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Review

AIoTES: Setting the principles for semantic interoperable and modern IoT-enabled reference architecture for Active and Healthy Ageing ecosystems

Clara I. Valero [a,*], Alejandro M. Medrano Gil [b], Regel Gonzalez-Usach [a], Matilde Julian [a], Giuseppe Fico [b], Maria Teresa Arredondo [b], Thanos G. Stavropoulos [c], Dimitrios Strantsalis [c], Antonis Voulgaridis [c], Felipe Roca [d], Antonio J. Jara [d], Martín Serrano [e], Achille Zappa [e], Yasar Khan [e], Sergio Guillen [f], Pilar Sala [f,g], Andreu Belsa [a], Konstantinos Votis [c], Carlos E. Palau [a]

[a] Communication Department Universitat Politècnica de València, Valencia, Spain
[b] Universidad Politécnica de Madrid, Madrid, Spain
[c] Information Technologies Institute Centre for Research and Technology Hellas, Thessaloniki, Greece
[d] HOP Ubiquitous, Murcia, Spain
[e] Insight SFI Research Centre for Data Analytics - Data Science Institute, National University of Ireland Galway IDA Business Park, Lower Dangan, Galway, Ireland
[f] MYSPHERA, Valencia, Spain
[g] ITACA Institute Universitat Politècnica de València, Valencia, Spain

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ABSTRACT

The average life expectancy of the world's population is increasing and the healthcare systems sooner than later will be compromised by its reduced capacity and its highly economic cost; in addition, the age distribution of the population is leading towards the older spectrum. This trend will lead to immeasurable and unexpected economic problems and social changes. In order to face up this challenge and complex economic and social problem, it is necessary to rely on the appropriate digital tools and technological infrastructures for ensuring that the elderly are properly cared in their everyday living environments and they can live independently for longer. This article presents ACTIVAGE IoT Ecosystem Suite (AIoTES), a concrete reference architecture and its implementation process that addresses these issues and that was designed within the first European Large Scale Pilot, ACTIVAGE, a H2020 funded project by the European Commission with the objective of creating sustainable ecosystems for Active and Healthy Ageing (AHA) based on Internet of Things and big data technologies. AIoTES offers platform level semantic interoperability, with security and privacy, as well as Big Data and Ecosystem tools. AIoTES enables and promotes the creation, exchange and adoption of cross-platform services and applications for AHA. The number of existing AHA services and solutions are quite large, especially when state-of-the-art technology is introduced, however a concrete architecture such as AIoTES gains more importance and relevance by providing a vision for establishing a complete ecosystem, that looks for supporting a larger variety of AHA services, rather than claiming to be a unique solution for all the AHA domain problems. AIoTES has been successfully validated by testing all of its components, individually, integrated, and in real-world environments with 4345 direct users. Each validation is contextualized in 11 Deployment Sites (DS) with 13 Validation Scenarios covering the heterogeneity of the AHA-IoT needs. These results also show a clear path for improvement, as well as the importance for standardization efforts in the ever-evolving AHA-IoT domain.

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* Corresponding author.
E-mail address: clavalpe@upv.es (C.I. Valero).

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1. Introduction

In last decades, the world's population has suffered an increase in the number of ageing population. According to the World Population Prospects 2019 published by United Nations (United Nations, 2019), by 2050, one in six people in the world will be over the age of 65, an estimation that trends to increase because longevity and health conditions are improving. The ageing population is increasing, thus it is necessary that healthcare systems align with the required needs from older populations as well as to ensure that long-term care models are appropriate and sustainable [1].

The term Active and Healthy Ageing (AHA) [2] defined by the World Health Organization is the process of optimizing health opportunities to improve the quality of life as people ageing. The AHA is an initiative that promotes healthy practices and use of technologies for improving healthy living as a way of keeping a good balance in lifestyle and living conditions. The AHA places special emphasis on prevention through the adoption of a healthy lifestyle for delaying as much as possible the physical and mental deterioration that is part of the ageing process. The combination of AHA along with information and communication technologies, such as IoT and big data, has accelerated the emergence of Ambient Assisted Living (AAL) [3] environments. The AAL area aims for developing personal healthcare and remote monitoring health systems or Telehealth. AAL environments main focus is providing improvements in the quality of life for people while living at their homes, as well as alleviate the high budgets that currently are spent on healthcare providers and also reduce the negative impact in relation to the social inclusion of people when they are confined in healthcare residences [3]. In 2007 the European Union recognized the importance of AAL by founding the AAL Joint Association. AAL has changed to Active and Health Ageing (AHA), as it has specialized on ageing adults. Thus in 2012 European Innovation Partnership on Active and Healthy Ageing (EIPonAHA) was founded.

In recent years, with the fast evolution of IoT and Big Data technologies, major efforts have been taken in European countries to address the increasing demand for providing AAL solutions that reach AHA population [4], however the lack of interoperability in the IoT landscape [5] and the diversity on IoT platforms hinders the possibility to have AHA architectures with seamless integration of devices and data and platforms integration. The existing solutions are mostly acting as isolated islands of technology and likewise producers of data silos, while their inter-connection would bring significant added value, the reality is that there is not such a interoperability standard way to achieve this objective. For these reasons, the creation of an AHA ecosystem that enable the interoperability and provide seamless connectivity withing devices and data is a challenge. The AHA ecosystem must be able to overcome the fragmentation of closed systems, architectures, and applications vertically oriented towards open systems and integrated environments capable of providing common solutions to users and service providers. Solutions must be unified also at services level, otherwise the overall impact of their implementation could be reduced.

The work described in this paper introduces AIoTES, an IoT-enabled reference architecture for AHA, built in the context of the H2020 ACTIVAGE project [6], During the course of the project 4345 users interacted with AIoTES. The AIoTES architecture enables the creation of a global ecosystem where different platforms, technologies and standards co-exist, enabling the deployment and operation at large scale of AHA IoT-based solutions and services. This paper also describes how AIoTES has been designed, implemented, deployed, verified, evaluated, and validated using qualitative and quantitative indicators. AIoTES approach rely in enabling local IoT ecosystems with the necessary functionalities to build standard and interoperable solutions on top of legacy IoT platforms as well as communication and data management infrastructures. By introducing AIoTES into those local ecosystems, a conversion of multiple local ecosystems into a interconnected ecosystem is achieved. This work specifically addresses the interoperability challenge and contributes to the IoT-AHA domain with providing the ACTIVAGE ontology, its inter-platform interoperability approach, the ACTIVAGE Marketplace and the security and privacy principles by design. Jointly they act as enablers of a Global AHA Ecosystem.

The remain of the paper is structured as follows: Section 2 describes current designs and approaches and they are discussed in detail. Section 3 presents the adopted stack for AHA providing details of the methodology, architecture design, device and semantic interoperability layers, the platform layer, the data and service layers , the security and privacy layer, the AIoTES API and Application Layer. This section also introduce the validation methodology and how it is used in validation scenarios. Section 4 presents the results derived from introducing AIoTES in the different local IoT ecosystems. Section 5 includes a discussion of the results obtained in the local IoT ecosystems where the benefits obtained and the costs associated with the integration of the framework are also analysed. This discussion is organized according to the objectives of the framework. Finally, the concluding remarks are presented in Section 6.

2. Related work

In recent years large number of IoT-based AHA solutions have been developed, mainly because the challenge that poses the increasing of ageing population in the world along with the evolution and maturity of IoT systems. Overall IoT-based AHA solutions aim to give a good quality of life to the increasing number of elderly people in their daily life. IoT technologies allow the development of services that, by increasing the autonomy, self-confidence, and mobility of the elderly, enable them to stay at home comfortably and safely. As a result, they can enjoy an independent life for longer, the elderly are not unattended and their caregivers with peace in mind can optimize their care efforts.

The AHA domain is very broad and there is a large number of applications that address different types of elderly care needs, in this section some of the most relevant ones and the way how they can be analysed by means of data are shortlisted; Monitoring of activities of daily living [7,8], allows establishing the user's behavioural patterns, the deviation of which could indicate the detection of an abnormal situation. Sleep pattern detection, the amount of time spent inactive, or conversely, the frequency and intensity of their activity while sleeping are crucial indications required by the medical condition that need to be monitored, additionally the recent incorporation of artificial intelligence to these solutions allows to learn the behaviour of each user and generate a personalized pattern from the obtained data [9]. Thus, the abnormal situation alert will depend on the user's behaviour patterns. There are also a multitude of applications focused on the monitoring of chronic conditions, for example diabetes [10], Parkinson's disease [11], cardiovascular disease [12] and hypertension [13] lead the list; in this area IoT healthcare solutions offer specialized services to elderly individuals so that they can enjoy a convenient and safe life from the comfort of their home. Other solutions focus on social inclusion [14] and communication services. These seek to detect, avoid and prevent elderly social isolation, which leads to cognitive decline, depression, and other mental health-related issues. They use different types of technologies to enable interaction between the elderly and their relatives and friends.

The fast evolution and extended use of electrical and electronic equipment have facilitated that technology reach the elderly and the healthcare sector is not an exception. In recent years the extended use of smartphones, tablets and smart watches have changed the perception about the benefits of using technology for our wellbeing and it has play a decisive factor on the increase in the use of wearable devices in tele-home healthcare. The number of health applications available in the Google Play Application store and Apple's App Store is increasing rapidly every year. for example there are a large number of portable ECG monitoring systems [15] that work with a mobile application. Moreover, since falls are a major factor of morbidity among elderly population, there is a lot of applications around wearable fall detection systems [16]. It is also important to highlight the importance of general purpose mHealth applications that focus in achieving health behaviour goals [17].

