# Integration of Ambient Assistive Living Technologies in Elderly Care: Lessons Learned from a Longitudinal Study

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Submitted to: Journal of Medical Internet Research
on: March 01, 2024

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## *Abstract*

Healthcare advancements have significantly extended life expectancy, marking a commendable achievement for humanity. Despite this, a variety of factors, chief among them being low birth rates, have led to a prevalent trend where most older adults live alone. In response to this challenge, ambient assistive living technologies emerge as a groundbreaking solution, promising to support older adults in maintaining a thriving life within the comfort of their own homes. Many such ambient assistive living technologies have been designed and tested. However, there appears to be a lack of long-term evaluation studies, with only a handful addressing the outcomes and challenges of real-life deployments. Deploying elderly-friendly smart home technologies needs a lot of preparation and operational problem-solving. This paper describes the lessons learned in the preparation, deployment, maintenance, and dismantling of a deployment site in Singapore. The lessons learned focus on actionable strategies to facilitate the routine embedding of ambient assistive living technologies in the care of older adults.

(JMIR Preprints 01/03/2024:57989)
DOI: https://doi.org/10.2196/preprints.57989

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## Viewpoint and Perspectives

# Integration of Ambient Assistive Living Technologies in Elderly Care: Lessons Learned from a Longitudinal Study

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## Abstract

Healthcare advancements have significantly extended life expectancy, marking a commendable achievement for humanity. Despite this, a variety of factors, chief among them being low birth rates, have led to a prevalent trend where most older adults live alone. In response to this challenge, ambient assistive living technologies emerge as a groundbreaking solution, promising to support older adults in maintaining a thriving life within the comfort of their own homes. Many such ambient assistive living technologies have been designed and tested. However, there appears to be a lack of long-term evaluation studies, with only a handful addressing the outcomes and challenges of real-life deployments. Deploying elderly-friendly smart home technologies needs a lot of preparation and operational problem-solving. This paper describes the lessons learned in the preparation, deployment, maintenance, and dismantling of a deployment site in Singapore. The lessons learned focus on actionable strategies to facilitate the routine embedding of ambient assistive living technologies in the care of older adults.

**Keywords:** Ambient Assistive Living, Sensors, Internet of Things, Older adults, Quality of Life, Normalization process theory

## Introduction

"*I am afraid of dying alone at home* [1]." This fear, expressed by an elderly woman in Singapore, underscores a growing global phenomenon. As healthcare advances have prolonged life expectancy [2], demographic projections suggest that by 2030, 1 in 6 people worldwide will be 60 years old or older, thus entering their elderly years. Unfortunately, many factors, including declining birth rates, changing norms, urbanization, and migration, have led to the evolution of family structures, causing a considerable proportion of these elderly people to live alone. In the USA, almost 26 million people aged 50 or more lived alone in 2022, a number that doubled since 2000 and represents 36% of the population within this age category [3]. Similar trends are seen across the globe, such as in Canada [4], Singapore [5], and France [6]. While there is nothing inherently wrong with seniors living alone, especially since living alone has been characterized as an indicator of robust health [7], older adults constitute a diverse population, and living alone remains challenging for some. Herein, we focus on the understudied group of impoverished, frail older people who live alone and rely on governmental or not-for-profit organizations.

Development in the Internet of Things (IoT) technologies and computational data science have heralded novel digital health interventions, including Ambient Assisted Living (AAL) technologies tailored especially for older adults [8, 9]. AAL technologies are a type of Smart Home technology that enables individuals to remain socially connected while living independently [10]. Smart Homes denote residences equipped with a high-tech network, linking sensors and other IoT-based domestic devices, appliances, and features that can be remotely monitored, accessed, or controlled and provide services that respond to the needs of the inhabitants [11]. The use of AAL technologies among older adults started to gain increasing research attention around the early 2000s [12, 13].

However, end-user adoption and continued usage of AAL technologies are still very low [10]. We believe that a significant obstacle to the sustainable usage of AAL technologies lies in the absence of a proper theory-driven approach to understanding how AAL technologies become routinely integrated and normalized in their social contexts. Intervention development and evaluation require a strong theoretical foundation [14]. Since social distancing protocols implemented during the COVID-19 pandemic have accelerated and mandated the adoption of AAL technologies [15, 16], we believe that work theorizing the processes by which AAL technologies become routinely embedded in elderly care is both relevant and timely. Thus far, there are three distinct bodies of literature on AAL technologies. One that derives from a technical perspective, a human perspective, or both [17]. The technical perspective primarily addresses design challenges and the implementation of AAL technologies. In contrast, the human perspective concerns the socio-psychological factors influencing adoption and shaping the use of AAL technologies.

While much good work has been done, recent research still highlights a lack of richer contextual and long-term approaches to understanding technology use among frail elderly [18]. Indeed, most theoretical tools researchers employ in the humanistic perspective of AAL technologies imply a psychological approach focusing on older adults as a unit of analysis. This is exemplified by the use of rational choice theories and theories of individual motivation, such as the theory of planned behavior, the technology acceptance model, and self-determination theory [e.g., 19, 20, 21]. Such psychologizing of AAL technologies' usage greatly curtails an understanding of how socio-psychological factors shape the routinization of these technologies in elderly care. It neglects that technology acceptance in the elderly context is culturally dependent and will vary from one society to another [18,22]. Indeed, older adults cannot be studied in isolation, especially those frail and in institutional living, because they live in interdependence with one another, their caregivers, and technological interventions [17, 18].

