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ORIGINAL RESEARCH

DOMUS: a domestic ontology managed ubiquitous system

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Abstract

In the last decades, researches in the fields of Ambient Assisted Living and Smart Home have adopted technological paradigms to provide inhabitants with tailored solutions able to help them in their daily life, enable energy savings and monitor safety. Within this context, this paper introduces DOMUS, a Domestic Ontology Managed Ubiquitous System aimed at enabling the Smart Home paradigm and supporting dwellers characterized by frailty in autonomous living, a condition affecting elderlies in both physical and cognitive ways. DOMUS leverages ontological modelling of many domains of knowledge to customize indoor comfort management and to assist the dwellers in some of their Activities of Daily Living. The presented system exploits the semantic modeling of inhabitant's health-related concepts to trigger the actuation of indoor comfort metrics inside the domestic environment. DOMUS's complexity is hidden to the dwellers, who can interact with the system via an adaptive ubiquitous interface—the Home Interactive Controller (HIC). In this work, DOMUS's architecture and its ontological framework are described in detail. Also, the functionalities provided via HIC and dedicated to the inhabitants are presented, focusing on customization of comfort and assistance in the process of meal preparation. Preliminary tests concerning the inferences produced by the ontologies, the evaluation of the usability of the system and its acceptance from target users are also presented: the first results highlight a good level of usability of DOMUS through the HIC, while its level of acceptance is encouraging and suggests some improvements.

Keywords Ontology engineering · Smart environment · Smart home architecture · Ontology-based decision support system

1 Introduction

In recent decades the Smart Home has emerged as one of the paradigms aimed at enhancing inhabitants' life quality, helping them in managing daily routine activities and providing them with tailored indoor comfort-related solutions (Alam et al. 2012). The Smart Home touches on a wide range of research fields, including Ambient Assisted Living (AAL), Context Awareness (CA), Ambient Intelligence (AmI), and the Internet of Things (IoT). Due to the variety of research fields that it crosses, the Smart Home has been widely addressed in literature as a set of technologies with the potential of providing solutions dedicated to ageing population's independent living, monitoring the domestic safety of the dwellers, preventing injuries and accidents, providing tailored indoor comfort and maximizing energy saving. These features are particularly relevant when considering the global population ageing trend portrayed by the World Health Organization (WHO) (2020): the number of people aged 60 or more is expected to increase from 12% in 2018 to 22% in 2050. Moreover, elderly population is more likely to develop several age-related chronic conditions affecting both cognitive and musculoskeletal apparatuses (such as frailty, mild cognitive impairment, dementia, and Parkinson disease), which require personalized care. Therefore, in the near future national health systems will have to face several challenges, including an increase in social costs and the inability to promptly deliver care. In this regard, Smart Homes can be deemed as a promising solution to adequately tackle ageing population issues: in a recent literature review, Bennet et al. (2017) underlined how researchers tightened the relationship between Smart Homes and healthcare, since the former provides the means to monitor environmental

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changes and inhabitants, elaborate data and provide tailored solutions—thus enabling decentralized healthcare. Moreover, the maturity of IoT technologies and the emergence of novel Artificial Intelligence (AI) paradigms bring new opportunities to Smart Home research, by enabling the connection and interactions of smart objects and the possibility to gather and further elaborate data to make decisions.

Despite the above-mentioned advancements, Smart Home has to face some concerns involving both social and health-related aspects not to jeopardize its large-scale development. In fact, from a social perspective, it has been highlighted since the early 2000s (Demiris et al. 2008) how the technologies needed to enable the functioning of the Smart Home may raise some concerns in the ageing population, as they may not be familiar with it. Also, privacy concerns arise when it comes to monitoring devices: target users' perception of being monitored results in their need for more privacy-aware settings (Zheng et al. 2018). In particular, the use of data gathered by Smart Home devices concerns users, who may want to be able to personalize privacy settings according to their expectations (Psychoula et al. 2018, 2020). With regard to health-related aspects, Smart Home research has adopted data-driven AI techniques to analyze data coming from wearables and environmental sensors as a promising approach to promptly detect different critical situations. However, this type of approach may lack adequate transparency (in particular for healthcare professionals) when it comes to making decisions, and may also neglect the user's clinical history, which covers a pivotal importance in both diagnosis and care. Relying solely on data-driven approaches can result in "black-box AI", thus making Smart Homes' automated decision-making potentially biased (Arrieta et al. 2020).

This work introduces the Domestic Ontology Managed Ubiquitous System (DOMUS) aimed at enabling a Smart Home paradigm to overcome the concerns described above. DOMUS is the main outcome of the Future Home for Future Communities (FHfFC) project (Future Home for Future Communities project 2019), an Italian research project whose purpose is to develop a prototypical smart home able to integrate several technological solutions to promote inhabitants' comfort and safety, and to support them in several Activities of Daily Living (ADLs) (Katz 1983). The prototype was developed for older adults characterized by frailty (Fried et al. 2001; Clegg et al. 2013), a condition involving muscular weakness, poor endurance, weight loss, cognitive and memory functions—conditions that can be aggravated by malnutrition (Artaza-Artabe et al. 2016). DOMUS has been deployed inside CNR-STIIMA's Living Lab in Lecco (in the Lombardy Region of Italy); it consists of a network of sensors deployed in the environment and leverages on semantic representation of the several domains of knowledge (data gathered by the sensors, indoor comfort metrics, inhabitants' health status and preferences, environment's status and devices deployed inside the environment) to provide tailored actuations to the dwellers through the exploitation of automatic reasoning. DOMUS provides the inhabitants with a set of functionalities that can help them in some ADLs and support them in managing the house via a simple and effective Graphical User Interface (GUI).

The adoption of Semantic Web technologies for DOMUS is motivated by the necessity to include both inhabitants and experts' knowledge, as well as representations of the devices and the data they produce. Contrary to a solely data-driven approach, DOMUS exploits WHO classifications to model dwellers' health conditions, thus enabling health professionals (dwellers' caregivers, physicians, etc.) to understand the extent of inhabitants' impairments. Leveraging semantic reasoning, DOMUS monitors inhabitants' environment to support them in some ADLs while helping them managing indoor comfort. The interaction with DOMUS is performed via a GUI—called Home Interactive Controller (HIC) (Pizzagalli et al. 2018)—which also allows dwellers to control several aspects of the domestic environment such as indoor comfort (in particular temperature, humidity rate, illuminance, and CO_2 concentration), dweller's personal calendar and the thorough meal preparation instruction (an instrumental ADL). To ensure dweller's privacy, the personal data modeled in the DOMUS knowledge base and data produced by sensors are stored on the Stardog semantic repository (Stardog Knowledge Graph 2019).