In general terms there are already a large number of applications and systems to improve the quality of life of older people, although the AHA domain yet misses the view of a whole ecosystem [18]. Most of the solutions (as the ones presented above) are mainly focused on the patient activity and not in the health conditions and thus the physician amongst other users of the ecosystem are neglecting their use; in addition, they often consist of ad-hoc architectures that are difficult to integrate into other networks. The fact that the architectures are tailored to the systems they are designed for, strongly limits their interoperability of their applications and data services. In other words, the import or integration with other health systems is complicated because the systems where the solution has been developed usually use different technologies and standards than the target systems. Furthermore, a concrete evaluation of the real usefulness, effectiveness and efficiency of the proposed solutions to meet the new needs is missing. In this panorama a clear need for solutions that look at ecosystems building following the existing relationships between user needs and the solutions offered and in addition include more rigorous evaluations and validations to integrate other methods and solutions by means of data sharing and exchange.

Some proposed architectures that look for this ecosystem building stand out. In [19–21], the authors design layered framework architectures for monitoring physiological changes of elderly people at home. These three architectures are generic and very similar to each other, seeing a correspondence between layers of one to another. They present architectures of up to six layers defined to allow the control of physical activity through IoT systems. The layers are: physical layer, communication protocol layer, data processing layer, internet layer, storage and preview layer and user application and service layer. Security and privacy are the aspects that stand out the most due to their omission in these architectures. This standard-layered design is an extremely important point because health data is particularly sensitive. However, these architectures do not incorporate a specific layer where to perform an analysis of the collected data. The analysis of the sensed data provides many applications [22] (such as detection of physical decline or diseases) that allow rapid intervention in patients or clinical decision support. In addition, there are no elements that promote the creation and expansion of an ecosystem. No tools are offered to facilitate the development and deployment of new applications or services, nor a marketplace to share them. Neither do they provide a solution to the intrinsic heterogeneity of IoT systems to facilitate the adaptation of solutions from one system to another. Thus, the scope of these architectures is limited to specific systems and their integration into other systems is complex.

On the other hand, an architecture for collecting and managing data related to elderly behaviour is proposed in [23]. It presents a scalable smart city-oriented system able to provide services for multiple cities concurrently in both, indoor and outdoor scenarios, putting special focus on the management of large amounts of data. Unlike the architectures mentioned above, this architecture includes a data abstraction layer that allows cities to maximize resources by reusing the existing IT infrastructure already deployed. However, it has been designed for a specific use case, and in spite it provides the means to include legacy systems as data sources for the applications and services based on their architecture and data model, it does not consider its integration with other applications and services.

The Alliance for the Internet of Things Innovation [24] (AIOTI) presented in its 2015 AIOTI WG5 - Smart Living Environment for Ageing Well report [25] a set of recommendations for creating an IoT AHA ecosystem. AIOTI was initiated in 2016 to support the European Commission in relation to the future of research and development on the IoT by participating in standardization and development of IoT policy recommendations. It is divided into different Working Groups (WG) where each one focuses on different areas of development. Specifically, WG5 Smart living environments for ageing well focuses on addressing the IoT support to the continuously growing population of elderly people in living longer, staying active, independent and out of institutional care settings. This working group also aims at reducing the costs for care systems and providing a better quality of life for vulnerable categories of citizens.

The AIOTI WG5 report provides background information and recommendations for IoT solutions and particularly their applications on

Large Scale Pilots (LSP) – Smart living environments for ageing well call, to which ACTIVAGE project belongs that can be summarized as follow. First of all, the proposed architecture should seek to achieve interoperability (at network, data and rules level) not only between third party devices on the LSP platform but also compatibility with other ecosystems. The inclusion of an integrated development environment (IDE) which provides tools to facilitate the connection and development of application and services in the ecosystem is encouraged. Secondly, regarding communication infrastructure, sensors and actuators should be easily added to the ecosystem and for that purpose they should be available and discoverable. The architecture should support a variety of devices and protocols in addition to use strict privacy and security standards. In order to support interoperability, data semantics and ontology schemes should be used. Thirdly, the sensors of the ecosystem need to be interoperable so that IoT services can use the sensor data of devices not provided by them. Lastly, user interaction interfaces for primary (person receiving care) and secondary users (e.g. caregiver/relative) should be provided. In line with interoperability principle sad follow of standards these recommendations have served as a basis for defining the AIoTES objectives, presented in Section 3.2. Furthermore, the choice of the platforms that constitute the core of AIoTES was made by including those recommendations that are highlighted. On the one hand, the universAAL platform [26] and its use in ACTIVAGE proved to be capable of enabling the development and deployment of IoT services for AAL in an extensive piloting plan. Additionally, the Open IoT platform [27] and some extensions towards wellbeing which were ongoing at the time of writing the document, it stands out for being a semantic-based platform.

3. Materials and methods

The ACTIVAGE project is the first Large Scale Pilot in the Ageing domain in the IoT Focus Area of the Horizon 2020 Work Program 2016–2017 of the European Commission. ACTIVAGE main objective is creating a single common Interoperable IoT ecosystem which permits large scale operation of AHA IoT based solutions and services. Globally, the project is composed of 9 different local ecosystems, called Deployment Sites (DSs), each having its own IoT platform infrastructure and AHA use cases, together they reached a total of 4,972 users (including end users, formal and informal caregivers, and others). They are in the following locations: Region of Galicia (Spain), City of Valencia (Spain), Region of Madrid (Spain), Region of Emilia Romagna (Italy), multiple cities in Greece (regions of Trikala, Athens, Thessaloniki), Region of Isere (France), the WoQuaZ elderly home in the city of Weiterstadt (Germany), City of Leeds (UK) and several municipalities in Finland. During the project, third parties (referred to as open callers) have been added to the project through two Open Calls (OC). In the first one, new service providers have integrated new solutions in the deployment sites while in the second one, three new DSs have been added to the ecosystem: city of Barcelona (Spain), city of Sofia (Bulgaria) and city of Lisbon (Portugal); enlarging it with new services, solutions, platforms, and users.

3.1. Methodology

In order to transform IoT-based health-related isolated ecosystems into a global one, the ACTIVAGE project has carried out a set of actions oriented to the definition and implementation of a reference AHA IoT architecture, the result is AIoTES, which offers a general approach to build interoperable smart active ageing solutions. The methodology (Fig. 1) used to define, implement and test this architecture comprises the following phases: requirements acquisition, product specifications, design, development process, verification and two-stage validation.

Firstly, functional and non-functional requirements for the architecture were identified. To this end, the needs and preferences of the users and the involved stakeholders were collected and analysed following a

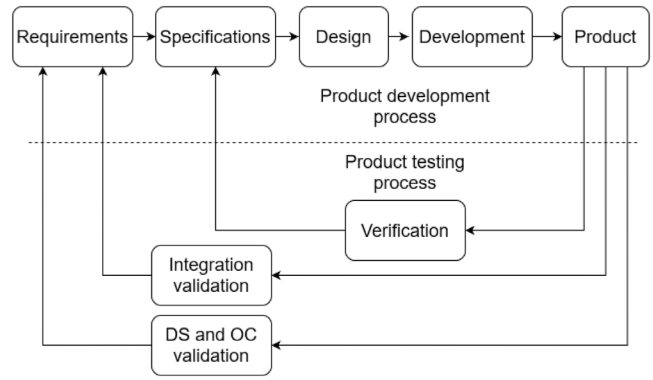

Fig. 1. Methodology for the creation of an AHA IoT architecture.

mixed methods approach that includes Logical Framework approach (LFA) [28] and User Centred Design (UCD) [29] methodology. The combination of these two methodologies has allowed us to identify the main stakeholders and, according to their influence on the AHA domain, discover: (i) the relationships between groups, (ii) their individual and collective needs and requirements, which then have been transformed into technical requirements for the architecture, as well as (iii) the requirements for individual components.

Secondly, The specification phase complemented the requirements with a technical information review of each DS was performed. The information was collected through registration forms focused on device, gateway, cloud and application domains; designed employing the STRIDE Methodology [30] and DREAD model [31] for threat identification and mitigation. This analysis considered the different DS topologies, the applications foreseen, the security and privacy mechanism implemented (and possible improvements) in the DSs as well as the servers and their locations. The security study considered the requirements, existing solutions and legislation related to data protection. Moreover, the analysis included a classification of the different devices used in each DS in order to identify commonalities, potential synergies and knowledge sharing between DSs. All this work contributed to define the specifications of AIoTES.

In terms of design, as an initial step for the definition of the semantic interoperability solution, a study of the state of the art and limitations of the different IoT technologies was carried out. The IoT platforms market was analysed, highlighting the assets and components that are important for the ACTIVAGE architecture definition. In addition, the differences and similarities among the ACTIVAGE IoT platforms were analysed and categorized in order to identify the possible reusable assets that they offer (see Section 2). However, the assets identified in this first step were platform-specific and, therefore, did not meet the objective of reusability throughout the ecosystem. For this reason, a new study was conducted to identify which new components should be developed or adapted to meet the specific ACTIVAGE requirements. The design of the architecture is summarized in Section 3.2.

AIoTES was implemented [32] on the basis of the identified requirements, specifications and design. Finally, its verification and validation was performed following an ad-hoc methodology which is described in detail in Section 3.3. The verification and validation results are included in Section 4.