Against this background, we seek to contribute to an emerging agenda of a rich sociological understanding of how older adults adopt and continue using AAL technologies by investigating an assemblage of sociotechnical linkages between different actors [18, 23]. Such a focus is vital because AAL technologies can significantly impact the Quality of Life (QoL) for both older adults and caregivers if and only if they can be effectively integrated into routine practice [14]. To this end, we draw on two longitudinal AAL technology deployment studies to address the following research questions: (1) How can AAL technologies be integrated and embedded into elderly care in context-dependent ways? And (2) What factors facilitate or impede the routine embedding of AAL technologies in elderly care?

The rest of this paper is structured as follows. First, we review related literature and introduce the theoretical framework guiding our narrative. Next, we detail the study's context and the specific AAL technology implemented. Finally, we share key lessons from the technology deployment process.

## Theoretical Foundations

## Related Work

While lessons learned by other researchers provide valuable insights, they lag in three key ways that motivate our work. First, a few of these studies have employed quantitative methods and found that several barriers, including usability concerns, a lack of perceived usefulness, and low technological efficacy, impede the routine integration of AAL technologies in elderly care [24-26]. While these are helpful, richer contextual insights are difficult to capture through quantitative data [27]. Beyond their contributions to specific areas of empirical research, qualitative narratives can also serve to reorient theories. They may influence theories not only relating to individual AAL technology users but also regarding the society within which the use occurs. This is done by bringing attention to the social and cultural dynamics through which the routinization of these technologies occurs [28]. There are exceptions, of course. Drawing insights from an ethnographic case study, Doyle et al. [29] presented recommendations on the four interrelated and dynamic life cycles of independent living technology development: ethnographic inquiry, design, deployment, and ongoing evaluation. However, this differs from our objective to investigate socio-psychological and cultural dynamics that facilitate or impede the integration of AAL technologies into elderly care.

Second, some personal narratives lack an overarching theoretical framework to organize the key recommendations. For example, Consolvo et al. highlight design insights supported by practical experiences, such as keeping the ambient sensors out of older adults' view and providing human touch from the sensor data [30]. However, there is a lack of an overarching theory to create a complete and meaningful picture by linking their work to existing theories and previous research [31]. This is understandable as their work is design-oriented and not psychosocial in nature. Still, to build a cumulative body of knowledge, personal narrative studies should be theoretically driven [32] as this will provide valuable support to the identification of patterns, themes, and connections in the narratives.

Third, only a handful of these studies were conducted in Southeast Asia. Most of those conducted in Southeast Asia employed rational choice theories and quantitative approaches [11, 33, 34]. As indicated earlier, we believe qualitative research is more suited to understand how AAL use evolves over time and why it evolves this way. The use of rational choice theories, with older adults being the primary data source, assumes that the decision to adopt and use a technology lies with the individual elderly user. The reality, however, is far different because AAL technologies are better understood as Complex Adaptive Systems (CAS), which are systems composed of interacting agents described in terms of rules [35]. Agents include the IoT components, older adults, and also caregivers [35]. Such a view of AAL technologies' usage focuses attention on the fundamental mechanisms of emergence [36]. That is, the interactions between users and AAL technologies, along with their caregivers, are intricately linked and shape the overall context of AAL use [37]. Adoption, acceptance, and usage are, therefore, culture-dependent and will vary from one society to another [18,22]. From such a perspective, the use of AAL technologies is viewed as (1) socially and culturally situated and (2) determined by multiple actors interacting in nonlinear and, at times, 'chaotic' ways [38].

## Overarching Theory for the Personal Narrative

Because a fundamental theoretical and empirical puzzle in the complex healthcare interventions literature relates to how the use of these technologies can transcend conscious behavior and become part of normal routine in care activities [14, 36], we anchor our narrative and present our lessons based on Normalization Process Theory (NPT) [14, 39]. NPT is a sociological theory explaining key mechanisms that facilitate or impede the implementation, embedding, and integration of new health techniques, technologies, and other complex interventions [39]. NPT is based on the premise that healthcare interventions are complex social interventions that require multiple people to work together to achieve a desired outcome [14]. It identifies four key mechanisms of the normalization process.

First, *coherence* pertains to target users' sensemaking—understanding the nature and purpose of the intervention. It is related to the notion of perceived usefulness in the Information Systems (IS) and Human-Computer Interaction (HCI) literature [40]. The intervention must make sense to the target users and be compatible with their values and expectations to be perceived as useful [41]. Second, *cognitive participation* means that the intervention must engage and include everyone at every healthcare system level, from patients and their families to healthcare professionals and administrators. Third, *collective action* means that the intervention needs to be integrated into routine practice and be supported by the necessary resources, infrastructure, and training. Lastly, *reflexive monitoring* means that the intervention needs to be evaluated and monitored regularly to ensure that it remains effective and sustainable over time. The adopted framework resulted in, on average, 14 months from approvals and development to reflexive monitoring (see Table 1). The process is not linear, as some activities can be conducted in parallel.