This paper is organized as follows: Sect. 2 underlines some of the remarkable works in the field of Smart Homes exploiting AmI, CA and semantic-based technologies, thus setting the scientific context and highlighting DOMUS peculiarities. Section 3 details DOMUS architecture, delving into the description of, the physical layer (i.e. sensors and actuators deployed in the home), the HIC, the semantic layer composed of different domain ontologies, as well as the middleware architecture deployed to provide intercommunication among these layers. Section 4 describes the functionalities that DOMUS can provide to its inhabitants by depicting a set of use cases. In Sect. 5 a preliminary validation of the inferences generated by reasoning process and the usability of HIC (focusing on ADL meal preparation) are presented. Finally, the Conclusions summarize the main outcomes and draft the future works that need to be implemented to enhance DOMUS.

2 Related work

Smart Home applications experienced a wide growth in the last decade and the use of semantic-based models has emerged as one of the possible solutions to provide formal knowledge bases in the context of living environments involving AAL, CA and AmI technologies.

In particular, ontologies—shared, explicit and Description Logic-based conceptualizations of the knowledge and the relationships among the concepts composing a domain (Gruber 1995)—are adopted to represent a variety of domains of knowledge. Thus, ontologies can provide some solutions to the issued of data interoperability, knowledge integration and intelligent decision support also in the context of Smart Homes, as depicted in the Semantic Smart Home (Chen et al. 2009a). The application of ontology and Semantic Web finds adoption also in Grid computing: ontologies can in fact provide a semantic foundation for distributed computing to foster resource sharing, while providing information interoperability (Chen et al. 2002). This approach allows integrating and managing the different activities of knowledge management, and is able to support complex process automation, as well as collaborative problem solving (Chen et al. 2006).

One of the challenges related to the adoption of ontology in the context of Smart Home is the representation of the domestic environments and the devices populating them. In Sorici et al. (2015) the authors leveraged semantic knowledge representation to model the context to tackle the problem of openness and heterogeneity in AmI applications. As a result, a formal model for context representation and reasoning (called CONSERT) was developed to provide formal descriptions of several entities and relationships occurring among a variety of actors involved within an intelligent environment. CONSERT is also equipped with a reasoning engine that can be used to recognize some ADLs contained in specific datasets and to evaluate the results obtained by the dwellers in performing such ADLs (Trăscău et al. 2018). The possibility to rely on the cooperation among various devices within the Smart Home is addressed by the Semantic Event Notifier, a middleware aimed at providing real-time events notification among the different devices of an AmI system (Modoni et al. 2018).

Also, semantic modeling of dwellers' profiles, their needs and preferences is a cornerstone for the Smart Home and is a widely investigated field: this challenge is essential to provide personalized services in smart environments. In Skillen et al. (2014) users' behaviors are characterized by leveraging ontologies of users' profiles; by exploiting semantic rule-based reasoning, the proposed approach grants services personalization for CA applications also in changing environments. An approach more focused on human activities is proposed by Ni et al. (2016), who developed a set of ontologies encompassing dweller's personal profile, ADLs description and smart home environment. This set of semantic models was engineered to support the development of Smart Home applications requiring the monitoring of human activities: activity monitoring, representation and recognition in AAL applications is still an open challenge. In this regard, Triboan et al. (2017) adopted semantic web technologies to segment real-time sensor data streams to enable complex activity recognition; this approach acknowledges many types of complex activities and allows users to define preferences and rules. Similarly, Noor et al. (2018) proposed a framework leveraging an Activity Ontology that allows describing the physical activities, the objects, the sensors and the interactions occurring among these actors; reasoning processes allow the smart home to recognize the activities performed by an individual inside the environment.

The representation of inhabitants' health status through ontologies for AAL applications constitute a challenge that some researchers tried to tackle: Spoladore and Sacco (2018) described a decision support system that leverages ontological representation of individuals, their health condition—relying on a World's Health Organization standard, the International Classification of Functioning, disability and health (ICF) (World Health Organization 2001)—and household appliances to support designers in the reconfiguration of living environments. The Smart Home Simulator (Spoladore et al. 2017), a mixed-reality application designed to support the reconfiguration of domestic environments, exploits a prototypical version of this decision support system to suggest designers the type and features of the appliances to be deployed inside the dwellers' homes, to facilitate them in some ADLs. A similar approach based on ICF was adopted also in RoomFort (Spoladore et al. 2018) and e-Cabin (Nolich et al. 2019; Mahroo et al. 2020) in which the authors developed two AmI applications relying on a set of domain ontologies to provide customized comfort for business travelers in hotel and cruise passengers; the applications exploit a rule-based system leveraging on the knowledge formalized regarding the business travelers, his/her preferences and the indoor comfort metrics measured by the sensors deployed in the room. Acknowledging the role of ADLs for ageing population, researchers dedicated some relevant works to model and foresee inhabitants' needs and behavior within smart environments. Okeyo et al. (2011) proposed an approach based on ontology evolution, in which a representation of ADLs is updated through the discovery of new users' behaviors inside the domestic environment; in this way, ontological models can leverage behavior recognition to provide personalized services. Kim et al. (2019) proposed a system able to recognize dwellers' intentions of performing an activity leveraging ontological representations of intentions. The opportunity of relying on datasets to better comprehend ADLs is addressed by IE Sim application (Synnott et al. 2014), which provides a graphical simulation tool easing the creation of reliable simulated sensor datasets for ADLs to help people affected by dementia.

As mentioned in the Introduction, data regarding users' health status and activity monitoring may rise perceived privacy issues among inhabitants. In this regard, fewer works delved into adopting Semantic Web technologies to mitigate inhabitants' perception of being monitored. A purely ontology-based approach is proposed in LIDoMS (Spoladore et al. 2020), a framework exploiting data coming from domestic devices to support them in ADL without tracing them: since the ADL recognition is based only on the user's location within the house the monitoring of the residents is limited. A more complex approach leveraging Deep Learning techniques and aimed at preserving health data privacy in AAL contexts is proposed in Psychoula et al. (2018): this work introduces a model aimed at achieving the privacy of input data before they are distributed to AAL stakeholders.

DOMUS peculiarity is to foster the adaptation of the domestic indoor comfort metrics leveraging on the representation of dwellers' health conditions in the knowledge-base. DOMUS opts for a clinical representation of inhabitants' statuses using the WHO ICF standard to provide a model of the individual's specific necessity and taking advantage of his/her clinical history. Following the work presented in LIDoMS, the proposed system avoids direct monitoring of the end users, thus preferring monitoring the environment and its characteristics. In this way, leveraging on well-established models for devices and comfort representation, personalized comfort metrics can be set by the inhabitant (or his/her caregivers) to help him/her achieving an indoor condition suitable to his/her health status. Moreover, by exploiting the knowledge regarding the inhabitants and a formalization of comfort metrics, DOMUS can provide tailored services to the inhabitants and support them with specific suggestions and actuations. Finally, the complexity of the DOMUS framework is hidden from the end-users, who can control several aspects of the domestic environment using a simple interface (HIC) accessible on several devices and rooms of the house.