3.2. Architecture design

The ACTIVAGE IoT Ecosystem Suite (AIoTES) is a reference architecture for Active and Healthy Ageing that uses, amongst others, the advantages of emergent IoT technology with the objective of providing a better quality of life for ageing people. The analysis of AHA architectures (Section 2) is essential for the identification of requirements that must be incorporated into AIoTES. AIoTES has been designed based on

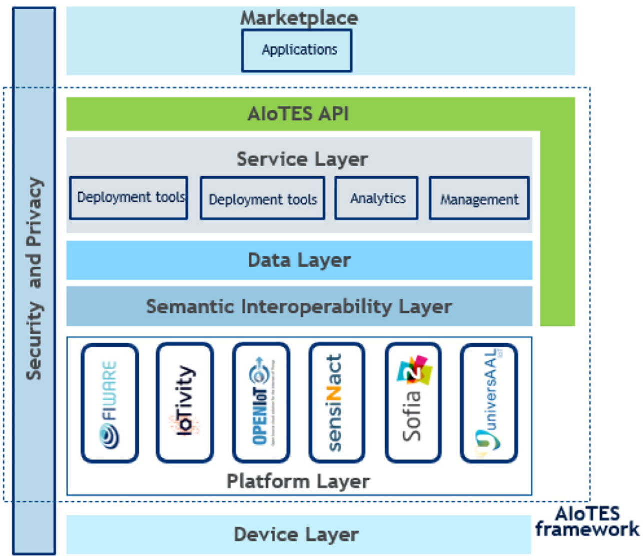

Fig. 2. ACTIVAGE reference architecture.

the results of the aforementioned studies and from the general elements of the IoT systems (devices, gateways and platforms), which were added as new necessary requirements that facilitate the construction of a global ecosystem from isolated IoT systems. For this reason, AIoTES can be considered a reference architecture in the creation and extension of IoT-enabled AHA ecosystems. AIoTES presents a holistic approach to the creation of IoT ecosystems for AHA, ensuring robustness and reliability, in addition to usability. Its objectives are aligned with the deficiencies found in previous AHA architectures for allowing ecosystem building. These objectives are: (a) to ensure interoperability of data across the ecosystem, (b) to offer a big data solution that allows storing, processing and knowledge extraction of the data generated in the ecosystem, (c) to facilitate application development and ecosystem building, (d) to provide security, privacy, data protection and trustworthiness, following the European regulations and policies.

The following layers describing AIoTES architecture have been defined: the Device Layer, the Platform Layer, the Semantic Interoperability Layer, the Data Layer, the Security & Privacy Layer, the Service Layer, the AIoTES API and the Application Layer. The AIoTES layers (see Fig. 2) and their main operation and characteristics are described in the following Sections.

In addition to the architecture, the AIoTES Framework was defined as the implementation of AIoTES, which presents a modular approach. The framework unites the implementation of AIoTES allowing a total or partial deployment of the solution. Once developed, each DS will choose (based on its needs) whether to integrate all the facilities offered by the framework or to deploy specific components in their cloud environment. Hence, AIoTES has a multicentric cloud oriented deployment approach.

3.2.1. Device layer

The device layer is a key part of the architecture focused on integrating the physical devices, such as wearable devices, home appliances, environmental monitors, and personal devices. Devices provide relevant information about user's behaviour, and consequently all of them take advantage of AIoTES integration to set-up smart policies, detection of patterns in data streams using rules engines and analytics.

The device layer has provided a set of IoT agents (which connect devices with IoT platforms) to map standard protocols as MQTT [33], OMA LwM2M [34], Bluetooth, ZigBee [35], Z-Wave [36] and other networks into the platforms in the Platform Layer; in order to enable access to the device information via a homogeneous, federated and secured platform interfaces. This access to information is what defines the first level of integration and what is targeted and reached for all the available networks.

The Device Layer offers the basic information access feature and beyond that it also look after for supporting specific protocols, more advanced support into two more levels. On the one hand, it offers control level, which enables the capacity to write, generally actuate, specific devices such as irrigation systems, Heating Ventilation Air Conditioning (HVAC), power control (smart plugs), lighting and so on. On the other hand, it provides device management, which implies capacities to adapt the behaviours and configuration of devices such as firmware upgrade or power management (battery life-cycle).

3.2.2. Platform layer

The Platform Layer consists of the set of IoT platforms deployed in the DS and connected in the architecture, which manage the data collected by their associated sensors from smart homes. It is important to note that each DS deployed its own IoT infrastructure based on the platform that they found the most convenient and no restrictions to this respect were defined in the ACTIVAGE project. The Platform Layer contains the platforms of the initial ACTIVAGE ecosystem, namely, FIWARE [37], SOFIA2[38], universAAL [26], sensiNact [39], OpenIoT [27] and IoTivity [40], as well as other lately included platforms (MC Cardio [41], ekenku [42], ekauri [43], openHAB [44]).

The Platform Layer is very heterogeneous and, since there are no universal standards in IoT [45], the access to the data and devices at this level depends on the particular syntax and semantic data model of each platform. In general, direct communication among different IoT platforms is not possible, as they employ different standards, data formats and semantics. For this reason, the exchange and replication of the services based on the platforms depends on the upper layers of AIoTES, in particular the SIL, which is described in the following subsection. The Platform Layer can be extended to incorporate new IoT platforms to the ecosystem.

3.2.3. Semantic Interoperability Layer

The Semantic Interoperability Layer (SIL) enables Semantic interoperability across IoT platforms, and between platforms and applications, SIL performs the necessary conversions to enable a common understanding among IoT platforms. This way, the platform-specific or AIoTES-specific syntactic format and semantics are converted into the corresponding receiver's format and semantics while maintaining the meaning of the information. The use of this abstraction layer to connect the platforms instead of interconnecting all platforms directly among themselves simplifies substantially the implementation of the interoperability mechanisms. From a privacy perspective, platforms decide the information to be shared with authorized users (typically platforms and external applications).

The SIL consists of two components, namely, Inter-MW and the Inter Platform Semantic Mediator (IPSM), as is shown in Fig. 3.

The Inter-MW [46] is responsible for handling the communication between platforms, receivers and subscribers (through a message broker). This component also includes the so-called platform bridges. They enable syntactic interoperability between the platforms and other AIoTES components or client applications and among different platforms. Each bridge is specifically designed to enable communication with a particular IoT platform. Bridges adapt its particular IoT platform data format to a common and generic format managed by the SIL. They perform a syntactic conversion in both upstream (platform to AIoTES) and downstream (AIoTES to platform) communications. To efficiently manage the flow of messages between both components, a message broker, which manages the data flow of the two steps translation, is used (Fig. 3). This broker is also responsible for ensuring low latency, providing high producer throughput, and supporting both, fast and slow consumers.

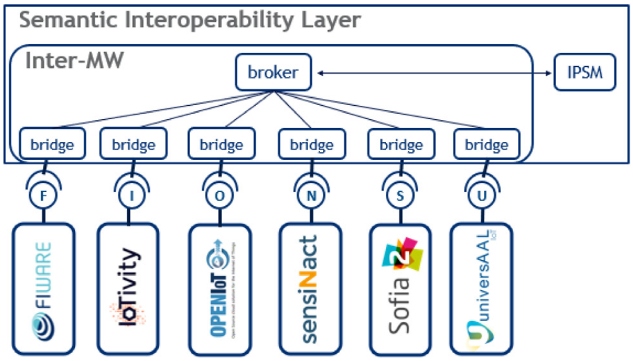

Fig. 3. Semantic Interoperability Layer.

The IPSM [47] manages the semantic mappings between senders and receivers and provides semantic interoperability through the translation between the different platform ontologies and the ACTIVAGE ontology (described in Section 3.2.4). This translation is based on the use of ontology alignments, which represent the rules for performing semantic translations between two different entities and are unidirectional. Hence, those alignments must be developed for the upstream and downstream communications.

An important note before closing the SIL section is that to incorporate a new platform that is different from the ones included in the Platform Layer, it is necessary to develop a new bridge and the proper semantic alignments. The addition of a new platform does not require any changes on the implementation of already existing bridges or alignments. This allows an effective decoupling at both conceptual and implementation middleware levels. Thus, the SIL should provide good extensibility and scalability, as the inclusion of each new platform requires a lineal effort.

3.2.4. Data layer

The ACTIVAGE data model (called ACTIVAGE Core Ontology) was designed to facilitate the exchange of a variety of data assets coming from different AHA local ecosystems. Initially, each DS had its own data model and therefore, seamless interoperability between them was not possible. To move from local to a global approach, an ACTIVAGE core ontology compliant across the AHA-IoT ecosystem has been created. To his effect, ACTIVAGE data model requirements were obtained taking into account the nine ACTIVAGE DS IoT architectures and their use-cases, which consider their IoT platforms, technologies and services [48,49].

The purpose of the ACTIVAGE Core Ontology is not to propose completely new vocabularies, but to group and foster reuse of ontologies from existing vocabularies and extend them where necessary to cover the AHA domain. The ACTIVAGE Core Ontology describes the inherent logical structure of the data within the AHA domain and by implication, the underlying structure of the IoT domain [50]. Among this collection of vocabularies we can find upper ontology definitions such as Semantic Web for Earth and Environmental Terminology (SWEET) Units [51] for establishing standardized units of measurement, OpenGIS GML [52] and GeoSPARQL [53] for outdoor location representation and calculations, and Semantic Sensor Network (SSN) SOSA (Sensor, Observation, Sample, and Actuator) [54], which is one of the most leading standards in sensor and device representation.