**Table 1.** Global Timeline from User Needs to Deployments

| | ***Activities*** | |
|---|---|---|
| **Month** | **Phase** | **Description** |
| M1 | Development & approvals | Observations, discussions, and prototyping |
| M3 | | Validation and demo |
| M5 | | Applications for ethics approval |
| | | Initial trial and field test |
| M5 | ***Coherence*** Pre-deployment | Briefing sessions |
| M6<br>M6 | ***Cognitive participation*** Participant recruitment | Recruitment sessions and consent forms<br>In-depth interviews and questionnaires |
| M7 | ***Collective action*** AAL Intervention deployment | Deployment and in-depth interviews |
| M8 | ***Reflexive monitoring*** Ground truth and data analysis | Feature updates and maintenance |
| M10 | | Questionnaire surveys and fine-tuning |
| M11 | | Feature updates and maintenance |
| M12 | | User engagement surveys |
| M12 | | Data analysis and feedback |

| | | |
|---|---|---|
| M14 | Feedback on AAL normalization | Interviews and impact on validation |

## Context

We situate our research within the context of frail elderly individuals living alone in Singapore's subsidized public housing. These seniors depend on professional caregiving services provided by Elderly Care Centers. Specifically, Senior Activity Centers (SACs), which have been integral to Singapore's elderly care landscape during our study period, are currently evolving. They are expanding their reach and services under the newly adopted concept of Active Aging Centers, located on the ground floor near the rental flats. The SACs provide various services, including social activities, monitoring frail or homebound elderly, befriending seniors, and responding to emergency alerts. As with any care facility, SAC's daunting challenge is a shortage of manpower. Therefore, AAL technologies were found to be an innovative promise to helping seniors age in place, which can be defined as remaining in the community, with some level of independence, rather than in residential care [42].

## Our AAL Technological Intervention

We developed an AAL technology platform termed Ubiquitous Service MAnagement and Reasoning archiTecture (Ubismart), a live web-based platform with multiple interfaces and communication channels that are continuously expanded [43, 44]. The platform has been deployed in real homes in France and Singapore. Herein we focus on Singapore deployments, which occurred in 3 waves with incremental features in 2016, 2017, and 2018 (see Table 2). Ubismart, depicted in Figure 1, unobtrusively monitors care recipients' activities of daily living. It consists of four modules.

**Table 2. Deployment Details**

| **Location** | **Timeline** | | |
|---|---|---|---|
| | **Duration** | **Starting Date** | **Number of Homes** |
| Geylang Bahru, Singapore | 1 Month | August 2016 | 3 |
| Geylang Bahru, Singapore | 6+ Months | March 2017 | 5 |
| Geylang Bahru, Singapore | 6+ Months | March 2017 | 5 |
| Ang Mo Kio, Singapore | 9+ Months | May 2018 | 6 |
| **Total Number of Homes** | | | **19** |


**Figure 1.** Ubismart setup


**Figure 2.** Deployment layout in older adults' apartment

*First*, multimodal sensors with wireless data transmission capability were installed at different locations (e.g., bedroom, kitchen, toilet, bathroom, and living room) to monitor and detect the activities performed by individual elderly, such as cooking, sleeping, going to the bathroom, going

out of the apartment, etc. As illustrated in Figures 1 and 2, we installed (1) *contact sensors* on the fridge and house doors, (2) *motion sensors* in the kitchen, bedroom, and toilet, and (3) *bed sensors* under the mattress. Contact sensors capture when doors are opened and closed [45]. Motion sensors emit a signal when there is a significant change in the infrared spectrum and, therefore, are used to detect movement. The micro-bend fiber optic pressure sensor mat was placed unobtrusively below the bed mattress or the bed sheet to measure heart and respiratory rates during sleep. This mat provides information on the sleep parameters, such as sleep-wake rhythms, and can be used to detect sleep disorders. The collected data was transferred through a secured gateway with Raspberry Pi to a dedicated server for data processing and analysis. A Raspberry Pi is a pocket-size computer commonly used in IoT applications because of its small size and ability to run Unix-like systems that ease the portability of algorithms. The installation is strictly devoid of any video and audio processing or recording to respect the privacy of our participants.
*Second*, we strategically placed Bluetooth beacons in public areas to track the engagement of senior citizens in outdoor events organized by the SAC. These activities include gardening sessions, bingo games, and various social gatherings. It is important to note that the beacons do not receive nor process any data, and they are not aware of any detections. They are placed at specific locations, and in regular intervals, they emit their own identifiers. The tracking is performed using a custom-made smartphone application that detects these signals and sends data to our servers.

*Third*, the data from the sensors was processed in real-time to provide a visualization of older adults' activities on a mobile application, as schematized in Figures 3 and 4. This app was accessible to the local staff at the Senior Activity Centre and the adult's relatives (if applicable). The goal of the application was to provide information on older adults' Quality of Life in a cognitively efficient manner. As shown in Figures 3-4, visualized data included sleep duration, relative duration spent indoors and outdoors, and washroom and kitchen activities [46-48].