3 DOMUS: the "Future Home for Future Communities" Smart Home

As mentioned in the Introduction, the Smart Home paradigm enables several smart services within the domestic environment to ensure tailored and customized indoor comfort while maximizing the inhabitants' wellbeing. In this context, DOMUS is a system that aims at providing the maximum level of comfort within the house; DOMUS is conceived as an Internet of Things (IoT) system in which interconnected devices sharing the pieces of knowledge cooperate to provide the dwellers personalized services and tailored comfort, while supporting them in performing some ADLs. DOMUS is composed of four layers:

1. The Physical Layer, including all the hardware devices, appliances, smart nodes—such as sensors and actuators; the physical layer consists of multiple ubiquitous devices which collectively form a network of interconnected and interrelated sensors and actuators, to sense, measure, collect, and exchange data.
2. The Home Interactive Controller (HIC), an intuitive GUI designed to act as a client-side remote controller for users to access and monitor home appliances. HIC can be used via tablet, smartphone or plain surfaces of the house using a projector.
3. The Semantic Layer, consisting of a set of domain ontologies developed with the W3C-endorsed languages Resource Description Framework (RDF) (Lassila et al. 1999), Ontology Web Language (OWL) (Antoniou and Van Harmelen 2004) and Semantic Web Rule Language (SWRL) (Horrocks et al. 2004), with SPARQL Protocol and RDF Query Language (SPARQL) (Sirin and Parsia 2007) as a query language.
4. The Middleware layer to connect, translate, and exchange data between the HIC and the semantic layer, and between the physical layer and the semantic layer.

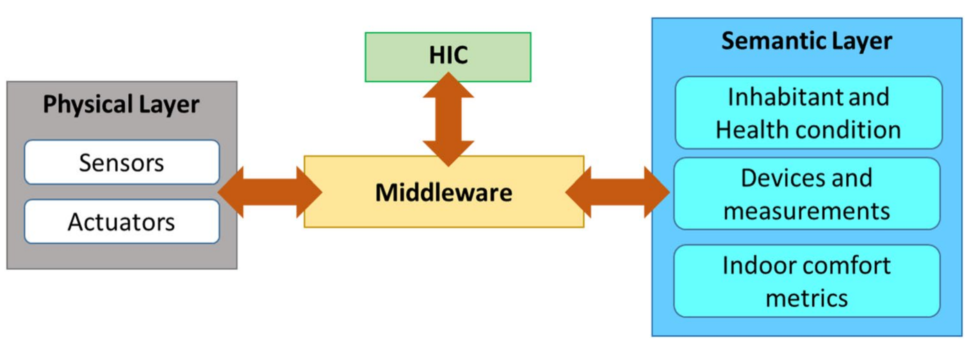


Fig. 1 A schema representing the general architecture of the DOMUS framework, composed of four layers

The following Fig. 1 provides a graphical representation of the overall architecture of the framework and its four layers.

It is worth noting that the entire DOMUS framework works in compliance with the European General Data Protection Regulation: users' consent can be revoked at any time. Health data (see further Sect. 3.3.1) are compiled by clinical personnel and a person's health condition is only shared with the patient him/herself (or one of his/her representatives, in case of users characterized by cognitive impairments) and the clinicians. In the following subsections, each of the four layers mentioned above is described.

3.1 Physical infrastructure

In DOMUS, the smart home is simulated within the Living lab of Lecco. The physical environment encompasses kitchen furniture, while the presence and functioning of kitchen appliances are simulated (using Virtual Reality)—to ease the process of introducing new appliances dedicated to different typologies of users and to allow the testing of new devices with virtual prototyping.

In addition, the physical infrastructure of the smart home is equipped with a network of interconnected smart and ubiquitous devices, to produce data streams to be transmitted to proper receivers. Thus, DOMUS encompasses a set of smart nodes to enable communication between the environment and the the system itself. Smart nodes are composed by microcontroller-enabled devices that can be divided into two categories; sensors, and actuators. Sensors on one hand, are the smart nodes that are able to sense, measure, and transmit data about an environmental condition such as temperature, humidity, CO_2 concentration and illuminance. The following sensors are deployed in DOMUS:

- AM2320 Digital Temperature and Humidity Sensor,
- TSL2561 Digital Luminosity/Lux/Light Sensor,
- 3709 Adafruit SGP30 Air Quality Sensor Breakout for VOC and eCO2;
- RFID Reader MikroElektronics MIKROE-262

On the other hand, actuators are those smart nodes that directly control home appliances and devices. The process of exchanging the data takes place exploiting embedded ZigBee-based (ZigBee Alliance 2019) IoT gateways—such as XBee (XBee Ecosystem 2019)—which must be mounted on the Raspberry Pi device (Raspberry Pi 2019) as a central computing device. ZigBee is a novel Radio Frequency communication standard, which is utilizing the IEEE 802.15.4 standard as the communication protocol (Song et al. 2012).

3.2 The home interface controller, HIC

This section delves into the hardware and software required for the Home Interface Controller (HIC) architecture. As mentioned earlier, in the context of AAL the possibility of including older adults and people with disabilities is essential. Although in past years it has been highlighted how elderly people tend to avoid using mobile devices' applications mostly because of accessibility reasons, this trend is rapidly reverting due to the pervasiveness of this kind of technology in today's society (Kim et al. 2016); besides, research shows that GUIs and other interactive approaches are adopted to assess and tackle complex health conditions involving also the cognitive sphere—as exemplified in Synnott et al. (2012).

For these reasons, DOMUS proposes HIC, an interactive multi-touch surface that can be run on any plain surface in order to have a huge touch surface, suitable for older adults and people with special needs, and on mobile devices (tablets and smartphones). HIC can adapt its features to help dwellers with special needs to overcome the difficulties imposed by their impairments, thus helping them in managing the domestic environment and performing some ADLs—as detailed in Sect. 4. In addition, HIC offers the possibility of manipulating the preferences and comfort settings from the smartphone through the simple client-side application on the user's smartphone.

The possibility to project the GUI could drastically ease the interaction between the elderly people with the application, since it provides a wider display; moreover, this feature allows the inhabitants to use HIC even if they are engaged in other domestic activities, such as preparing a meal (e.g. while cooking and their hands are dirty, or when they are using some tools and cannot use a mobile device with two hands). The interactive projector used in the DOMUS is the EPSON EB1430wi: this device is provided with an infrared emitting laser unit for multi-touch detection (tap, pinch zoom, flick, scroll, drag, two-finger rotation) and offers projection areas up to 100 inches. This projector is connected to the main computer station inside the house in which the application software is running (Fig. 2 provides a sketch of the HIC architecture).