The ACTIVAGE core ontology is complemented by other included ontologies such as the generic ontology of IoT Platforms (GOIoTP [50]), which represents the core terminology for interoperability of the ACTIVAGE ontology. This ontology is developed within the framework of the H2020 INTER-IoT project [55], there are other ontologies from other IoT related research projects such as BIG IoT [56], FIESTA IoT [57], VITAL IoT [58], and OpenIoT [59] each adding and extending the IoT specifications and associated services. To represent security services and standards HL7 Version 3 Standard Security and Privacy Ontology is employed. On top of all this representation Specific AHA domain concepts and relations, such as activities, heart rate, or stress levels are modelled in the AHA ontology, which is a living project stemming from the effort in ACTIVAGE.

It is important to note that existing IoT data models vary widely in the form in how data is manipulated and how it is accessed using query data models; thus, in ACTIVAGE, the problem is more particular on defining globally how to offer data via APIs, data shared functionalities, and cross-optimization data capabilities [60–62].

The data model is published online [63] in JSON [64] and OWL [65] formats.

3.2.5. Service layer

The Service Layer is responsible for providing common functionalities and services throughout the ecosystem and represent a significant part of the AIoTES architecture to interconnect services globally, which this layer is located above the Platform Layer and the SIL, taking advantage of the abstraction established in the lower layers. The DSs must be able to use any of the elements of their layer regardless of their IoT infrastructure or platform. The Service layer benefits from the homogenization of data coming from and for other the IoT platforms. The Service Layer includes four main components, namely, Analytics, Development tools, Deployment tools and Key Performance Indicator management tool.

The objective of the Analytics component in the service layer is to facilitate the extraction of useful information collected from IoT sensors supporting human decision-making. In the lower layers of the architecture, raw data are collected by different IoT platforms and stored in various formats, namespaces, and database schemes, specific to the individual IoT platforms used in each DS. Even though the SIL unifies all these different data representations into common semantics, further processing is necessary to extract knowledge from the available data. The Analytics component comprises three sub-components, namely, Data Lake, Data Analytics and Visual Analytics. The Data Lake component is an infrastructure for storing and processing high-volume of data coming from sensors in a distributed manner. The Data Analytics and Visual Analytics components offer a set of methods for the analysis and visualization of the data contained in the Data Lake. The Data Analytics component allows extracting high-level information by applying Machine Learning methods and it also provides methods for the extraction of the information that is meaningful for humans, such as summarizations of data and patterns detected in them. The Visual Analytics contains components capable of presenting the results of the analyses in an intuitive and comprehensive manner.

The ACTIVAGE development tools are defined as a set of applications that employ web-based GUIs and provide developers with an easy way for using the functionalities of the AIoTES components. They allow to easily design, implement and test new AHA IoT AIoTES-compliant applications. The development tools are divided into five categories: Support tools, SIL tools, Data Lake tools, Data and Visual Analytics tools, and Integrated Development Environment (IDE). The Support tools provide documentation and information to help in developing applications within the AIoTES infrastructure and resolving issues. The SIL tools facilitate the use of the SIL and provide access to the ontologies. The Data Lake tools, together with the Data and Visual Analytics tools, offer support to access and analyse integrated data, making use of the components described previously. Finally, the IDE supports application developers in the creation of AIoTES smart applications, services and AIoTES-related code.

The deployment tools are a set of web applications that facilitate the deployment of AIoTES in the DSs. They are divided into two categories, namely, IoT infrastructure management tools and deployment management tools. The IoT infrastructure management tools support a service-oriented functionality, allowing the users to access, register or edit devices and services of AIoTES, as well as for semantically discovering and testing them. The deployment management tools allow creating, editing and maintaining the deployment installation and also platforms and devices that are installed into the system. Since most AIoTES components are designed to be deployed using Docker [66] and Docker Compose [67], deployment tools are docker oriented.

The Key Performance Indicator (KPI) management tool is a global ACTIVAGE dashboard web application that provides monitoring features of DSs. The purpose of this tool is to offer the ability to visually monitor, interact and analyse data collected through various IoT Platforms installed in the DSs. Through a dedicated public API, the KPI management tool extracts both, past and current values of DS KPIs, offering means of evaluating the evolution of DS performance status. The KPI management tools has a variety of integrated technical KPIs that can be monitored. For instance, there are KPIs regarding availability (like current and target number of installed sensors) and KPIs regarding use (which concern aspects of database properties, API requests and triggered alerts).

3.2.6. Security & Privacy Layer

The Security & Privacy Layer (S&P Layer) provides the necessary degree of security across the described layers, guaranteeing protection of sensitive information and complying with the ethical and legal requirements for privacy and confidentiality. The S&P layer has been designed to provide a simple and transparent way to secure the interoperability layer with the minimum modification or not impact on the SIL module. Security and privacy are key features in the ACTIVAGE architecture and its implementation and integration with other services should not be perceived as a delaying nor a hardship process for final users, for this reason, the proposed solution should provide security and privacy for user and service management as a completely independent layer.

Access control and security administration are implemented taking advantage of a well-defined authorization architecture according to oneM2M [68] standard and the RFC2753 [69] and RFC3858 [70] recommendations. Fig. 4 presents the components of the S&P layer and their interfaces with the rest of the components and services. The functional blocks constituting the S&P layer are the following:

- Administration Point (PAP) is in charge of creating, updating, deleting and managing the policies.
- Decision Point (PDP) evaluates and issues authorization decisions based on the policies in the Policy Database and from the user or services requesting any action.
- Enforcement Point (PEP) is in charge of intercept users' access requests to a resource and enforce PDP's decision.
- Information Point (PIP) provides external information to a PDP, such as LDAP attribute information.

The S&P architecture is complemented with an Identity Manager playing the role of Identity provider for users and services, and information point (PIP) for the PDP. It should be noted that the components detailed here, namely, PEP, PIP, PDP, PAP and Identity Manager (IdM), are not mapped directly to tools. The purpose of these components is to provide a clear and cohesive view of the functions and flows that must be executed in the system to achieve a secure authentication and access control process.

To carry out this process, the services must be registered in the PDP and provided with a unique identifier that allows them to demonstrate who they are. Next, thus the method of access control is determined. Depending on this method, the necessary permissions and policies are created to establish an adequate access control to the system. Finally, in order to secure the component, a PEP is available as a proxy. That is, the PEP intercepts each of the requests made to the service, redirecting it to the PDP and waiting for its response in order to permit or deny the execution of the operation in the system.

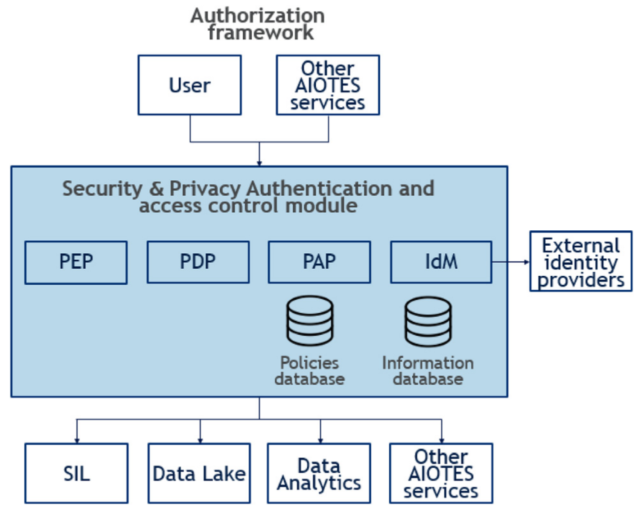

Fig. 4. Architecture of the security and privacy layer/module.

The interaction with the S&P layer includes registration in the IdM and the subsequent authentication each time a request is made using the API of a secured service, always including in the request the token authenticated in the system and provided by the IdM, following a unique way to resolve Security & Privacy Layer concerns from the point of view of the user.

The deployment and integration flow is based on OpenID Connect [71] for identification and authentication, JSON Web Token, and a set of access control mechanisms, which follows AIoTES Design principles.

The GDPR [72] requirements also need to be fulfilled in terms of data sovereignty with the access control and authorization based on policies. This is achieved by enabling the control to specific security scopes (data domains) based on the context, users preferences and national regulations.

3.2.7. AIoTES API

The objective of the AIoTES API is to offer a single entry point for the use of AIoTES. It exposes all AIoTES Framework functionality through a unified set of RESTful operations providing access to the back-end components (SIL, Data Lake and Data Analytics) and a unified access to the user interfaces of the tools. This component works together with the S&P layer to enable user authentication, authorization, and confidentiality. The AIoTES API make use of HTTPS with valid certificates and require user authentication.

3.2.8. Application layer

The ACTIVAGE Marketplace [73] is an open online one-stop-shop where caretakers and healthcare professionals can find applications that are ready to be used in the ACTIVAGE ecosystem. Moreover, developers and service providers can easily upload and share their applications with others DSs. Besides standard upload, download, moderate and manage functionality, the Marketplace also offers its own intelligent App discovery method, between the vast variety of applications, from behavioural monitoring with sensors to intervention support with applications. Moreover, it aims to provide all resources on how to become a developer, then publish, monitor and monetize applications, built on any of the ACTIVAGE IoT platforms. Finally, the Marketplace offers users general analytics showing historic trends of downloaded applications, comments and more.

The need to create different functionalities for three main user roles was identified during the requirements phase. They are the following:

- **Users** are general visitors and application users from patients, elders, carers, family, and healthcare professionals to tech support and deployers of AHA services that wish to obtain, install and use applications hosted in the Marketplace.
- **Developers** are programmers and engineers already working in the ACTIVAGE platforms or other parties that have the knowledge and intention to develop compatible applications. Developers have the ability to upload and host applications, monetizing them and widening their reach. They can also track performance, receive ratings and review insights.
- **Administrators** have full access to its setup, manage users and applications. Their main task is the validation of applications for compliance. For this, the Marketplace offers automatic virus checks and the ability to review the applications that developers submit prior to publication.