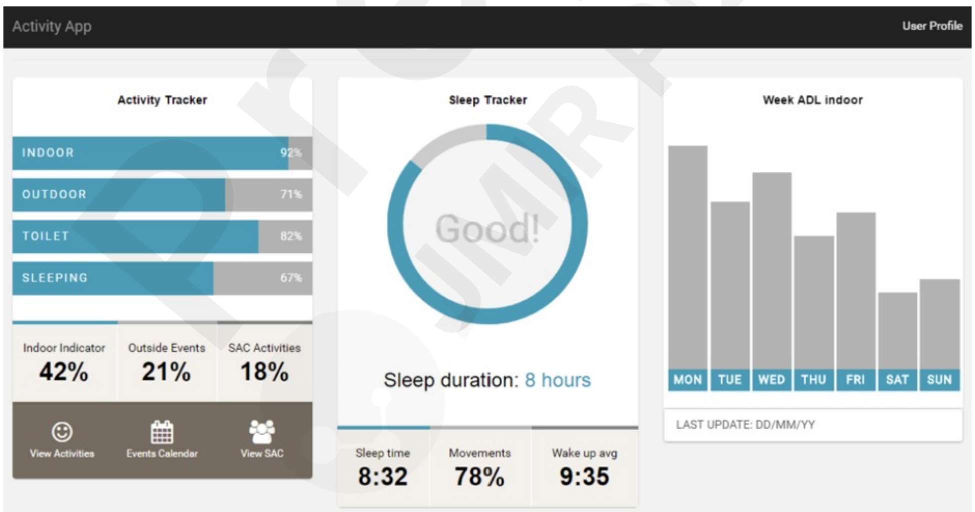


**Figure 3.** Screenshot of older adult activities of daily living, Ubismart

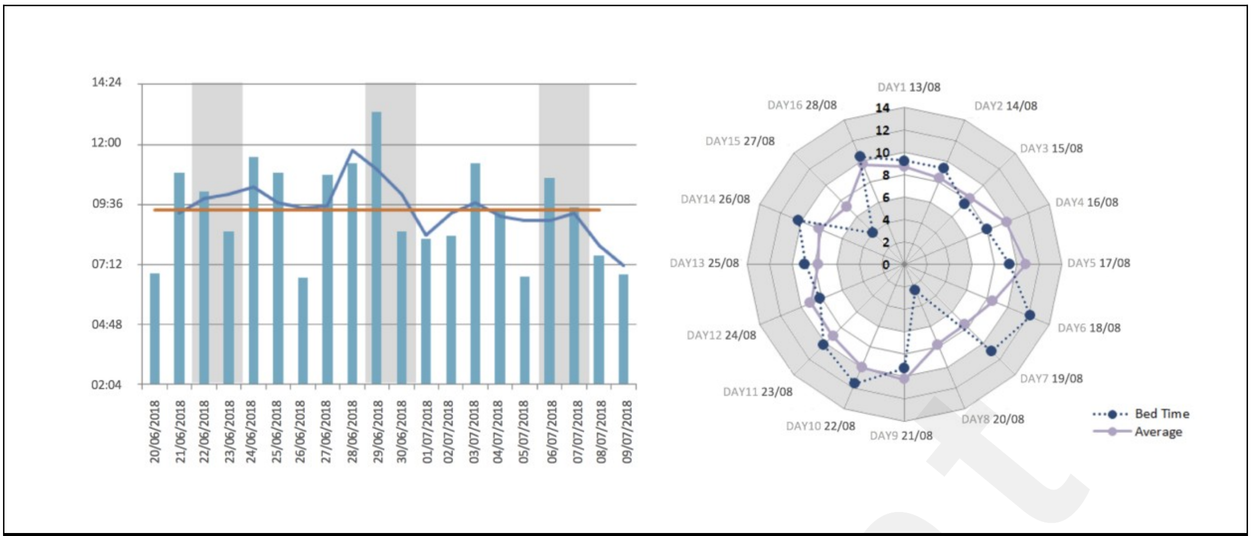


**Figure 4.** Visualization of an older adult's daily sleep activity, based on the data collected by Ubismart

*Fourth*, caregivers receive notifications of any irregularities (such as deviations from the established baseline) through the mobile application. The baseline activities of daily living (ADLs) for older individuals were established through comprehensive semi-structured interviews before deployment (refer to Table 1). Risk alerts are activated when there are indications of significant and concerning behavioral changes. These can be detected through various parameters, including reduced participation in social events (as recorded by Senior Activity Center data), noticeable deterioration in performing basic ADLs, including mobility or challenges in preparing meals during regular hours, and a decrease in sleep quality or sleep-related concerns.

## Lessons Learned and Recommendations

The following sections present lessons learned at different phases of the AAL technologies' integration and normalization process.

### Coherence

Coherence is crucial in the introduction of new practices or interventions, as it represents the process by which *individuals and groups make sense of the purpose and value of these changes* [39, 43]. This is especially true when introducing AAL technology to older adults and SAC caregivers, where understanding its relevance to their existing routines and needs is essential. We discovered that thorough preparation and a deep understanding of older adults' living environments are key to facilitating this understanding. To this end, our technical team constructed a laboratory-based replica of the elderly homes. Despite the expense, this realistic model serves two critical purposes. Firstly, it enables a better grasp of the residences' architectural layouts, allowing for the development of a detailed checklist to streamline the deployment process. Secondly, it acts as a testbed for technical evaluations and adjustments prior to actual deployment. This approach ensures that when explaining the benefits of the intervention, we also convey a comprehensive understanding of the living spaces, making the older adults and caregivers feel included and considered throughout the intervention's lifecycle. Based on these insights, we recommend:

> *Recommendation 1: Construct a live replica of the target residences to evaluate the AAL intervention, detect and overcome potential challenges.*

In terms of conveying the value of the AAL technology, we first engaged the Senior Activity Centers (SACs) and briefed them on the potential benefits. Having predominantly relied on manual processes hitherto our intervention (e.g., visiting the older adults' homes to review wellbeing), they perceived the technology as a valuable enhancement to their caregiving routines. In terms of communicating with the older adults, we observed that they held the opinions of the SAC caregivers in high regard, considering them akin to family. Therefore, although the research team conducted the briefing, the SAC caregivers were also invited to the older adults' briefing to help explain the potential benefits of the AAL intervention.