Moreover, the possibility to use HIC even from a remote device via the mobile application can be supportive for the elderly characterized by motor impairments, who may face difficulties in moving from one room to another. HIC and its mobile application are developed using Unity 3D (Unity 3D 2019)—because of its very effective 2D/3D rendering with high visual graphics, in addition to the cross-platform essence of Unity, which makes it perfect for DOMUS application to support different platforms—with simple and intuitive design in order to work in parallel with HIC main running via projector. The mobile application is connected

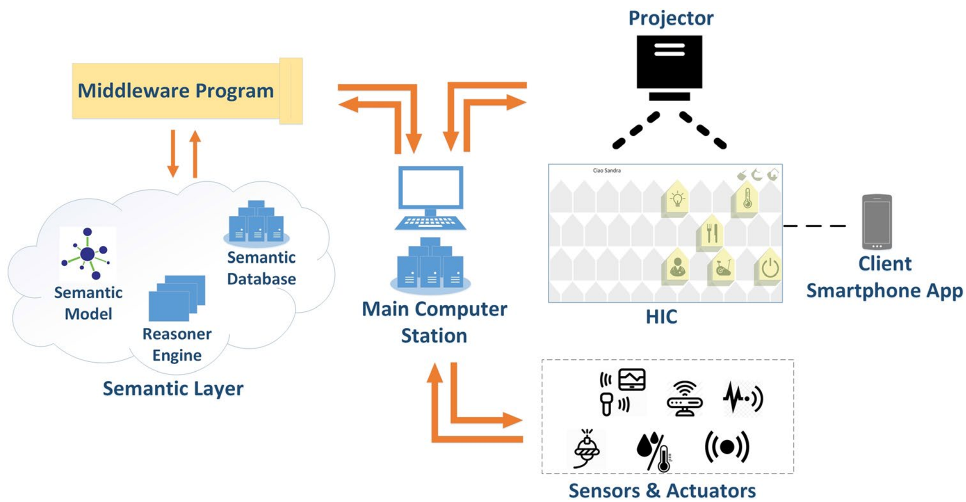


Fig. 2 The architecture of the HIC and its relationship with the semantic and physical layer of the DOMUS

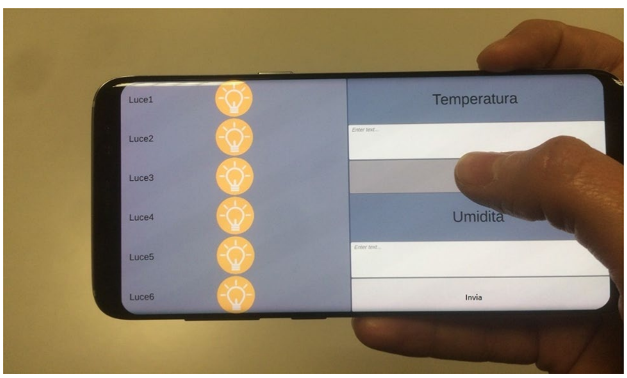


Fig. 3 A screenshot of the HIC in its mobile device version: in this examples, the inhabitants can manage comfort metrics and remotely control lights

to the main application via an internet hotspot and is able to exchange data—thus allowing inhabitants to manage DOMUS from their smartphone or tablet (as shown in Fig. 3).

HIC can therefore, act as a "control center" and "remote controller" of the house, according to the number of projectors deployed within the house or to the availability of mobile devices. The usability of the HIC and target users' acceptance are investigated in Sect. 5.

3.3 The semantic layer

The ontological layer underlying DOMUS was developed adopting the NeOn Methodology (Suárez-Figueroa et al. 2012), an ontology engineering methodology that facilitates the reuse of already existing ontological models and allows to identify the non-ontological resources to be modeled. The following domains of knowledge were found interesting for DOMUS: the dweller and his/her health condition; the devices (appliances, sensors, actuators) deployed in the environment and their measurements; four indoor comfort metrics (temperature, humidity rate, illuminance, CO_2 concentration). To avoid inhabitants' privacy concerns, the ontological layer does not provide the means to model or recognize the indoor activities performed within the domestic environment.

Following the scenarios provided by the NeOn Methodology, the semantic layer relies on a set of domain ontologies already modeled in other works (as further detailed in the following subsections); these models are adapted and pruned to befit to DOMUS's purposes. The ontologies are developed using the open-source editor Protégé (Knublauch et al. 2004) and uploaded to an instance of the Stardog semantic repository. The following subsections present a detailed description of the domain ontologies, specifying the reused models.

3.3.1 Inhabitant and health condition

The first domain ontology provides the means to describe inhabitants and their health conditions, as illustrated in Fig. 4.

Each dweller's personal information is modelled reusing the Friend-Of-A-Friend (FOAF) vocabulary (Graves et al. 2007), a widely-used model developed for the description of networks of people. Following an ontology design pattern already exploited in previous works (Spoladore and Sacco 2018), each inhabitant is assigned to his/her health condition, which is further detailed using the International Classification of Functioning, Disability and Health (ICF).

This WHO standard conceptualizes the functioning of an individual and was developed with the aim of easing the communication among health-stakeholders (including therapists, clinicians, and caregivers), thus providing a standard and worldwide comparable description of the functional experiences of the individuals. The classification

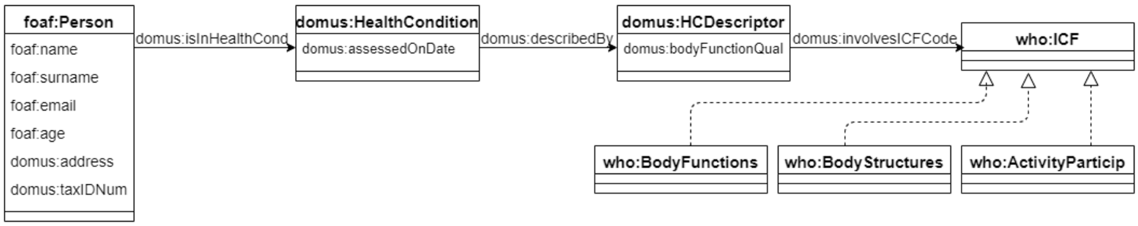


Fig. 4 A class diagram representing the classes composing the ontology related to inhabitants and their health conditions. Full arrows indicate object property, dashed arrows indicate the "rdfs:subclassOf" relation. Datatypes properties are listed within the class box

is organized into four main components ("Body functions" indicated with the letter "b", "Body Structures" indicated with the letter "s", "Activity and participation" indicated with the letter "d" and "Environmental factors", indicated with the letter "e"), each of which can be further deepened into domains to identify the kind of problem addressed. According to the number of digits following the component, it is possible to get a category (a code in the form of "cXXX.q"), whose length indicates the level of granularity in the description of the health issue—up to five digits. Figure 5 provides an excerpt of the ICF classification, highlighting its structure. The functioning or disability of an individual can be assessed by selecting the suitable category and its corresponding code, and then adding a qualifier (an integer ranging from 0—"no impairment" to 4—meaning "complete impairment").

Moreover, ICF has been modeled into an ontology (ICF ontology 2012), here reused in DOMUS as a reference model. Leveraging ICF, DOMUS allows specifying the health status of inhabitants by describing their functional impairments, thus providing the means to model the inhabitant's clinical history.

3.3.2 Devices and measurements

For the description of sensors, DOMUS relies on a subset of Sensor, Observation, Sample and Actuator model (SOSA) (Janowicz et al. 2019), which is part of the W3C-endorsed initiative Semantic Sensor Network ontology (SSN) (Compton et al. 2012). SOSA is a lightweight and self-contained core ontology consisting of a set of classes and properties to describe sensors and actuators and their measurements (observations). SSN and SOSA are adopted as reference models in many IoT projects (Al-Osta et al. 2019).