3.3. Validation methodology

The methodology followed for the verification and validation of AIoTES is defined in three phases (Fig. 1) which are detailed below.

3.3.1. Component verification

Component Verification is mostly a unit test of independent components and sets of components, before and after their integration into a reliable, stable and functional system. The aim of the tests is to verify that each AIoTES component meets its specifications in a standalone setting. In this phase, the integrated test of some components is limited to those whose interdependence requires them to be integrated and, thus, it is required to test them together.

3.3.2. Integration validation

The validation corresponds to meeting the user requirements at the system level after a partial or full integration. The validation of the AIoTES aims therefore at checking the fulfilling of the user expectations. This phase comprises the integration tests. They are performed in "Testbeds", which are controlled environments very similar to end users' installations. The purpose of these tests is not only to validate the integrated system in a controlled environment, but also to be able to analyse the problems when the system fails, being able to provide full logs without worrying about de-anonymizing the data, as there are no real users involved.

3.3.3. DS and OC validation

This phase consists of the deployment and validation of AIoTES in a real environment (the DSs), using or not a solution with a technology provided through the OC. During component verification and integration validation, it is possible to test overall key aspects and features that require the full installation and set-up of AIoTES. However, DS and OC validation focus on ensuring the correct operation, appropriate performance and user acceptance of the AHA-IoT services rather than testing the technology.

3.3.4. Validation scenarios

This validation phase is defined to ensure a homogeneous validation and considering the fact that each DS had particular use cases, a set of Validation Scenarios (VS) which cover all the use cases, AIoTES objectives (Section 3.2), and features are defined. The VS are used in both, integration validation and DS and OC validation. Consequently, each VS describes a generic technological set up and conditions, which are open enough for DSs and Testbeds to comply with (even without AIoTES itself), but concrete enough to ensure that the specific aspects of AIoTES are assured to be in use.

The VS are classified in three categories:

- **Interoperability**, which examines the minimal basic elements needed for the minimal use of AIoTES, which are the syntactic bridges and semantic alignments introduced in Section 3.2.3.
- **Interoperability Use Cases** (IUC), which portray a set of manners of using the SIL to reuse, exchange and extend DS use cases across the ACTIVAGE ecosystem.
- **Feature** category, which bundles set of components into logical usage.

Below there is a summary on each VS, with identified specific data for analysis.

Firstly, the Interoperability VS is defined as the capability of sharing information independently of the data format and models used. This is a value centred on enabling seamless data exchange and interpretation. The different components of AIoTES may use different formats (such as XML, JSON, Turtle or CVS) as well as data models (data definitions and relationships between data points), yet they are compatible (and interchangeable) because it is all harmonized. Two levels of interoperability are distinguished. The elements used to validate syntactic interoperability are the SIL bridges. Semantic interoperability is equivalent to validating the SIL alignments.

Next, the Interoperability Use Cases VS are defined as follows:

- **IUC1 - Interoperability between devices**: DSs can import third-party devices, where the devices interact with applications through the SIL. The implication is that DSs are able to use any set of devices they need, independently of the IoT Platforms that each of them require.
- **IUC2 - Interoperability between platforms**: The capability of importing third-party applications, where the applications exchange data through the SIL. DSs can use any application, or set of, independently of the IoT platform they are based on. This frees DSs from the decision of which IoT platform to use, and avoids incompatibility issues when importing, or exporting, applications or data.
- **IUC3 - Interoperability between Applications**: Enhance existing applications through any feature offered by AIoTES. Existing applications can be enhanced by importing new devices, interoperating with other applications, or taking advantage of the service layer of AIoTES. This has the potential impact of DSs being able to evolve existing applications without the need to periodically replace their solutions.
- **IUC4 - API Interoperability**: Create native AIoTES applications on top of the API, essentially offering a modern REST API interoperability mechanism for application developers. This reduces the friction of developers with the framework, allowing them to integrate in the current de-facto standard.
- **IUC5 - Continuous monitoring**: Technical AHA-IoT KPIs are continuously monitored through the KPI feature of AIoTES. It allows DSs to make decisions on the usage success (or failure) of technology, as well as quickly react to new situations and trends.

Lastly, feature VS are defined as follows:

- **Data Lake Federation & Data Analytics**: The capability of storing, sharing and analysing data sets. In the age of Big Data and Machine Learning, being able to collect large data sets from different DS is very valuable. The data sets can then be analysed, and the results of this analysis can indicate how to refine services, create new services, or even revolutionize the way AHA services are provisioned by being processed and extracting potentially new knowledge from them.
- **Security & Privacy**: The provision of integral internal security and privacy services for the DS. This includes not only communication protection, but also the use of state-of-the-art authentication and authorization mechanisms, where existing mechanisms in the DS can also be imported. Single Sign On is also a potential value, as users can use the same credentials independently of the application they interact with, even if it is imported from another DS.

Table 1
Component evaluation results.

AIoTES objective	Component	Modules	Tests	Pass ratio
Interoperability	Bridges	6	138	86%
	Alignments	18	18	100%
Big Data solutions	Data Lake	4	27	100%
	Data & Visual Analytics	23	32	97%
Ecosystem building	Marketplace	1	16	100%
	Development & Deployment tools	21	110	96%
	KPI	1	1	0%
Security & Privacy	Security & Privacy	1	8	100%
	AIoTES API	22	108	100%
Total		110	441	94%

- **Marketplace**: Not only sharing applications and components between DSs, but also the infrastructure that facilitates the exchange.
- **Development and deployment Tools**: Facilitating the adoption of AIoTES for developers creating new or adapting existing applications, as well as the deployment and management of the different instances of AIoTES.

A VS matrix (presented in Section 4) was created to define how each DS or OC can implement each VS. Thus, after at least two months of continuous operation with AIoTES, feedback and data were collected. Individual interviews between AIoTES evaluation team and each DS were structured, by defining basic questions for all VS, as well as specific data collection for each VS, and general comments of different facets of the software suite.

Additionally, during the open calls a set of challenges to be resolved (using AIoTES) by third parties were proposed. The implementation processes of these challenges constitute validation scenarios for the framework. Evaluating whether, and how easy it is for third parties to able to integrate and make use of a substantial portion of AIoTES functionalities is an excellent indicator for the uptake and success of AIoTES.

4. Results

In this section the quantitative and qualitative results following the validation methodology described in Section 3.3. is presented. AIoTES has been validated through a three-step process. Explained in Section 2, at the time the ACTIVAGE project began general purpose architectures for AHA did not exist. The literature in this domain was focused on ad-hoc architectures for health [18] to solve specific use cases [7,15,19]. The most significant contribution to a general purpose AHA architecture was IHoH [20]. However, as indicated by the authors, the contribution is purely theoretical, it only presents the different architecture layers without including any concrete results. A comparative study with other solutions is not possible to carry out due to the lack of similar studies and it is also outside the scope of this paper.

4.1. Component verification

The first level of validation or first step, during this step also called component verification, results proved that the individual AIoTES components fulfilled their expected functionality. Table 1 summarizes the component validation, with 110 independent modules to be tested and 441 individual tests this phase is characterized by analysing the main functionalities of the implementation systematically. It is also proven that most of the implementation works after obtaining an overall 94% pass rate. The distribution of tests is concentrated around the bridges, Marketplace as well as the Security & Privacy components. With regards to the most successful components, again Marketplace and the Security & Privacy components pass all their tests, something that is also true for Alignments, Data Lake, and the API. The KPI component shows a negative result, even though it only has a single test, it did not pass it. This is due to the implementation delays of this component which stretched beyond this first validation step; thus, it was not possible to test it at the same time as the other modules. Retrospective validation was not performed due to its successful direct integration with DS and proficient demonstrator provided in the later stages of the project.

4.2. Integration validation

The second level of validation, called integration validation, four Testbeds were deployed in different countries. Each Testbed had their independent instance of AIoTES. The tests performed in this phase have two fundamental differences with respect to the previous one. First, the designed tests define the system as a whole, not just as a collection of components. In most cases, this means that in order to set up a test, most of the system needs to be deployed before additional components are set up and fine-tuned to fit the test specifications. Second, integrated validation has an increased focus on real world scenarios. Each Testbed defines testing according to their local capabilities, guided by global objectives. For that reason Testbeds are validated using the VS (Section 3.3.4) that fit their characteristics. However, not all the VS were used in this phase. Only example and default bridges and alignments (already tested in the previous step) where used, and thus the singularities DSs could have where not examined (a full Interoperability VS was not feasible). Regarding the Features VS, only the elements that are DS independent (Deployment & Deployment tools and Security & Privacy) were validated. The remaining elements are validated in the next phase. On average each Testbed successfully carried out 19 tests. Table 2 shows the details of the successful testing. Even though fail tests are not shown, the average success rate is about 71%, which is in most cases explained by tests being blocked due to delays in the integration of some components for the tested version; all of which were corrected for the formal release of AIoTES for DSs and OCs.

Beyond the quantitative results, Testbeds also provided valuable reports on different topics of the framework which included among other:

- need for better installation procedure,
- more graphical user interface-oriented management,
- better user interface synchronization,
- better security management

This set of validation tests were useful to determine the technical prerequisites for the suite. All components were monitored for main memory and disk usage, on average each component would consume 245 MB of RAM and 650 MB of disk space; thus, the recommended host setup was 16GB of RAM and 30 GB of free disk space for full suite installation.