Besides, a significant proportion of the older adults predominantly communicated in Chinese dialects, including Hokkien and Cantonese. The SAC caregivers played a pivotal role in facilitating translation during the briefing. Drawing from this experience, we recommend the following:

> *Recommendation 2: Examine the relationships between older adults and caregivers and leverage the older adults' rapport with their caregivers to foster a stronger sense of trust and understanding. Consider conducting joint briefing sessions involving both older adults and influential others.*

> *Recommendation 3: For non-English speaking countries, it is crucial to ensure language accessibility. Bilingual or multilingual materials, interpreters, or translated resources should be readily provided to accommodate diverse language requirements. This proactive approach will foster a more inclusive and comprehensible environment during the briefing sessions, effectively engaging older adults and facilitating their understanding of the intervention's benefits.*

## Cognitive Engagement

Cognitive engagement focuses on the *active engagement of individuals in the intervention*. Routine integration of AAL technologies into the care of older adults hinges on their willingness to actively engage in the field deployment and commitment to maintaining the presence of ambient sensors within their homes. Initially, we assumed that a strong coherence, indicating a deep comprehension of the AAL intervention's perceived usefulness, would naturally lead to high participation.

However, hindsight revealed that we focused solely on SAC caregivers' influence, overlooking other potential levels of influence. As our research progressed, we found that a subset of older adults who initially showed keen interest in the intervention were reluctant to proceed with the deployment phase. Our probe revealed that one older adult who seemed to wield significant influence over the rest expressed concerns that these ambient sensors have been linked to radiation exposure. When he opted out, others followed, resulting in low engagement. While we had addressed other concerns, such as privacy and electricity consumption. We had not considered radiation exposure as an issue of concern as the components of the system are all freely available consumer electronics. Drawing from this, we recommend the following:

> *Recommendation 4: Consider a more comprehensive assessment of various levels of influence among older adults. Identify older adults who hold sway over their peers, address their concerns, and involve them as advocates for the intervention.*

> *Recommendation 5: Provide ample time for reflection on the proposed intervention. Although we asked the older adults about their concerns at the joint briefing, we may not have given them sufficient time to reflect. Therefore, it would be best to allow older adults sufficient time (e.g., a few days) for reflection, encouraging them to document their apprehensions for a thorough concern mitigation process.*

## Collective Action

Collective Action addresses *how individuals work together to enact the new intervention* [39]. It involves understanding the collaboration, communication, and coordination required to successfully implement the innovation. As mentioned earlier, collective action also includes deploying the AAL intervention. Therefore, we report our experiences of different aspects of the deployment.

## Internet Connection

Although the live replica of the actual homes was helpful, there were still some challenges. In 2016's deployment, the network communication was performed via an ethernet cable connected to the resident's router. The network connection was very stable. However, our participants had no internet connection for the second and the third deployments, so we provided 3G modems (mobile routers) Huawei E5330Bs-2. Although USB-powered, these modems contain a battery and provide two modes of connection (USB modem and WiFi). The primary drawback is that once turned off, these devices can only be reactivated by manually pressing the physical button; there are no alternative methods to switch them back on. This issue arises if the system is inactive for an extended period, such as during a blackout. A related challenge is the need to top up the SIM card in the modem. Ideally, securing a contract with a local carrier would be beneficial, but this was not feasible for our deployments in Singapore. Therefore, we recommend:

> *Recommendation 6: Collaborate with local carriers to negotiate SIM card deals that align with your project's needs. Establishing a partnership with a carrier can facilitate smoother operation and address connectivity challenges more efficiently. We would highly recommend considering a monthly subscription to eliminate the complexities of frequent top-ups.*

## Indoor sensor deployment

It is crucial to respect general and manufacturer-specific instructions for pasting stickers: the receiving surface must be clean and smooth, and the sensor must be held in place for at least 30 seconds. Per our experience, a non-greasy wall can successfully hold a sensor. In our conditions, the surface can often be hot (refrigerator without proper cooling) or greasy (kitchen tiles). We tried hook-and-loop fastener ("Velcro") stickers and dimensional double-sided tape ("3M"). We obtained a more stable positioning with double-sided tape. Based on these insights, we offer the following recommendations:

> *Recommendation 7: Explore screw-in options as a priority. Generally, it's advisable to avoid using adhesive materials. If screw-in options are not feasible, consider placing devices on ledges that are out of reach. Ensure that the surface for pasting is thoroughly clean and free from grease and that its temperature remains stable.*

A frequent problem with sensors is their tendency to either fall off or deplete in power. Falling off not only risks damaging the sensor but can also render it inoperative. Even without any damage, it compromises the data quality or the intended functioning, e.g., a fallen motion sensor does not monitor the intended area, or a door contact sensor stops sending the data altogether. In several cases, the entrance door contact sensor disappeared, probably because of regular building corridor sweeping. In one case, the sensor was painted over with the rest of the gate.

Another expected problem is running out of power (i.e., batteries). Maintenance should be scheduled. The lifetime of a battery can be estimated the best with a test deployment for an extended period of time. It is worth making sure that the sensor configuration is optimal. For instance, a sensor sending data every 10 seconds instead of every 4 minutes makes the battery drain 24 times quicker. In some cases, we observed that sensors were sending only one type of event (e.g., "off" signaling absence and never presence) – in this case, the problem was of a software nature. Therefore, we recommend the following:

*Recommendation 8: Carefully configure sensor settings to optimize battery usage while capturing relevant data. Avoid excessively frequent data transmission intervals that could drain batteries prematurely. Regularly review and adjust configurations based on usage patterns and feedback.*

*Recommendation 9: Implement fail-safe mechanisms that alert the technical team or administrators when a sensor's battery is running low or data transmission is disrupted. This proactive approach can help prevent data loss and ensure timely maintenance.*

It is also crucial to recognize that altering the factory default settings of sensors may become necessary as issues emerge. For instance, sensors may be set to emit signals every 10 seconds by default, whereas a more suitable interval might be every 1 minute. Any changes to these default settings should be meticulously documented. This ensures that, in the event of sensor replacement, the team can maintain consistency with the adjusted settings as per the modified protocols. Therefore, we recommend:

*Recommendation 10: Establish a protocol for regularly reviewing and adjusting sensor settings from their factory defaults to suit specific deployment needs. Ensure thorough documentation of all changes for consistency in case of replacements or system updates.*

## Outdoor sensor deployment

We chose surfaces shielded from rain and wind, typically under roofs or shelters. The places where the devices are to be installed are often difficult to access (possibly with accumulated dirt), necessitating physical effort and gloves for protection. Notably, sensors must be fixed to their support or a vertical flat surface. The choice of the place has to consider the optimal position for tracking and the position where the sensor is not easily tackled (salient or near the way for the residents). Even if the optimal solution is to use screws, it is often impossible to drill holes in walls, and the only option is to use adhesive materials to keep sensors in place. Drawing on this experience, we recommend the following:

*Recommendation 11: Recognize that installation conditions and requirements can vary from site to site. Design your sensor deployment with flexibility in mind to accommodate a range of attachment methods and positioning strategies based on the specific constraints and opportunities presented by each installation location.*

*Recommendation 12: Consider involving the local community in the decision-making process if the sensors are placed in residential areas. Consult with residents to gauge their preferences and concerns regarding sensor placement. This can help avoid conflicts and ensure a collaborative approach to data collection.*

## Remote Connection

Operational problem-solving was enabled by a remote connection to our gateways using a secure shell connection where the gateways maintained an SSH tunnel to our server. In such a way, we were able to gather information about multiple parameters (CPU temperature and load, RAM, and storage). Therefore, we recommend:

*Recommendation 13: Implement automated monitoring tools that continuously track the parameters that may indicate issues with the deployed infrastructure. Set up alerts to trigger notifications when certain thresholds are exceeded or abnormal patterns are detected. This proactive approach allows for swift intervention before issues escalate.*

## Visualizations

As previously discussed, the AAL intervention involves an unobtrusive monitoring system and a combination of indoor and outdoor sensors. These devices gather signal information from elderly participants, generating data on Activities of Daily Living (ADL), mobility, and lifestyle patterns. The caregiver platform, supplemented by a reasoning engine, refines this raw data into an array of visualizations and services. These tools are designed to evaluate the Quality of Life (QoL) of the elderly participants, encompassing aspects like behavior change tracking, activity recognition, vital sign monitoring, and ADL metrics. These services, co-created with caregivers, facilitate timely and appropriate interventions. We have experimented with various front-end visualizations for the users, ranging from simple data signal displays to more complex computed data metrics and comprehensive dashboards that integrate open data (as shown in Figure 5) and external factors like air quality or environmental data.

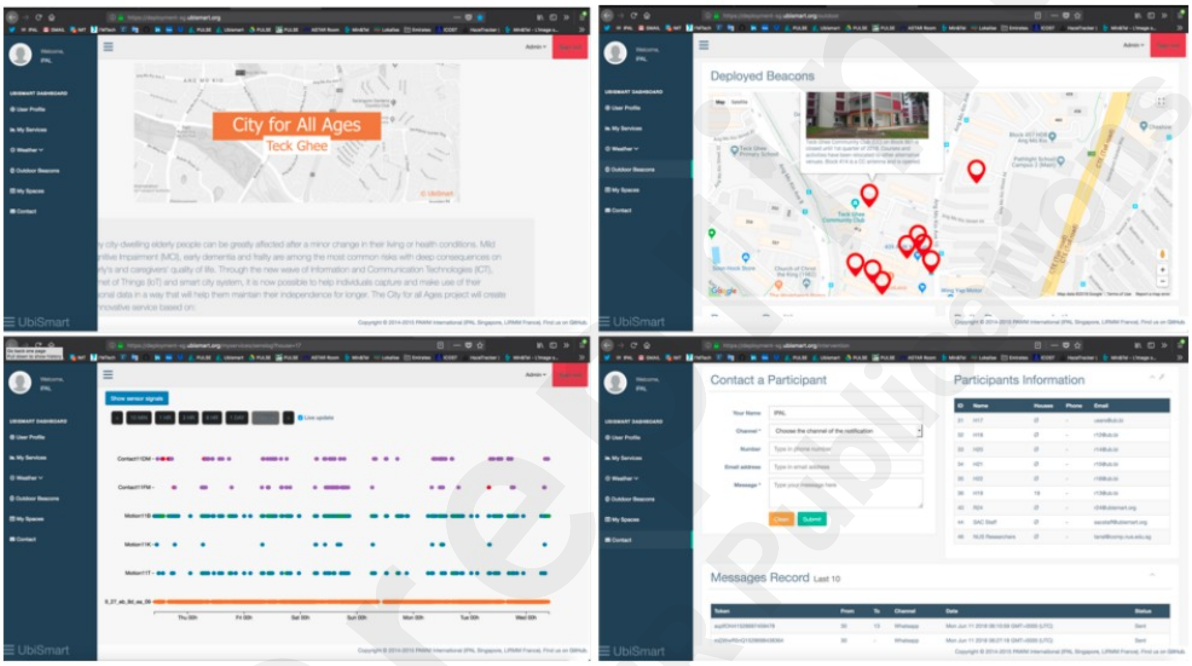


**Figure 5.** Dashboards available to the caregiver in Ubismart: top left project information top right placement of Bluetooth beacons, bottom left real-time events view, bottom right messaging to participants

Based on these developments, we suggest the following recommendations:

> *Recommendation 14: Continuously analyze the data collected to derive insights about participants' well-being, trends, and potential areas of concern. These insights can inform improvements to the intervention and provide valuable knowledge for caregivers and participants.*