The modeling of domestic appliances reuses the Smart Appliances REFerence (SAREF) ontology (SAREF 2019), a model providing classes and properties for the representation of the functioning of devices—including sensors and actuators. SAREF and SOSA are partially overlapping (for instance, the pairs sosa:Actuator and saref:Actuator, sosa:Sensor and saref:Sensor describe the same concepts), and an attempt of ontology mapping from SSN to SAREF has been conducted in (Moreira et al. 2017). SAREF is a reference model in many IoT projects, mainly due to the fact that the ontology has been developed with experts working in the appliance industry (Daniele et al. 2015). This ontology is completed with a simple representation of the rooms of the house, which in the DOMUS case are limited to two individuals (kitchen and living room).

3.3.3 Indoor comfort and its customization

Regarding the description of comfort metrics, DOMUS relies on a domain ontology—ComfONT (Spoladore et al. 2019)—that overlaps partially with SAREF. This ontology allows formalizing the comfort metrics (i.e. the physical magnitudes) with the class comf:Comfort_Metrics(≡ saref:Property) that are measurable by sensors and customizable by the dwellers. DOMUS allows the modeling of four comfort metrics: illuminance, air quality (CO_2 indoor concentration), temperature, and humidity rate.

Fig. 5 An excerpt of the ICF classification detailing a component into its categories

b *«Body Function»*	Component
b2 *«Sensory functions and pain»*	Chapter – first level item
b210 *«Seeing functions»*	Second level item
b2102 *«Quality of vision»*	Third level item
b21020 *«Light sensitivity»*	Fourth level item

Each of these comfort metrics is represented as a concept in the ontology and dweller-based specific values for each metrics can be specified. Inhabitants can set their own comfort preferences through the HIC, which allows them to select the comfort metrics and insert the values composing the range (as described in Sects. 4 and 5). Caregivers can also use this feature to assist dwellers with particular conditions (cognitive impairments and/or unfamiliarity with comfort metrics); in any case, the comfort ranges for each metric must be set according to national and European laws and regulations, which provide the following thresholds:

- heating during winter must be 20° C (± 2° C) (Decree 412 1993);
- indoor illuminance for continuously occupied environments must be at least 200 lx, up to a maximum of 1250 lx for activities requiring high precision, such as sawing, thin-cutting, reading (EN 12464-1 2002)
- CO_2 concentration in domestic environments must not exceed 1000 ppm (National Plan 2000).

DOMUS encompasses the concepts and relationships necessary to model the environmental comfort metrics in order to enable actuation: inhabitants' activities inside the home are not monitored, thus contributing to enhance their perceived privacy.

3.4 Middleware for exchanging semantic data

The middleware layer is designed and implemented to act as a medium between the semantic layer, the physical layer and the HIC application (Fig. 6): it enables the sharing of data among DOMUS actors, since it allows HIC to draw and manage knowledge both from sensors and ontologies (Chen et al 2006). The middleware allows gathering environmental measurement data from sensors and adding them into the knowledge base by executing SPARQL query INSERT. However, sensors produce unstructured data unintelligible for machines: therefore—following a widely adopted approach (Chen et al. 2009b), the middleware enriches raw data with the semantics represented in Sect. 3.3.2 and insert them into the semantic knowledge base using an INSERT SPARQL query. The information regarding the current status of the domestic environment collected by the sensors can be used within the semantic layer to check if the current environmental status is within the comfortable ranges set for the dweller or not. When a measurement value is found exceeding the comfortable threshold, the middleware dispatches a trigger to the actuators to turn on or off the related appliance (as detailed in Sect. 4.1). In case the dweller or the caregiver has set the system in such a way not to trigger the actuators automatically, the middleware sends a warning to the HIC to inform the user about the inconvenience and proposes actuation options that can be desirable for the user. If the option proposed by HIC is accepted by the inhabitant, it then sends the prompt to the actuators to set and activate the proper appliances accordingly.

Since HIC is customizable for diverse groups of users according to their particular needs and preferences (as detailed in Sect. 4.2), it must be able to access information stored in the semantic layer: the middleware enables the retrieval of user data about his/her preferences from the semantic layer to trigger GUI modifications.

Each time HIC is active and the user is detected (via sensors, or manually indicated by the inhabitant him/herself via HIC itself), the middleware performs a SPARQL query to retrieve the information about that particular inhabitant and his/her preferences. The middleware receives an input JSON file from HIC containing the inhabitant's name and tax identification number and generates a SPARQL query SELECT to retrieve the comfort preferences and health condition of the inhabitant from the semantic repository. The

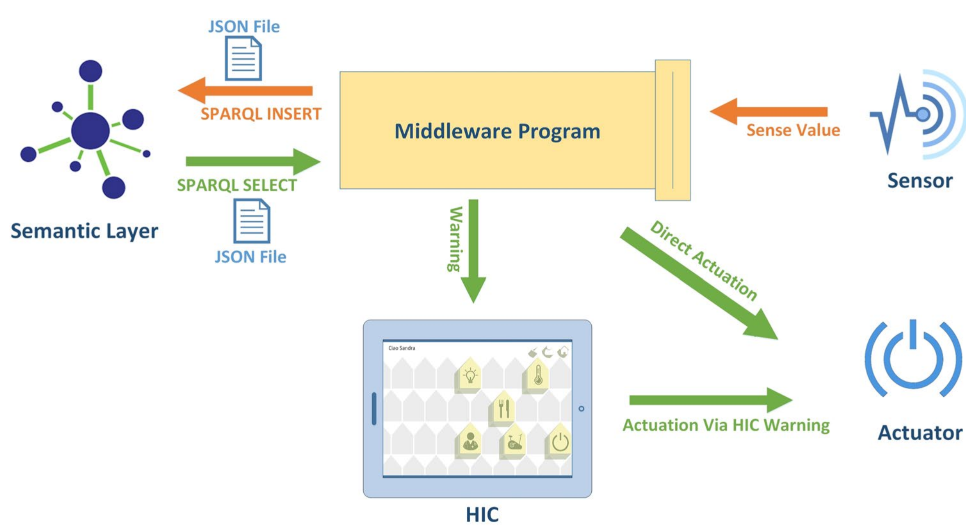


Fig. 6 The architecture of the middleware illustrating the dataflow of DOMUS components

program runs the Stardog server and executes the SPARQL query provided by the middleware to retrieve the inhabitant's preferences and comfort metrics in the form of a JSON file.

4 DOMUS functionalities provided via HIC

DOMUS leverages HIC to provide some functionalities that can support the frail inhabitant in managing indoor comfort and preparing meals—two activities that can be traced back to the Instrumental ADLs "Cleaning and maintaining the house" and "Preparing meals" respectively. Therefore, DOMUS functionalities are designed to provide assistance to a population of users characterized by frailty, with other age-related complications (e.g.: mild impairments in short-term memory, respiratory issues and visual functions). This section proposes an overview of DOMUS functionalities.