These first two steps helped to identify issues and set further improvement for AIoTES, which were essential for the proper execution of the last validation step.

Table 2
Successful tests in each of the Testbeds in each country.

	IUCs					Features	
	IUC1	IUC2	IUC3	IUC4	IUC5	Deployment tools	Security & Privacy
TB - France	2				1	3	8
TB - Greece	1	1			1	9	8
TB - Germany	2				1	8	8
TB - Spain	1		1	1		12	8

Table 3
AIoTES validation participants profile. Organizational and technical representatives of each DS.

Gender	Male	11
	Female	5
Age Range (years)	26–30	2
	31–35	2
	36–40	5
	41–45	3
	46–50	3
	50+	1
Education Level (ISCED 2011 [74])	6-Bachelor	2
	7-Master	10
	8-Doctoral	4
Area of Education (UNESCO Nomen [75])	12-Mathematics	6
	33-Technological Science	9
	53-Economics	1
Experience (years)	Mean	14.88
	Standard deviation	9.47
Participant in project (months)	Mean	34.19
	Standard deviation	10.63

4.3. DS and OC validation

The last step of validation, DS and OC validation, was also carried out through the different VS (introduced in Section 3.3.4) and constitutes the main results we present in this Section. This third step is characterized by real-world execution in heterogeneous environments. This means that the emphasis is placed on qualitative data, which is collected through interviews at the end of at least two-month period of continuous execution of the experiment. Table 3 summarizes the profiles of the participants in these interviews. Participants are 16 people representing each DS from the organizational and technical perspectives. The participants have different backgrounds. While most of them have a technological background, but mathematicians and economists are also present; moreover, most of them have Master's degree. In terms of experience in general, the mean is almost 15 years of experience in their sector, while their understanding of the project is denoted by the mean of almost three-year participation. There are twice as many males as females, and the age distribution is mostly uniform in the age ranges from 26–50, with more representation in the 36–40 range.

Given the heterogeneity of the DSs, not all of them implemented all the offers of AIoTES and, therefore, their functionalities could not be validated in all of them. For this reason, the VS validation matrix, which contains the results of the AIoTES validation, was defined (see Table 4). It collects the perceived complexity (in a scale from 0 to 10, where 0 is trivial and 10 is impossibly complex) by the DSs in each of the VS they implemented. It is important to highlight that the VS validation matrix is strongly related to the general objectives of AIoTES (presented in Section 3.2).

Participants confirmed the complexities of the framework. Concretely the way it implements semantic interoperability, through the alignments, consumed most of their integration resources. Generally, what is observed is that when the ecosystem provides ready-made solutions (such as ready-made bridges or alignments) less resources are needed and the complexity decreases. Simplifications on the operational and implementation aspects of the framework, as well as supporting tools, also have relevant impact on the experience and the value reported by participants, even if some further development is required in this field. In line with previous observations, another valuable outcome is the availability of a simple to use and state-of-the-art security framework DSs can rely on to delegate security functions, while at the same time ensuring compatibility between DSs and interoperability between various solutions. In total, participants have reported that there are 4345 users interacting directly with or taking advantage of AIoTES or its tools and features.

In the following Sections the relevant qualitative analysis of the interviews, and the results from the Open Calls are summarized.

4.3.1. Interoperability results

AIoTES has demonstrated the capability to interoperate amongst different IoT Platforms by providing, validating, and using seven different IoT Platform bridges allowing for syntactic interoperability with said platforms. Interviewed participants corroborate this by stating that, from all DSs and new DSs, there are a total of 2,540 users directly connected to the ecosystem through bridges. This level of interoperability is enough to be able to share data, but the applications may be using different semantic models for their data. In order to achieve semantic interoperability, DSs employed six platform bridges (out of the seven available) and implemented eighteen custom alignments, mapping individual and generic data models to the ACTIVAGE common data model, and, in most cases, these mappings have been performed bidirectionally. All 12 DSs have at least deployed bridges and alignments in real life environments.

Additionally, in the first Open Call the AHA community was challenged to provide interoperable applications, through which we can observe the overall process. Following are two examples of successful integration processes that demonstrate the capabilities and flexibility of the framework to interoperate with heterogeneous platforms and architectures.

Strengthens Your Brain is a third-party technological platform which includes a mobile applications and an *Exergaming* solution characterized by a motor-cognitive dual-task-based game battery aimed to stimulate elderly' executive functions by means of physical activity. *Smart Flooring* is a third-party service for fall prevention and detection.

Table 4
Subjective Perceived complexity (from 0 to 10) of the Validation Scenarios (columns) in DSs (rows) according to their representatives. Some DS have implemented a VS in two distinct and independent ways, this is reflected as two values per DS and VS as the analysis is performed per VS. Blank spaces in table reflect those VS where the DS was not participating, whereas N/A represents a DS who participated in the VS but could not provide reliable data, e.g. in some cases their DS only benefited from the DS and could not evaluate the complexity of its implementation.

		Interop.		IUCs					Features					
		Syntactic	Semantic	IUC1	IUC2	IUC3	IUC4	IUC5	Data Lake federation	Security	Marketplace	Data Analytics	Development tools	Deployment tools
Initial DSs	Galicia	7.5	4	4	6.5		N/A	5		N/A			3.5	3.5
				4			N/A							
	Valencia	5	8.5			7		4	5		2			
	Madrid	7.5	8					7	7.5	3	1		3	4
	Region Emilia Romagna	9	8								1			
	Greece	9	10	8				5	8		2	5	6	6
				8										
	Isere	6	9	9				2		3	1			
				6										
	Woquaz	5	8	8				2			N/A	N/A	N/A	N/A
				1.5										
	Leeds	7	8.5	N/A	3			N/A		N/A	N/A			
	Finland	8	9	2		5.5		5	8					
New DSs	Barcelona	7	8.5	6.5		4								
	Sofia	3	6			6	9		6					
	Lisbon	7	0			3	3.5							

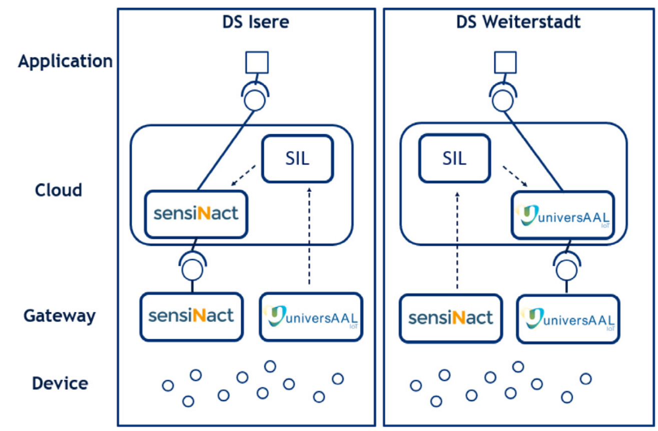

Fig. 5. DS Isere-Weiterstadt device exchange.

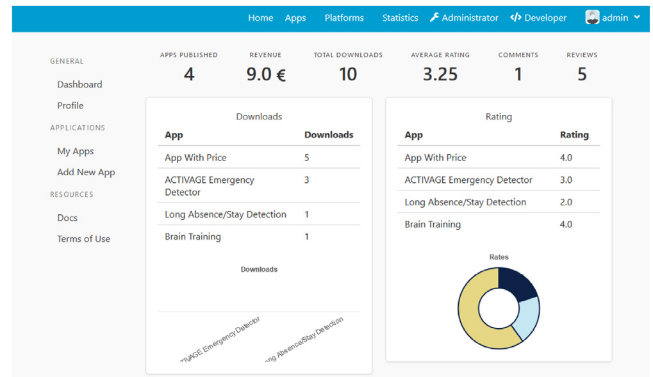

Fig. 6. Marketplace developer dashboard with analytics [73].

It consists of smart flooring technology that operates in real-time and significantly improves homecare and long-term well-being of ageing people. These solutions are integrated with independent IoT platforms; however, the data produced can be consumed by other applications, even if they rely on other IoT Platforms. Thanks to the bridges, these applications become part of the overall AIoTES ecosystem as described by Section 3.2.

4.3.2. Interoperability use cases results

The Interoperability use cases were described in relation to SIL and other associated components. Out of the five Interoperability Use Cases, we highlight two specific implementation examples within our results. The first one demonstrates the interoperability between devices (IUC1). The DSs of Isere and Weiterstadt–Germany identified that both had providers for a device which performed similar measurements: a bed sensor. Having identified their devices, and acknowledging that each had their own qualities (e.g. the device in Isere had better precision, but the device in Weiterstadt was cheaper), both devices could hypothetically be used independently of each application for each DS.

The device exchange between both DSs was successful. Isere's bed sensor was deployed in Weiterstadt and connected to its system, and vice versa (see Fig. 5). The SIL was crucial in this exchange, as Isere's native IoT Platform was sensiNact, whereas Weiterstadt's was universAAL. In both cases, the SIL was deployed with both IoT platform bridges, as well as both IoT platforms. Additionally, the necessary semantic alignments to perform the semantic transformations between the specific IoT Platform semantics and the AIoTES common ontology, as well as the inverse transformations, were developed specifically for this device exchange. The overall result is that Isere and Weiterstadt were able to make their application with no dependency from any device used, giving them more freedom to choose devices, thanks to the IUC1 feature of the framework.