## Data Collection and Interpretation

Another major challenge was the assessment of sleep quality. The sleep fiber optics sensors can detect body movement, heart rate, and respiratory rate. When the bed is empty, the output signal is mainly noise (averaging around the same amplitude). A change of position of the monitored person, such as sitting up or lying down, provokes a sudden peak in the signal. When lying down still, the system detects lung expansion and even heartbeat as smaller peaks. Zooming progressively into the body-related amplitudes detects the "respiratory patterns" signal. We successfully matched the analysis of bed sensor data with the self-reported data from the questionnaire and semi-structured interviews about the older adults' activities of daily living (see Table 1) to ensure an accurate interpretation of the sleep data. The self-reported data aimed to confirm their sleep patterns. We asked questions such as: 1) What time do you usually go to bed? 2) Do you tend to wake up in the middle of the night? If so, how many times? 3) Do you sleep during the day? Therefore, we recommend:

> *Recommendation 15: Correlate and establish matching of sensor data with self-reported assessments.*
>
> *Recommendation 16: If possible, enhance the sensor's analytical capabilities and accuracy by integrating advanced signal processing techniques. By implementing sophisticated algorithms that can differentiate between true body movement, heart rate, and respiratory rate signals versus noise, you can improve the sensor's ability to provide reliable sleep quality assessments. This enhancement can reduce the reliance on self-reported data and ensure a more precise interpretation of sleep data, enhancing the overall effectiveness of the assessment process.*

## Reasoning

The reasoning engine applies rules at the runtime. The engine runs when the sensor events arrive or after a timeout when no event is produced in a specified time period. It collects the data from various sources, including public open data. The applied rules transform the raw data into processed data corresponding to the ADL metrics, mobility measurements, and other relevant information.

As the aforementioned problems happen, the reasoning must be flexible enough to consider the events that arrive after the time of their supposed processing. An example of such a situation is when the 3G router stops working, sensor events keep arriving at the module responsible for sending them, and they wait until the connection is restored. Due to limited access to people's homes, this can take several days. The reasoning cycle should consider the late events and recompute the past activities according to the new information about that time [48]. Our reasoning is based on an ontology and triples describing the knowledge base containing the information about the system status instantiated for each participant. It is a rule-based system making inferences over triples (subject, predicate, object).

*The knowledge-oriented approach in semantic web:* Organization of the data in triples provides a more flexible way of handling models: it describes the environment, and allows to integrate many sources. The challenge lies in algorithms that have to be defined in a different way than usual imperative programming that tells a computer what to do. Instead, in declarative programming, we describe knowledge (input), conditions restrictions (rules), and select the output (query); thus, the reasoning engine provides us with the result in the defined form.

*Generating an ontological model*: The model of a specific problem is formulated as an ontology and involves several elements: classes or concepts that identify types of objects that are significant in the system. These classes (concepts) have roles or properties that define their features. In addition, restrictions (or facets) may be applied to classes to further refine their characteristics. The knowledge base contains the ontology and its instantiation. This means the actual instances (or "objects") that correspond to the classes defined in the ontology. For example, a class of a Person is instantiated as a participant01 with an associated name, being connected to our system via a specific set of instances of equipment. The knowledge base is illustrated in Figure 6 as a knowledge graph on the left side, while the ontology is presented in a tree structure on the right-hand side of the figure. An ontology defines a common vocabulary for researchers who need to share information in a domain. It includes machine-interpretable definitions of basic concepts in the domain and relations among them. Drawing on the above, we recommend the following:

> *Recommendation 17: Enhance the reasoning engine's flexibility to accommodate delayed data to address situations where events arrive late due to technical issues.*

