UNIVERSITY OF SALAMANCA

INTERNATIONAL DOCTORAL THESIS

Multi-agent platform for the management, storage and computing of information in smart-homes with different computing techniques

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Declaration of Content

This International Doctoral Thesis consists of a compendium of three scientific papers published in high impact factor international journal that are specified below.

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CERTIFY

That the present document, entitled "Multi-agent platform for the management, storage and computing of information in smart-homes with different computing techniques" has been prepared under their super-vision at the Computer and Automation Department of the University of Salamanca by Diego Manuel Jiménez Bravo, and constitutes his thesis in the modality of compendium of articles for the degree of Doctor of Philosophy in Computer Engineering.

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Declaration of the Academic Commission

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Coordinator of the Ph.D. program in computer engineering

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"Education is the passport to the future, for tomorrow belongs to those who prepare for it today."

Malcolm X

Abstract

Multi-agent platform for the management, storage and computing of information in smart-homes with different computing techniques

by Diego Manuel JIMÉNEZ BRAVO

The increase of big and medium cities along with the irruption of the Internet of Things has supposed a new challenge for governments and city councils. It seems that they have wagered for the transformation of cities to a more smart environment. This transformation does not only mean the transformation of the city itself but also the transformation of buildings, homes, and the implementation of new and useful services for the citizens. The Internet of Things technology and artificial intelligence are the main responsible for this transformation. These technologies can completely transform these environments and increase the benefits for citizens. However, it is also important to use these technologies not only to improve users' benefits but also to improve the quality of life in our neighborhood or city. Right now, one of the mains social problems is climate change. Therefore, it is important to use these technologies to fight and reduce the effect that climate change is provoking in the world. This Ph.D. thesis aims to research on a multi-agent architecture for smart-homes that tries to reduce the effect that non-renewable energies have in the environment. The thesis addresses the characteristic of an IoT system and the most important protocols and/or technologies used for communication in these systems; it also describes some of the most important algorithms in the artificial intelligence field of study; finally, it describes the characteristics of a multi-agent system. The case studies designed along with the architecture designed have demonstrated to work perfectly and with good results as it is showed in this work. Hence the main contributions of this works are: (I) a review of the state of the art in the fields related with the Ph.D. topic; (II) a multi-agent agent architecture for IoT environments, especially smart-homes; and (III) different case studies to reduce the consumption of non-renewable energies in homes.

Resumen

Plataforma multiagente para la gestión, almacenamiento y computación de información en viviendas inteligentes con diferentes técnicas de computación

por Diego Manuel JIMÉNEZ BRAVO

El aumento de las medianas y grandes ciudades junto con la irrupción del internet de las cosas ha supuesto un nuevo reto para los gobiernos y los ayuntamientos. Parece que han apostado por la transformación de las ciudades a un entorno más inteligente. Esta transformación no sólo significa la transformación de la ciudad en sí misma, sino también la transformación de los edificios, las casas y la implementación de nuevos y útiles servicios para los ciudadanos. La tecnología del internet de las cosas y la inteligencia artificial son los principales responsables de esta transformación. Estas tecnologías son capaces de transformar completamente estos entornos e incrementar los beneficios para los ciudadanos. Sin embargo, también es importante utilizar esta tecnología no sólo para mejorar los beneficios de los usuarios, sino también para mejorar la calidad de vida en nuestro barrio o ciudad. Actualmente, uno de los principales problemas sociales es el cambio climático. Por lo tanto, es importante utilizar estas tecnologías para luchar y reducir el efecto que el cambio climático está provocando en el mundo. Esta tesis doctoral tiene como objetivo investigar sobre una arquitectura multiagente para entornos del internet de las cosas que intente reducir el efecto que las energías no renovables tienen en el medio ambiente. La tesis aborda las características de un sistema de internet de las cosas y los protocolos y/o tecnologías más importantes utilizados para la comunicación en estos sistemas; también describe algunos de los algoritmos más importantes en el campo de estudio de la inteligencia artificial, y describe las características de un sistema multiagente. Los casos de estudio diseñados junto con la arquitectura diseñada han demostrado que funcionan perfectamente y con buenos resultados como se muestra en este trabajo. Por lo tanto, las principales contribuciones de estos trabajos son: (I) una revisión del estado del arte en los campos relacionados con el tema del doctorado; (II) una arquitectura de multiagente para entornos del internet de las cosas, especialmente casas inteligentes; y (III) diferentes casos de estudio para reducir el consumo de energías no renovables en las viviendas.

