although employing communication technologies such as video conference applications could help, she finds using them extremely challenging.
Required components	• A *sensors* on TV remote. • A *database* system to save the logs and recordings. • A *reasoning engine* to recognise the activities and events. • An *interface* to present the reports.

Table A.3: Use case 4: Misplacing personal items

Title	#4 Misplacing personal items
Concept	People misplace personal items inside a home. However, in PwDs' case it occurs more often. Although the system should inform PwDs and their caregivers about the incidents and the location of misplaced items, it should operate in a way that not causes PwDs constantly depend on it for finding the misplaced items.
The rationale of system reactions	The system *invites awareness* and *urge*. The system notices the incident via rendering the sensors readings (e.g., passive infra-red, contact switches). When there are no risks, the system should only act in cases that PwD could not realise the incident and solve them independently. Also, the system should log the number of incidents as it illustrates the dementia progress.
Scenario	**John** is an elderly person with MCI; he lives independently in his home. He often misplaces the personal items such as keys and the toothbrush. This behaviour is described as slight confusions by his dialogue of care. His formal caregivers suggest that the behaviours will occur more often as his dementia progress.
Required components	• A set of RFID tags *sensors* on personal items. • A *database* system to save the logs and recordings. • A *reasoning engine* to recognise the activities and events. • An *interface* to present the reports.

Table A.4: Use case 5: Losing personal items

Title	#5 Losing personal items
Concept	In contrary to the #4 use case table, in this use case PwDs has a more severe dementia. Therefore, it is improbable that they can remember where the lost or misplaced items are. The system should simply help them to find the items.
The rationale of system reactions	The system *urges*. The system monitors the location of items using the sensors (e.g., RFID). Considering the stage of the PwD's dementia, it is unlikely that he/she can find the items by him/herself. Therefore, after a pre-specified amount of time the system announces items locations through an interface (e.g., TV speaker).
Scenario	**Margaret** is diagnosed with AD. She lives in her home with her family. She often loses her personal items and cannot find them. This event causes frustration; she usually accuses surrounding people of stealing the items.
Required components	• A set of RFID tags *sensors* on personal items. • A *database* system to save the logs and recordings. • A *reasoning engine* to recognise the activities and events. • An *interface* to present the reports.

Table A.5: Use case 7: Remembering time and date

Title	#7 Remembering time and date
Concept	The system suggests. It receives the PwD's request via microphone or a time and date button in the TV remote controller. It announces the time via a voice calendar utilising the TV speakers.
The rationale of system reactions	The system *suggests*. It gets activated rendering the sensors readings (e.g., CSS). As the PwD begins to use the newly added appliance, the system prompts him/her the operation instructions employing the available interfaces (e.g., radio speaker).
Scenario	**Joseph** is a person with AD. He lives in his home with his son. Due to the orientation obstacles caused by disease, he often cannot remember the day, date, month, seasons and the year. This situation causes him stress and anxiety.
Required components	• A set of microphone **sensors** to collect speeches; a button on the TV remote. • A *database* system to save the logs and recordings. • A *reasoning engine* to recognise the activities and events. • An *interface* to present the reports.

Table A.6: Use case 8: Experiencing pacing patterns

Title	#8 Experiencing pacing patterns
Concept	Pacing is a common obstacle for people in early stages of dementia. It happens when PwDs need to use the toilet or drink water during the night time. PwDs face orientation obstacles, therefore when they wake up during the night, they get confused and start walking through the house. The system should support the PwD to go back to sleep.
The rationale of system reactions	The system *invites awareness*, *suggests* and *prompts*. The system identifies pacing using the PIR sensors readings and prompts the PwD's location to him/her and state how the toilet can be reached. The pacing periodically occurs in late stages of MCI, and early stages of AD, hence an increase in the number of its occurrence indicate the disease progress.
Scenario	**Doris** is an elderly person with MCI living independently in her home. She walks (paces) in the house during the night. Many of her pacing incidents begin because she needs to use the toilet at night. She wakes up and leaves the bed; she forgets why she left the bed.
Required components	• A set of PIR motion *sensors*. • A *database* system to save the logs and recordings. • A *reasoning engine* to recognise the activities and events. • An *interface* to present the reports.

Table A.7: Use case 9: Experiencing night-time wandering

Title	#9 Experiencing night-time wandering incidents
Concept	Night-time wandering incidents occurs during the late-stage dementia. They can be seen as advanced pacing. As they are extremely dangerous for PwD's health and safety, the system should quickly respond to them.
The rationale of system reactions	The system *urges* and *performs*. It notices the night time wandering incident through rendering the sensors readings (e.g., passive infrared, GPS) and urges the PwD to return to bed or to go to the toilet. The prompt is stated using a familiar person's voice (e.g., informal caregivers), and it is delivered through devices such as radio or TV. If the PwD kept wandering and tried to leave the house, it triggers an alarm to inform a caregiver. If the caregivers do not respond, or they were far away from the home and the PwD was trying to leave the house, the system locks the exit doors and calls an emergency number.
Scenario	Ruth is an elderly person with late-stage dementia. She lives in her home with her family. She often encounters night-time wandering incidents. She wakes up during the night and walks inside or sometimes goes outside the house. Obviously, without an instant action from a caregiver, her night-time wandering is a threat to her health.
Required components	• A set of PIR motion and pressure (on the bed) **sensors**. • A *reasoning engine* to recognise the activities and events. • An *interface* to state the prompt through speakers and to present the reports.