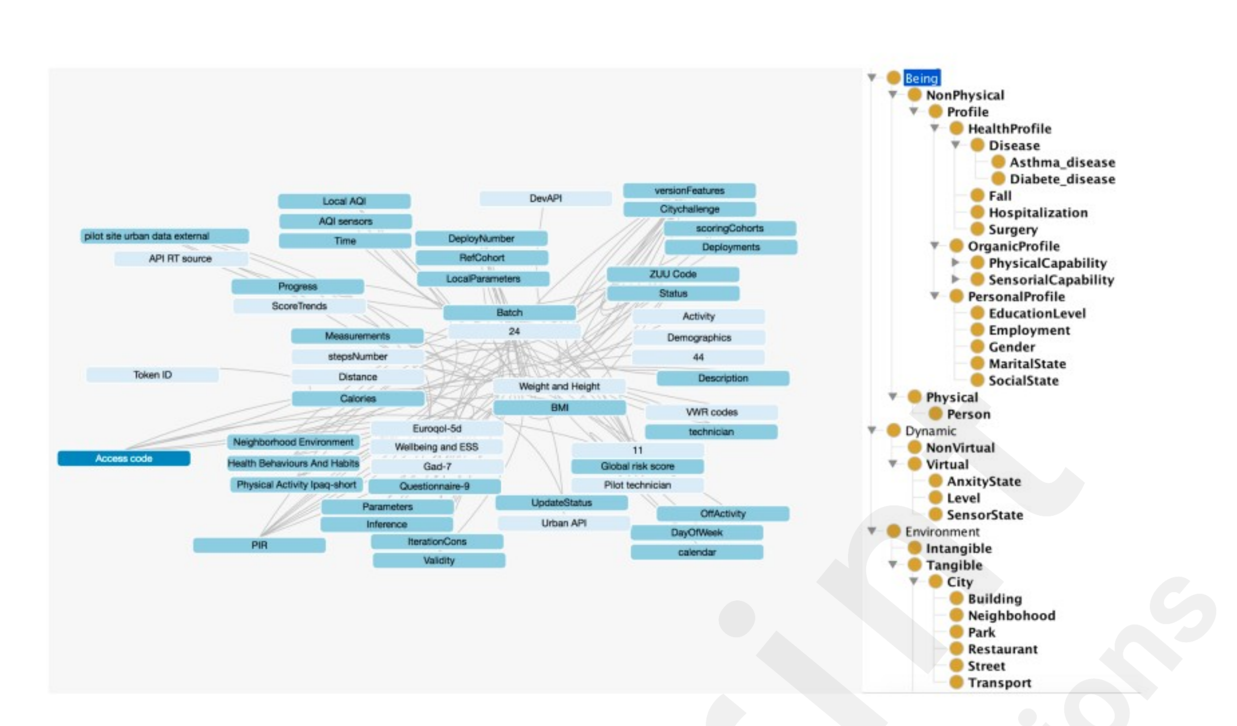


**Figure 6.** Ontology hierarchy (links and classes)

## Reflexive Monitoring

This phase of the NPT is concerned with *how users will perceive the intervention once it has been in use for a while* [14]. As mentioned and shown in Table 1, we conducted semi-structured interviews with older adults and caregivers. We also used questionnaires to capture the older adults' perceived quality of life.

The SAC caregivers continued to be supportive of the AAL intervention. One shared, "*we are very supportive of this because we feel this approach is non-intrusive. It respects the seniors' privacy… and we are able to ensure that they are okay at home.*" Thus, caregivers continued to exhibit keen enthusiasm for the AAL intervention, recognizing its capacity to facilitate personalized care provisions.

The impact on the Quality of Life for older adults is noteworthy. The prevailing sense of security both at home and within the city, facilitated by monitoring technologies, significantly influenced users' daily experiences. The reassurance of being safe in familiar surroundings and the local community served as a motivating force for enhancing overall lifestyle. As one older adult articulated, "*it is like having an insurance for us. If anything happens to us, the headquarters (the SAC caregivers) will know, for example, if we have a fall*." Another individual emphasized the value, stating, "*that is very good indeed, I'm afraid no one will know if anything happens to me. So, it's great to have something like this. I'm worse off without it!*" This heightened sense of security catalyzes positive behavior changes, underscoring the technology's profound impact.

Interestingly, we uncovered an unintended consequence. A notable case exemplifies this: a participant among the older adults expressed how the intervention contributed to her heightened sense of safety. However, she also revealed that the caregivers' attentiveness has diminished as they increasingly rely on the AAL intervention for monitoring and support. She shared that "*my life is quite difficult. I just hope that those downstairs [caregivers] will look up the old people more often. I am lonely in this flat, and should have someone come up to visit me, right? For example, if I have a son or his wife, I would say, no need, right? Here is an elderly who cannot conveniently move her hands and legs, and yet there is no one to visit. If no one else, who will?*" It appears that while AAL technological interventions solve the problems associated with timely interventions, they can create another problem of loneliness and isolation if mechanisms are not put in place to ensure that older adults still have frequent visits. Indeed, the caregiver mentioned that due to the implementation of the AAL intervention, they now prioritize visiting those who are unwell.

Drawing from these experiences, we recommend the following:

> *Recommendation 18: While the AAL interventions offer valuable benefits in terms of safety and monitoring, ensure that caregivers remain engaged and attentive to older adults' emotional and social needs. Encourage caregivers to continue their interactions and visits to address the feelings of loneliness and isolation some older adults may experience.*
>
> *Recommendation 19: Consider integrating social activities or events into the intervention approach. This can help address feelings of loneliness and isolation among older adults by providing opportunities for interaction and connection with caregivers and peers.*
>
> *Recommendation 20: Integrate AAL interventions with non-digital strategies, such as involving university students or non-profit organizations to provide in-person visits and support.*

## Discussion And Conclusion

The aging population represents a significant demographic trend of the 21st century [49]. This phenomenon is largely due to factors such as declining birth rates, leading to many older adults living alone. While living alone may not pose a significant issue for healthy seniors, it becomes a concern for those who are impoverished and frail. Ambient Assistive Living (AAL) technologies are often lauded for their potential to aid these elderly individuals in aging comfortably within their own homes.

However, there has been a scarcity of systematic studies examining the routine integration of these technologies into elderly care. Consequently, both researchers and practitioners find themselves with limited guidance on the effective design, deployment, and maintenance of these systems in contexts of elderly care. To address this gap, this study shares processes involved in the design and deployment of an AAL technology intervention in elderly care. Adopting a sociological perspective, we investigated factors that promoted or impeded the integration of AAL technology into elderly care. This perspective allows us to view the use of AAL technologies as a network of distinct agents engaging in a sociocultural dynamic. Drawing from our experiences, we share 20 recommendations to guide future researchers and practitioners in the successful deployment and integration of AAL technologies into elderly care.

Important to note, however, is that these are not dogma but recommendations based on our team's lived experiences. As mentioned earlier, technology acceptance in the elderly context is culturally dependent and will vary from one society to another [22]. Hence, these recommendations should not be viewed as inflexible doctrines. We encourage other researchers to contribute their own lived experiences, further enriching the body of knowledge concerning the sociological aspects of technology adoption and usage in elderly care. This collective effort can lead to a synthesis of culturally specific and universally applicable strategies.

## Acknowledgements

This work was supported by the European project City4Age that received funding from the Horizon 2020 research and innovation program under grant agreement number 689731. We would like to thank all the participants who accepted to be part of this experimentation and all our collaborating geriatricians and professional and informal caregivers.

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