A second example that highlights interoperability between platforms (IUC2) is the service and application exchange between DS Leeds-United Kingdom and DS Valencia-Spain. DS Leeds exported IoT Datasets, which are then used in DS Valencia to improve the performance of their application. The local database at DS Leeds is populated with IoT data originating from *Samsung SmartThings* and *Energenie mihome* systems. Through an NGSI-JSON interface the data is made available to FIWARE Platform. The data is aligned to the AIoTES data model through the bridge and IPSM transformation process. At this stage, the data is now readable by any application that uses the ACTIVAGE Core Ontology Model, which then makes it easy to import it and process it at DS Valencia. As a result, DS Valencia has a dataset which is generalized, i.e. not *Samsung SmartThings* nor *Energenie mihome* specific data but generic presence, magnetic and other daily activity monitoring sensors. This dataset is used to train Machine Learning models so that their solution can better resolve presence sensor data originating from their proprietary sensor platform.

4.3.3. Features results

In this Section we present the results of the feature VSs (introduced in Section 3.3.4). Validation of the different features has been performed at different levels with many instances of features being analysed and validated.

At the time of writing this paper, the Marketplace was populated with a total of seventeen applications, in all areas of interest of AHA-IoT domain. There were sixty-two registered users, twenty-seven of which were registered as developers (potential uploaders of applications). In total, there have been seventy-seven applications downloads, where the most popular application is the Alignment Tool with twelve downloads. This information is available at the Marketplace's landing page [73], and even more detailed insights and trends are available through the administrator's and developer's dashboards (Fig. 6).

In relation to the Developer and Deployer support tools, although the AIoTES API enables the development and integration of application software in the ecosystem, Development tools facilitate the development of applications for the community. DSs have stated that they have successfully used these tools to reduce the development time for tasks such as semantic editing of resources, developing semantic alignments, generating code representation of ontologies for particular platforms, composing complex services from simpler ones, and creating IoT dashboards.

AIoTES offers a fairly complete suite for data and visual analytics already, even though however the project proposed a specific challenge to integrate new and specialized data analytics solutions into DSs. This highlights the importance of analytic tools in IoT-AHA to make sense of all the collected data. One proposition for this challenge is *FILOS*. It aims to foster the autonomy of elderly people by supporting their cognitive capacities linked to memory thanks to the adoption of assistive IT tools (based on IoT, Machine Learning and Mobile technologies). *FILOS* can access historical data for a particular user and, from there, construct models and estimate the cognitive capacity of the user. The system successfully integrates with the Data Lake and historical data services of AIoTES, thus proving that these types of data analytic applications benefit from the framework.

AIoTES proposed a challenge With Security and Privacy VS to third parties using an open call for this. The challenge focused on providing new mechanisms for protecting the overall AIoTES system and the data extending the Security Module. In response to this challenge, two open callers presented their authentication methods easy to use by AHA users. Their proposed solutions, namely, the Modular and Open-Source *User Authentication Hub* Modular system, which offers the capability of identifying users through RFID cards, and *BehavAuth*, which enables a multi-modal continuous behavioural authentication through the use of the smartphone internal sensors, are integrated in the Security & Privacy Module. Each solution was tested in two independent DSs, totalling four, integrating and extending their deployed Security module and enabling native applications to authenticate users transparently. This extension is performed through OpenID connect and allows for flexibility on how the authentication mechanism is used. It can substitute other authentication mechanisms or extending them as a second factor of authentication. Both cases demonstrate the capability of the framework to incorporate new authentication mechanisms, through the use of standards, and transparently incorporate them into AIoTES applications.

5. Discussion

This Section provides an insight into the benefits about the adoption of AIoTES and also the estimated costs related. In particular, the advantages, costs and difficulties derived from the use of AIoTES in the DSs for each of its offerings are discussed. It also includes an analysis presented from the point of view of a third party interested in joining the ecosystem, in addition to the future lines of work. Since the VS are directly related to the AIoTES objectives, for simplicity, the discussion has been divided according to them as addressed in the following sections.

5.1. Interoperability

IoT is a very heterogeneous domain, thus a solution such as AIoTES, which proposes inter-platform interoperability instead of just being another IoT Platform, is quite challenging form the perspective of enabling levels to interoperate. This challenge is more prevalent in the AHA domain, where for example, offering solutions developed for a single platform which can then be transparently deployed into other platforms is a key selling point. Interoperability will impact users by broadening the catalogue of technologies and solutions they can access, as well as enabling the combination of solutions without needlessly replicating components (e.g. reusing the connected sensors for a different solution, instead of buying and deploying two sets of incompatible sensors).

An essential element for interoperability is the ACTIVAGE ontology, which represents the common language to exchange data in the IoT-AHA ecosystem, providing the means for data exchange or simply to complement what from a previous semantic model was incomplete. Another premise for interoperability is that an application that makes use of a common data model and is able to communicate with the AIoTES API could be deployed in any DS, provided that DSs have the proper devices or services to feed the application with data. The ACTIVAGE data model extends from other data models, since this is an extended practice in semantic communities it is expected that the model is easily extendable with new concepts. This feature enables existing and future applications to rely on standardized data formats to interoperate without much effort.

The proposed AIoTES approach has demonstrated that it emphasizes and enables semantic interoperability among different platforms that may use different data models and formats, as described in the previous section. This approach is demonstrated by the quantity of tests designed to test bridges, alignments and interoperability in general; from component testing, where bridges and alignments were extensively tested, to Testbed and DS validation, where important interoperability use cases, such as device exchange (IUC1) and data exchange (IUC2) display an important qualitative result in itself by effectively resolving these kinds of interoperability in real world environments. Hence, the AIoTES framework allows not only the creation of platform-independent applications or services, but also the extension of a local ecosystem with new devices or applications that work natively on a different IoT platform.

It is important to emphasize that providing interoperability between platforms is not a trivial matter and the implementation of the necessary mechanisms to provide this seamless communication requires some level of expertise in the field of semantics and time that is required for the process. AIoTES have taken a further step for the initial development that would be needed in setting-up of a device or application exchange in order to provide the necessary semantic alignments to translate the data from the semantics of the source platform to the target's semantics.

To address this particular issue, AIoTES, through its legal entity, will continue to work on improving the developer experience in this regard. The roadmap includes the improvement of the existing tools, as well as better integration and improvement of documentation. However, the most interesting approach is to include in front line the capabilities to semantically discover and match services, enabling the offering and consumption of any type of service without altering the API. In addition, changes to the alignment system have been proposed in order to better manage them through combination and sharing. These changes will definitely improve the developer and deployer's experience, which could also be improved even further by the introduction of more abstract and standardized mapping languages (e.g. R2RML [76], RML [77], Column-Based data source [78]) to generate the alignments from them.

5.2. Data analysis

The use of a common ontology enables the creation of platform-independent datasets that might contain anonymized information from different local IoT ecosystems, which would make them suitable for training Machine Learning methods. This is precisely the case demonstrated by the third-party development *FILOS*, as shown in the previous section. The Service Layer of AIoTES provides the accessing the historical data through the provided interfaces as an example in how the use of shared data can be successfully exploited. It is also an example on how the Service Layer can be securely extended with new specialized solutions.

The use of a common syntax and semantics would increase the availability of data for training the Data Analytics methods provided by the Service Layer as well as third-party Machine Learning components. Then, those Big Data services will be able to analyse the data obtained from AIoTES in order to provide new platform-independent solutions for AHA.

The advantages that technology brings in the assistance living services (as demonstrated by the main ACTIVAGE results); are the automatic gathering and analysis of big data sets from individuals, it also brings earlier, faster, more reliable and more precise deductions for services (such as risk stratification, behavioural analysis, fall detection, and even diagnosis). This in general will help service providers to provide better care and ultimately prolong and improve the user's life.

The inclusion of additional state-of-the-art methods for data analysis and visualization is identified as Future work within the data analytics functionalities of AIoTES, as well as the fine-tuning of the implemented APIs in terms of flexibility and usability through specialized services, for example, the generic service (mentioned in the roadmap for interoperability), or the inclusion of other AI standardization efforts. This will also simplify the procedure of adding new data analytics services through RESTful APIs, thus enabling external users to extend the platform even further with new state-of-the-art functions, where each can bring their expertise while participating in the standardized data lake of AHA data. The API could also be extended to support the inclusion of ready-to-use visual analytics methods in applications to extend additional functionalities, such as offering visual analytics-as-a-service. For this purpose, web-based visualization languages could be examined that allow the specification of complex visualizations in a textual description (e.g. Vega [79]).

AIoTES will need to continue working to include an edge computing approach, where local processing, independently or securely with the assistance of a remote cloud, can perform data analysis. This will enable the introduction of new use cases, such as the one presented in [80]. In addition, the architecture could be expanded to include machine learning and deep learning data analysis [81].

5.3. Development of applications and ecosystem building

An important aspect in communities and ecosystems is to facilitate the development of applications. AIoTES provides several offerings that facilitate the development, sharing and deployment of compatible applications and, in turn, its ecosystem growth. This is a huge offering of tools, which have also been validated, as can be seen from the component validation tests.

The AIoTES tools were set upon feedback and consideration from third parties. After being consulted, third parties expressed their interest in some of the tools offered by AIoTES. Special interest were expressed in those development tools focused on providing support in the creation of alignments, ontology representation and service composition.

It is important to note that DSs must have a Technology Readiness Levels (TRL) 6 or 7 when they joined the ecosystem, hence the perceived lack of interest in those tools during the validation. However, it was observed that most of their effort integrating IoT platforms and devices was devoted to the development of alignments and understanding the ontological context of the framework. Thus, we think that development tools could be of greater interest and provide more benefit to DSs that have lower TRL, or any DS with earlier access to, and training in these tools.