4.1 Actuation to enable indoor comfort

As described in Sect. 3, HIC provides a GUI to allow the dweller to manage comfort metrics. Whenever one of the acquired measurements related to one of the metrics exceeds the threshold set in the semantic layer (by the inhabitant or his/her caregiver), the DOMUS alerts the dweller by sending him/her a warning via HIC—as illustrated in Fig. 7. The warning sent is always in the form "[A comfort metric] measured in the [room] is outside the preferred ranges: do you want to activate/turn off [actuator]? Yes/No" and the inhabitant, by clicking the "Yes" option activates a device inside the home. In any case, the dwellers can always manually modify indoor temperature and humidity rate—within the limits provided in the Italian regulation for indoor temperature (Decree 412 1993).

However, DOMUS also allows the automatic actuation of the indoor devices every time a measurement regarding one of the four comfort metrics exceeds the ranges modeled in the ontology—thus avoiding the sending of warnings via HIC. This feature can be helpful for frail older adults characterized by cognitive or motor impairments, since it provides automatic restoration of comfort metrics within the living environment without burdening the dweller with reading warnings and/or making decisions and not requiring him/her to move to HIC's surface or fetching the nearest mobile device. Similarly, HIC acts as a "remote controller" for domestic actuation of comfort metrics as it is shown in Fig. 8, enabling the remote activation/deactivation of lights.

4.2 Adaptation of HIC's appearance

Since frailty is a condition that may affect a dweller's eyesight, HIC is designed to change its graphic appearance according to the inhabitant's health condition modeled in the semantic layer. HIC adaptation helps users with vision-related impairments or neuro-motor impairments by modifying its input/output modalities. For instance, if the retrieved health condition reports an impairment in one of the ICF fourth level categories related to the b2100—Visual acuity functions, the characters composing HIC's text and instructions are magnified up to 2.5 times to improve legibility; if the impairment is located in the b2102—Quality of vision codes and is severe (qualifier ≥ 3), the HIC switches to its "high contrast" modality (depicted in Fig. 9). In this modality, the GUI blackens the background and colors all the buttons and texts in white. The graphical representation of the house is simplified in such a way that it only encompasses black and white icons for single lights. The warnings sent by HIC are subjected to the same graphical modification as

Fig. 7 A screenshot of the HIC alerting the dweller that the indoor temperature in the room is higher than his/her preference, and asking him/her whether he/she desires to restore the preferred temperature

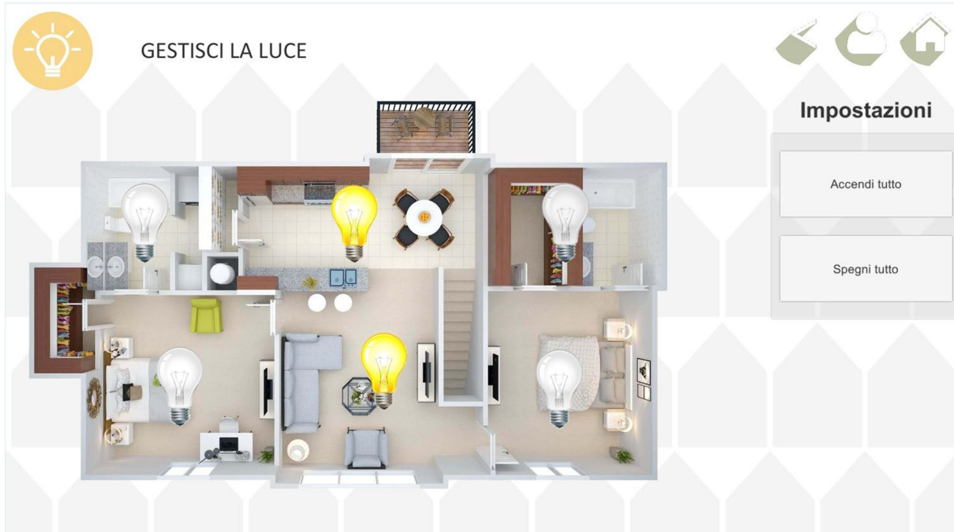
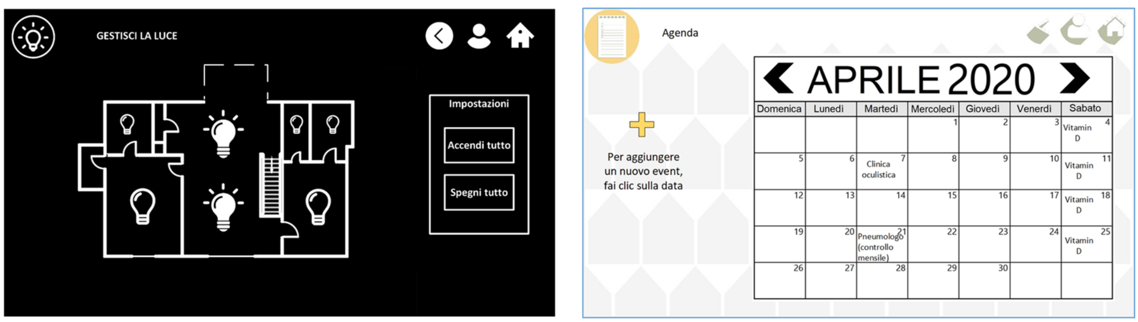


Fig. 8 A screenshot of the HIC allowing the dweller to remotely control the lighting in different rooms



A B

Fig. 9 The HIC in high contrast mode (**a**), and a screenshot of the inhabitant's calendar (**b**)

well. To help dwellers characterized by a health condition encompassing an impairment in the ICF codes regarding the control of voluntary movements and the correlated structures (such as b7603—Supportive functions of arm or leg, s730—Structure of upper extremity, d445—Hand and arm use), HIC can activate vocal commands to allow the inhabitant to interact with the DOMUS using his/her voice; the dweller can pronounce loudly the text depicted in a button to select the corresponding option. The adaptations regarding visual modifications are applicable on both the mobile and projected interface, while—at present—the adaptation involving vocal commands are available only on the projected interface (using the support of the microphone installed on the laptop running the DOMUS application).

4.3 Dweller's calendar and medication alerts.

HIC provides a calendar function (Fig. 9), in which the dweller can write his/her appointments and notes. For inhabitants suffering from memory-related impairments, HIC provides a system to set proper alarms reminding them of their relevant appointments and to take medications. This feature can be set up by caregivers for those dwellers that may have issues in reminding how often during the week and how many medications they have to take.

4.4 Guide the user in the preparation of dishes using the Recipe Book functionality

HIC can also provide assistance in preparing a dish, using the Recipe Book function available. This functionality allows the user to select a dish (among appetizers, main course, sides, and desserts) and to follow the step-by-step preparation. The first step illustrates all the ingredients needed for the recipe, while the other steps delve into the sequence of actions that are required to complete the preparation. Each step is further detailed with a picture, while short videos illustrate the most difficult passages: the clips can be stopped, paused and played back using three buttons located under the video frame. There are currently 5 recipes inside the HIC Recipe Book (1 appetizer, "Bruschetta"; 3 main courses "Breasola rolls", "Chicken salad" and "Gazpacho"; 1 side, "Mixed fresh salad"), all of which are cold dishes—but more can be easily added. The preparation of a dish using the Recipe Book functionality is tested in Sect. 5.