Table A.8: Use case 10: Forgetting names

Title	#10 Forgetting names
Concept	Forgetfulness is a common dementia symptom that gets worse as the disease progress. It causes different problems for PwDs, an overwhelming one is forgetting acquaintances' names and faces. The problem will occur for all the AD patients. The only way to reduce the progress speed and the PwDs' frustration is to constantly remind the acquaintances' names and faces to them.
The rationale of system reactions	The system *invites awareness* and *suggests*. It detects the changes in the number and quality of personal hygiene tasks via analysing the sensor readings (CSSs bedroom cupboard doors, PIRs in the bathroom). If PwDs ignore the tasks, they will be reminded. For instance, for dressing, the system suggests what to wear and where to find them.
Scenario	**Eleanor** is an elderly person with moderately severe dementia. She lives in her home with her family. Her interests in proper dressing, personal grooming and performing hygiene tasks (e.g., brushing teeth) decreased with the progress of the disease. This lack of interest reduces the personal hygiene and directly decreases the quality of life.
Required components	• A set of PIR and CSS *sensors*. • A *reasoning engine* to recognise the activities and events. • An *interface* to state the prompt through speakers and to present the reports.

Table A.9: Use case 11: Seeing in dark

Title	#11 Seeing in dark
Concept	Vision difficulties have a noteworthy role in the PwD's accidents (e.g., falling) inside the home. Lack of proper lighting causes the majority of these accidents. The system should provide adequate lighting.
The rationale of system reactions	The system **performs**. Since, one of the most significant causes of visual problems for PwDs is the absence of decent lighting. The system sustains the house light level and makes sure that the lights are on when the PwD wakes up during the night.
Scenario	*Richard* is an elderly person with mild dementia living in his home with his family. He does not see the surroundings correctly and hits household objects frequently, particularly during the night time.
Required components	• A set of photocell light *sensors*. • A *reasoning engine* to recognise the activities and events. • An *interface* to state the prompt through speakers and to present the reports.

Table A.10: Use case 12: Performing the personal grooming

Title	#12 Performing the personal grooming
Concept	Late-stage dementia severely affects PwDs' self-awareness consequently they face problems in areas such as personal grooming and hygiene. The system should help the PwD for performing personal grooming and hygiene-related tasks.
The rationale of system reactions	The system **invites awareness** and **suggests**. It detects the changes in the number and quality of personal hygiene tasks via analysing the sensor readings (CSSs bedroom cupboard doors, PIRs in the bathroom). If PwDs ignore the tasks, they will be reminded. For instance, for dressing, the system suggests what to wear and where to find them.
Scenario	**Eleanor** is an elderly person with moderately severe dementia. She lives in her home with her family. Her interests in proper dressing, personal grooming and performing hygiene tasks (e.g., brushing teeth) decreased with the progress of the disease. This lack of interest reduces the personal hygiene and directly decreases the quality of life.
Required components	• A set of PIR and CSS sensors. • A *reasoning engine* to recognise the activities and events. • An *interface* to state the prompt through speakers and to present the reports.

Table A.11: Use case 13: Monitoring vital signs

Title	#13 Monitoring vital signs
Concept	Regardless of the SH elderly residents' dementia stage, they benefit from a health monitoring system that also responds to the residents requests for help in emergency situations.
The rationale of system reactions	The system urges, and performs. It monitors elderly residents' health via various health monitoring sensors and send regular reports to the caregivers. Also, If the elderly resident request for help, it will inform the dialogue of care.
Scenario	**Charles** is an elderly with no cognitive decline. He lives independently. He could benefit from a system for recognising his request for help. For instance, when he falls and have injuries that not allows him to move. Also, the visual presentation of his health status enables the formal caregivers to predict and prevent critical health situations.
Required components	• A set of sound **sensors** to detect shouting, and a set of health monitoring sensors. • A *reasoning engine* to recognise the activities and events. • An *interface* to state the prompt through speakers and to present the reports.

Appendix B

B

Table B.1: NASA-TLX details

Participants	***Mental Demands TLX***	***Physical Demands TLX***	***Temporal Demands TLX***	***Performance TLX***	***Effort TLX***	***Frustration TLX***	***Over-all TLX***
P1	4	0.333333333	4	2	6	2.666666667	19
P2	2	0.333333333	6.666666667	2.666666667	5	6.666666667	23.33333333
P3	5.333333333	0.666666667	7	4.666666667	3.333333333	10.66666667	31.66666667
P4	9	0.266666667	4	4	8	10	35.26666667
P5	14	7.333333333	3.333333333	7.333333333	12	10	54

Abbreviations

Acronyms

AAL Ambient-Assisted Living

AD Alzheimer's Disease

ADL Activity of Daily Living

ANN Artificial Neural Networks

BAN Body Area Network

CSS Contact Switch Sensors

DBMS Data Base Management Services

EUD End-User Development

HCI Human-Computer Interaction

MCI Moderate Cognitive Impairment

openHAB The open Home Automation Bus

OSGi Open Services Gateway Initiative

PIR Passive Infrared Sensor

PwD Person with Dementia

RBS Rule-Based System

RE Requirements Engineering

RFID Radio-Frequency Identification

SH Smart Home

SOA Service-Oriented Architecture

TRIMF TRiangular-shaped Membership Function

TSK Takagi-Sugeno Fuzzy Model

UML Unified Modelling Language

VSR Vital Sign Reading