AIoTES offers its own Marketplace for providers to monetize applications and services and for consumers to discover and make use of registered AHA applications, developed for multiple European IoT platforms, which are already validated in several sites. The AIoTES marketplace place a relevant role, it is the first of a kind in the field of technology-based AHA services. The added value of the ACTIVAGE Marketplace is to provide a uniform portal for all the ACTIVAGE IoT platforms and solutions, thus crossing the boundaries of heterogeneous systems and allowing developers and end-users have AHA resources accessible and to take advantage of cross-site application deployment, along reaching new audiences and expanding the ecosystem of IoT for AHA. The AIoTES Marketplace and application support functionality have been successfully validated, demonstrating that it is a key component not only for ecosystem building but also for the exploitation of AIoTES. AIoTES marketplace is bridging boundaries of multiple IoT platforms, DSs, use cases and countries has ensured a large user and application base for the Marketplace. However, even greater efforts in multiple directions are needed to grow the Marketplace and the ecosystem beyond this stage. Such directions involve both the business and the technology sector. For instance, marketing and promotion campaigns, hackathons and educational events could expand AIoTES beyond its user base. Regarding technology, even more incentives for developers could include hardware stores and native platform clients (e.g. in Android, iOS and IoT gateways) to ease development and deployment together with strategic partnerships with IoT and the health industry. Finally, scaling up the Marketplace would need a distributed cloud platform and even smarter ways to search and suggest applications.

5.4. Security & privacy

Security and privacy are in the central point in importance and relevance in the AHA domain. AHA Systems typically contain health-related information which is especially sensitive, however there are also others parts of the information which should also be protected, such as GPS locations, activities at home, or even time spent with a particular application. Any AHA system must adopt and have implemented security and privacy by design principles, something that can be understood in AIoTES by the quantity and success rate of security and privacy component testing as well as the mandatory execution of security and privacy testing in Testbeds. However, it is acknowledged the run tests will never cover all the possible attack vectors nor privacy situations, thus security and privacy are also a continuous improvement effort.

The Security & Privacy module in AIoTES rely already on standard protocols, it is by design interoperable with different security systems, such as authentication, where existing authentication mechanisms can be easily included in the system. Thus, it also offers the possibility to extend functionalities to multiple mechanisms enabling an easy way to federate access to data and services in a DS and across DS as well as service providers. As has been demonstrated, novel mechanisms can be implemented on top of existing security protocols, extending interoperability horizontally.

The same discourse applies to other security features, for example authorization. In fact, the plans for the future include dynamic authorization, where dynamically registered services (using for example Loopback4 [82]) can be protected on the fly. Another interesting feature to be considered is the ability to synchronize consent forms with authorization through the integration of Blockchain technology. Another security feature considered is integrity of the applications. In particular, because the bulk of the system is based on docker technology, Docker Content Trust can be used, images are signed by developers, and thus a chain of trust can be established.

The current implementation of the Security & Privacy module has some limitations. The first limitation is that it does not consider Edge computing approaches, and in particular end-to-end (E2E) confidentiality. Although E2E is the golden standard, this could not be achieved because the lack of a standardized Public Key Infrastructure (PKI) is not adequate for IoT, which could require a more distributed deployment and smaller resource footprint than other widespread standards such as X509 or Blockchain technologies. Even the cloud-centric development has the limitation that access control is limited to the service invocation, and not referred to the data (e.g. you might have access to a database service, but that does not mean you should access all the data in it). This is very important for IoT-AHA, as caregivers will only need to access particular data, and they may even have delegated access from the end users. Thus, this is a challenge still to be addressed by the IoT community. Another limitation is that data donation, as enabled by GDPR, needs to be better supported. For example, through anonymization and de-identification, user's data (e.g. home position) can be anonymously added to datasets as to improve services. To this respect, as future work, there are plans for including Privacy Rights as a Service (PRaaS), and enforcing consent in order to make the framework GDPR compliant by default.

5.5. AIoTES as a enabler for global AHA ecosystem

The IoT AHA ecosystem is the core concept around which AIoTES is built. This concept impacts all stakeholders of the domain, from End Users being able to securely access for more relevant services; to a group of Developers being able to learn from, and combine with other developments and hardware. sometimes even unknowingly, Service Providers are being able to reach more people at more competitive costs; the global effect is to achieve being a more cost-effective care system for all the community. The bigger the ecosystem is, the more of these benefits stakeholders can benefit from. The ecosystem itself has multiplicative effects, from our own results we show how just 2,540 users interfacing with application directly integrated through AIoTES that can benefit more than 5,000 users in the whole project (DS users and second Open Call users), meaning that for each user we demonstrate that there is another person positively impacted by the introduction of AIoTES. This is because in the IoT-AHA domain the stakeholder interactions are complex, for each person there is a network of formal and informal carers, as well as other users.

The presented AIoTES architecture, discussed in previous sections, allows the creation of a global IoT AHA ecosystem, allowing to replicate and extend to new DSs the current available use cases and IoT-based AHA services. This has been demonstrated by the concrete examples of the implementation of device exchange (IUC1) and service exchange (IUC2). Although the integration of a new platform in the ecosystem is not trivial, as has been explained in Section 3.2.3, the effort invested in this does not imply any changes to the existing platforms or applications and, moreover, it is supported by AIoTES (Section 3.2.5). Hence, the integration is amply rewarded since, once the platform has been incorporated into the system, it can make use of all its offerings and other third-party solutions previously added to the ecosystem. Moreover, the validation results show that, with a rich ecosystem, the overall individual experience is smoother, thus showing the great value of the ecosystem that ACTIVAGE is building. Simplifications on the operational and implementation aspects of the framework also have great impact on the experience and the value reported by DS; however, AIoTES must continue improving in this path. Hence, the existence of a developer community will be critical for the acceptance of the proposed architecture. The Marketplace will be an essential tool for the ecosystem building, it also shows promising results, which can certainly be extended as the ecosystem grows. This has been validated not only through the inclusion of the original ACTIVAGE ecosystem solutions but also through third party developments.

AIoTES has been designed as a static set of modules that can be deployed in a DS. This design allows the definition of a standard API and facilitates interoperability, but it does not consider the possibility of including custom components in the framework. AIoTES at this point lack of support for federation, which is a consequence of the focus of the ACTIVAGE project on the local ecosystems. AIoTES has been designed for Cloud deployment and, as a consequence, its components are too large for Edge deployment, which may be more convenient for its use with IoT platforms designed for Edge Computing. To overcome these limitations, a possible improvement would be the creation of a 'lite' version of AIoTES for Edge Computing or the implementation of specific mechanisms for the connection of IoT platforms designed for Edge Computing, which would improve the scalability of the solution in DS that use this type of platforms.

A common topic in AIoTES design and deployment processes was the need for federative features. These features would enable users to "roam" between DSs, receiving services from different service providers in different ecosystems. Federation would also facilitate the architectural conception within a DS, enabling for example more than one AIoTES deployment, each focusing on a different set of services or devices. As interesting as a federated AIoTES might be, there are several considerations to be discussed. The concept of DS and local ecosystem would be radically changed. Federation will remove the need for a local ecosystem as the central point of service; instead, service providers could provide services across localities (municipalities, regions, etc.) and users would be responsible for the aggregation of services. This model is very similar to existing mobile application market, where each device owner decides which services to consume; there might be however other ecosystem models, aside from local ecosystem and distributed service provision, which might be more useful both for a federated AIoTES and AHA business models. A cost analysis needs to be performed because adding federative functions to any system is not trivial and, thus, it might be more expensive than the benefits it brings.

6. Conclusions

This paper introduced a one of a kind IoT reference architecture for AHA which enables the creation of smart active ageing solutions. The architecture is formed by eight blocks, namely, Data Layer, Device Layer, Platform Layer, SIL, Service Layer, S&P Layer, AIoTES API and Application Layer.

The Data Layer includes a reference IoT-AHA Data Model, which includes, organizes, and standardizes the elements that can be presented for senior assisted living environments, thus creating a common information structure for AHA solutions. The Device Layer is the access point to the real world and is where the sensors that collect information from the elderly and the environment are located. The Platform Layer contains all the platforms in charge of receiving and processing the information coming from the sensors. The unification of the data provided by the heterogeneous platforms is achieved thanks to the SIL, which creates an abstraction layer for the upper layers. Thus, the intrinsic interoperability limitation of IoT is eliminated and seamless interoperability is achieved. The Service Layer can leverage from the SIL to offer a multitude of services and functionalities focused on satisfying the different needs of the users. The Security and Privacy block covers all the above layers and components and ensures both the protection of the users' sensitive information and compliance with ethical and legal requirements of privacy and confidentiality. The AIoTES API provides a set of RESTful operations to work with the AIoTES Framework by exposing all their functionalities in a unified and secured way. Finally, the Application Layer offers a first in the field of technology-based AHA services. A Marketplace that permits to monetize and to discover AHA applications developed for multiple European IoT platforms.

AIoTES has been validated in several scenarios, most of which were focused on interoperability. The validation results show that semantic interoperability has been achieved among the different platforms of the ecosystem. Thanks to semantic interoperability, devices and applications from a DS can be easily deployed in a different one, regardless of which platforms are the base of their IoT infrastructure. Moreover, the AIoTES framework enables the development of cross-platform applications and services. In addition to the access to real-time data, the AIoTES framework facilitates the creation of platform-independent datasets, which can be used by Big Data or Machine Learning methods in order to offer AHA-oriented services. Finally, many of the cybersecurity features offered are modular and can be easily incorporated into other systems or extended with new functionalities that could be appropriate for an AHA scenario.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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