5 Preliminary validation of the DOMUS semantic layer and HIC

In this section, preliminary validations for the inferences produced by the semantic layer and HIC are described.

5.1 Preliminary validation of semantic inferences

The inference generated by the semantic layer of DOMUS and related to the detection of environmental comfort were tested. For this purpose, two personas characterized by frailty and different impairments were developed in the semantic layer:

(a) John Parker, a 69 years old man whose health condition is characterized by a severe impairment in b21020—Light sensitivity and b21022—Contrast sensitivity. His functional impairments produce moderate limitations to several daily activities.
(b) Clara Stuart, a 68 years old woman whose health condition is characterized by moderate impairments in b440—Respiration functions, b4301—Oxygen-carrying functions of the blood, and a severe impairment in b2700—Sensitivity to temperature. Her health status is the result of some respiratory condition.

The two personas' specific comfort settings were also developed in the semantic layer and specified as follows:

(a) John Parker's specific impairments are related to the illuminance and temperature comfort metrics. Therefore, a comf:CustomizedComfortSetting was developed to specify that the lowest acceptable value of illuminance for John is set to 250 lx (50 lx more than the lower limit set by EN 12,464–1), while the highest acceptable value is 1250 lx (necessary for reading and cooking). The following excerpt of code represent John's customized comfort settings for indoor temperature:

```
Individual: comf:Parkers_CS
    Types:
        comf:CustomizedComfortSetting
    Facts:
     comf:specifiesIlluminanceValues
comf:Parkers_Illuminance_Specs
Individual: comf:Parkers_Illuminance_Specs
    Types:
        comf:IndoorIlluminanceSpecs
    Facts:
     comf:MAX_IlluminanceValue  "1250"^^xsd:int,
     comf:MIN_IlluminanceValue  "250"^^xsd:int
```

(b) Clara Stuart's respiratory issues require specific CO_2 concentration, humidity rate and temperature settings. Her customized comfort settings are defined as follows: CO_2 concentration must not exceed 650 ppm; humidity rate must be kept under 30% during summer and 45% during winter; winter temperature must range between 19 and 22° C, while summer temperature must range between 23 and 27° C.

In order to validate inferences produced by the semantic layer, a set of values was simulated for each comfort metric relevant for the two personas (Table 1). These data are either eligible values that could be detected by the physical layer, or specifications any inhabitant could input for his/her comfort metrics—although some of them may exceed the limitations foreseen by regulations (and therefore are not legally acceptable) or they may not fit into the personalized comfort settings (thus being non-acceptable for a specific user). The reasoning process allowed to correctly classify all the values according to the results provided in Table 1.

For John's visual impairment, the acceptance or rebuttal of the sensed values is based on his customized comfort settings: each time a measurement is found lower or higher than the limits expressed in the customized comfort setting it is classified as a comf:UnacceptableIlluminanceValue. Similarly, Clara's specified indoor temperature, humidity rate and CO_2 concentration determine the acceptability (or unacceptability) of the measurements simulated for her persona. If Clara specified as her CO_2 maximum threshold 2500 ppm, her input would be inferred to be a member of the comf:UnacceptableIndoorCO_2Specs, since it exceeds the legally acceptable ranges, which—for the CO_2 concentration comfort metrics—are modelled in the ontology as follows:

```
Class: comf:Unacceptable_CO2_CS
 EquivalentTo:
  comf:CustomizedComfortSettings  and  comf:MAX_CO2Conc_level
only xsd:decimal[> 1000.0]
```

Table 1 The classification of simulated values for the two personas (John on the left, Clara on the right). Each value is classified also according to the thresholds specified by the regulations adopted as references in the semantic layer

	Sensed value	*Legally acceptable*	*Acceptable for John*
Illuminance (lux)	2944	no	no
	1136	yes	yes
	311	yes	yes
	458	yes	yes
	1189	yes	yes
	3655	no	no
	8734	no	no
	14	no	no
	173	no	no
	96	no	no

	Sensed value	*Legally acceptable*	*Acceptable for Clara*
CO_2 Conc. (ppm)	156	yes	yes
	653	yes	no
	768	yes	no
	1075	no	no
	492	yes	yes
Winter temp. (° C)	27	no	no
	19	yes	yes
	21	yes	yes
	23	no	no
Summer temp. (° C)	28	yes	no
	19	yes	yes
	25	yes	yes
	31	yes	no
Winter humidity rate (%)	44	yes	yes
	39	yes	yes
	72	yes	no
	22	yes	yes
Summer humidity rate (%)	47	yes	no
	32	yes	no
	62	yes	no
	28	yes	yes

SWRL rules allowing the actuation of indoor lights and HVAC system were also tested: in particular, the rules concerning the detection of a comfort metric value and actuation of a device were tested using simulated data. Each values unacceptable for the two personas reported in Table 1 correctly triggered the SWRL rules. For example, the following rule.

Person(?d), isInHealthCondition(?d, ?hc), HealthCondition (?hc), isDescribedBy (?hc, ?des), HC_Descriptor(?des), involvesICFCode (?des, b2102), Quality_of_vision (b2102), bodyFunctionQual (?des, ?q), greaterThanOrEqual (?q, 2), isLocatedInRoom (?p, ?r), Room(?r), Lighting_device (?light), isDeployedIn (?light, ?r), IndoorIlluminanceSpecs (?ill), MIN_IlluminaceValue (?ill, ?x), EnvIlluminance (?enill), hasMeasurementValue(?enill, ?m), lessThan (?m, ?x)—> setsLighting (?light, ?ill).

detects an indoor illuminance inferior to John's specification and suggests to turn on the light with the MIN_IlluminaceValue provided by John's setting. The suggestion is showed via HIC (as illustrated in Fig. 7).

It is worth noticing that the only rules requiring to know the inhabitant's position within the environment are those dedicated to actuation: as specified in the previous sections, DOMUS does not monitor the dwellers and their activities, preferring instead to monitor environmental conditions.

5.2 Recipe book: a preliminary validation with SUS and TAM3 questionnaires

HIC's functionality "Recipe book" underwent a preliminary validation. The problem of food preparation for a population characterized by frailty is common and affects both male and female individuals (Moss et al. 2007; Porter 2007), therefore the preliminary validation focused on this topic. The meal preparation function is the one that requires the highest number of interactions with HIC (selecting the recipe, following the written instructions, play or stop the video instructions, etc.), therefore it was selected to be tested. HIC was tested in its standard layout—not adapted for any particular impairment—to evaluate its usability and acceptance. The sample involved in this testing was composed of 10 persons aged between 56 and 67 years old and, therefore, belonging to the pre-elderly and elderly demographic segments (the former ranging between 50 and 64 years old, the latter ranging from 65 years old) (Morrow-Jones and Kim 2009). Participants were chosen among a population coming from the same geographical region (the provinces of Milan and Lecco in the Lombardy Region) and with different cultural backgrounds (from people who attended only to compulsory education to people with a university master degree—Median value 8, interquartile range 8–11,75). The sample was composed of four females and six males. Participants were asked to complete the preparation of the "Bresaola rolls" recipe following the instruction provided via HIC. The instructions for the recipe encompassed text, images and videos; the participants were provided with all the ingredients, dishes and cutlery necessary to perform the task—as depicted in Fig. 10.

Once the preparation of the recipe was completed, the participants were auto-administered the System Usability Scale (SUS) (Brooke 1996) questionnaire—a ten-item questionnaire with a 5-point Likert scale answer ranging from "1-strongly disagree" to "5-strongly agree"—and Technology Acceptance Model (TAM3) (Venkatesh and Bala 2008)—a questionnaire for evaluating perceived usefulness, the perceived ease of use, and cognitive instrumental processes with a 7-point Likert scale (ranging from "1-strongly disagree" to "7-strongly agree"). The two questionnaires were adopted to investigate the perceived usability of the HIC, and the potential intentions of adoption of this technology by users in the pre-elderly and elderly age range. TAM questionnaire was adapted to the examined context, excluding the "Image" and "Voluntariness" subscales—which are related to the actual use of a technological product within the real-life context and do not fit the context of experimentation.

5.3 Tests results

HIC's general usability measured with SUS questionnaire scored a mean value of 88 (SD = 3.69), a result indicating that the interaction with HIC has been evaluated as excellent in terms of its usability. Figure 11 shows the position of SUS score on the acceptability scale.

The results of TAM3 subscales are shown in Table 2.

TAM 3 subscales highlighted that the highest result was obtained in the "Perceived usefulness" (6.27, SD = 0.6): HIC proved to be useful in assisting users in completing their recipe. "Perceived enjoyment" scored rather well (6.20, SD = 0.5), indicating that using the HIC was generally considered a pleasant experience. This score may be related to HIC's easiness of use (captured by the subscale "Perceived ease of use", 5.67, SD = 0.52) and to the perception of having the situation constantly under control (represented by the "Perception of external control" subscale, 5.67, SD = 0.56) that the participants manifested. It is worth noticing that

Fig. 10 The test materials provided to the participants to complete the preparation of the recipe (on the left), and one of the participants in the act of performing HIC's instructions (on the right)

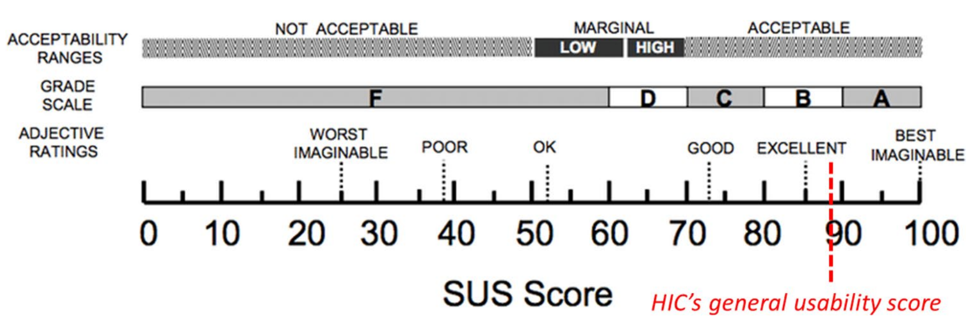


Fig. 11 A representation of SUS score; a score above 85 indicated a very good usability of the product

Table 2 A recapitulatory table illustrating the results of HIC's Recipe Cookbook testing with TAM3 subscales. For each subscale (listed in the left column) the mean score obtained and the standard deviation (in brackets) are presented

TAM 3 Subscale	Mean Score
Perceived usefulness	6.27 (0.60)
Perceived ease of use	5.67 (0.52)
Computer self-efficacy	3.27 (0.79)
Perceptions of external control	5.67 (0.56)
Computer playfulness	4.12 (0.65)
Computer anxiety	3.00 (0.66)
Perceived enjoyment	6.20 (0.50)
Job relevance	5.96 (0.97)
Output quality	6.16 (0.47)
Result demonstrability	5.22 (0.18)
Behavioral intention	5.63 (1.49)

also "Output quality" gained a fairly relevant score (6.16, SD = 0.47) and that the relevance of HIC's tested functionalities in daily life totalized a relevant score ("Job relevance" subscale, 5.96, SD = 0.97): the highest result in "Job relevance" and "Behavioral intention" SDs is due to the fact that male participants—who do not take care of meal preparation in their daily routine—were unable to see an immediate use of this HIC function, although they somehow recognized its relevance in domestic contexts.

The lowest result was obtained in evaluating participants' "Computer anxiety" (3.00, SD = 0.66) and "Computer self-efficacy" (3.27, SD = 0.79)—respectively, the degree of a person's apprehension, or even fear, when she/he is faced with the possibility of using computers, and a person's belief of his/her own capacity to perform a specific task with a computer (3.6, SD = 1.02): this data derives from the presence of less-schooled participants who do not have the chance to use computers very often and feel the need to have a tutorial before actually using the HIC in daily life activities. These results are particularly relevant for further developments of HIC, since they indicate that elderly may suffer from diffidence caused by their inexperience with digital and computer-based technologies.

6 Conclusion and future works

In this paper, a Domestic Ontology-Managed Ubiquitous System (DOMUS) is presented. DOMUS leverages ontological representation of the domains of knowledge involved within a smart home to assist the inhabitants in performing some Activities of Daily Living; dwellers can interact with DOMUS using the Home Interface Controller (HIC), which allows them to control indoor comfort metrics and provide them with assistance in meal preparation. The use of HIC in meal preparation is tested with a sample of pre-elderlies and the results highlight an elevated score for the interface's usability and perceived usefulness of the solution with regard to the assistance it provides.

As future work, DOMUS' semantic knowledge base will be enriched to include some features from the International Classification of Diseases (Selb et al. 2015), thus encompassing the representation of most of the conditions characterizing elderlies; this classification also allows to formalize diseases related to nutrition. To provide an assistive feature for meal preparation, the recipes in HIC's Recipe Book will be semantically annotated to identify allergens and factors affecting the most common food intolerance (Spoladore and Sacco 2020). Moreover, HIC's adaptation involving the possibility to input vocal commands will also be improved with the use of indoor microphones (to be deployed within the domestic environment) and HIC will be provided with the possibility to output audio messages to help people with neuro-motor disabilities or severe vision-related impairments. For dwellers characterized by health conditions involving some slight cognitive impairments in fields related to focusing attention, the possibility to provide a combination of adaptations will be investigated with the help of psychologists. Finally, considering the preliminary results of the validation, HIC's adaptations will be evaluated with dedicated cohorts of elderly patients (people with vision-related impairments and people with impairments in moving and/or using arms and/or hands) to assess their usability, acceptance and willingness to adopt and use this technology in daily life and to enhance the adaptations provided so far. As the preliminary results suggested, it is advisable to provide users with ad hoc tutorials to reduce their potential levels of anxiety when using computer and to improve their confidence in using DOMUS through the HIC.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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