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List of Abbreviations

6LoWPAN	IPv6 over Low-power Wireless Personal Area Network
AODV	Ad hoc On-Demand Distant Vector
AR	Action Research
BLE	Bluetooth Low Energy
CB	Content-Based filtering
CF	Collaborative Filtering
CNN	Convolutional Neural Networks
CoAP	Constrained Application Protocol
DDS	Data Distribution Service
DTLS	Datagram Transport Layer Security
HF	Hybrid Filtering
HTTP	Hyper-Text Transport Protocol
IIoT	Industrial Internet of Things
IoT	Internet of Things
IP	Internet Protocol
IREP	Incremental Reduced Error Pruning
JCR	Journals Citation Reports
***k*-NN**	*k*-Nearest Neighbors
LoRaWAN	Longe Range Wireless Area Network
MAS	Multi-Agent System
ML	Machine Learning
MQTT	Message Queue Telemetry Trasport
NFC	Near Field Communication
NILM	NonIntrusive Load Monitoring
OSI	Open Systems Interconnection
PART	PARTial decision trees
Ph.D.	Doctor of Philosophy
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PLC	Power Line Communications
PLC	Programmable Logic Controllers
RBF	Radial Basis Function networks
REPTree	Reduced-Error Pruning Tree
RIPPER	Repeated Incremental Pruning Produce Error Reduction
RNN	Recurrent Neural Network
TCP	Transmission Control Protocol
TF/IDF	Term Frequency Inverse Document Frequency
UDP	User Datagram Protocol
UTC	Coordinated Universal Time
WLAN	Wi-Fi Local Area Network
WSN	Wireless Sensor Networks
ZB	Zettabytes

To my niece Paula for teaching me to keep growing even in difficult times.

Chapter 1

Introduction

Nowadays, citizens trend to live in medium and large cities rather than small cities, towns or villages. The industrialization and the rise of opportunities promoted the exodus of the population from the countryside to medium and large cities [1]. This situation allowed to increase the area of the cities and the economical power of the cities industries and companies. Also, with time this economic power can be seen in the medium and high class of society. This new position of most of the citizens and the decrease of the prices in the technological market allowed most of the population to obtain electronic devices. Today, one of the most used devices every day is the smartphone. According to a recent study [43], there are 3.50 billion of active smartphone users, which means 45.04% of the global population.

Although, the smartphones' increase is evident, there are not the only electronic devices that people have. People, especially young people tend to accumulate smart electronic devices that they use in their daily life. The use of these devices allows people to access a huge amount of knowledge and information available on the Internet. This is the key to this kind of devices, they are connected to the Internet. However, there are not the only devices that have this feature. All the devices connected to the Internet comfort the famous Internet of Things (IoT). A recent study [22] shows that in 2027 there will be 41 billion IoT devices and right now 127 new devices are connected to the Internet every second. These two pieces of information remark the idea that today and future companies will be based on IoT technology.

Furthermore, IoT is not only the devices connected to the great network that suppose the Internet. IoT is also the data generated, transmitted or measure by these devices. In general terms, the Internet generates new data every minute. For example, the Google search engine runs 3,877,140 searchers every minute of the day, Amazon ships 1,111 packages, Netflix's users stream 97,222 hours of video, Youtube's users watch 4,333,560 videos, Twitter's users send 473,400 tweets and Instagram's users post 49,380 photos between others [24]. Moreover, physical IoT devices will produce by 2025 79.4 zettabytes (ZB) of data [44]. Consequently, IoT and Big Data research areas will continue being important due to the new challenges that these circumstances will bring.

This big amount of data suppose one of the big challenges to solve. Companies, governments, and technological industries know it and they have put many of their efforts in resolving the task to extract any valuable information hidden in the data. To extract this value, it is important to define a good strategy to obtain, transmit, store, and analyze the data. Hence, the appropriate behavior could help to reduce cost, and obtain effectively the valuable information from the data that allows improving their activity, discover users/citizens' interest, forecast behavior, ... Also, the amount of data allows researchers to study new techniques and models that can automatically interpreter the data and fin the knowledge behind them faster than humans beings and on many occasions with a better performance.

Taking into account this information it is easy to understand that the appropriate definition and construction of an IoT system is basic to obtain relevant results. All the system has to work as one entity to achieve its propositus. Sometimes, and especially in IoT systems, this is not an easy task. IoT systems include different hardware components distributed in a real environment and they do their act independently from the rest of the system. Therefore, it seems crucial to study the appropriate definition and construction of the IoT system.

On the other hand, there is also another big problem in today's society that has to be confronted. This problem is climate change. The year 2019 had supposed the key moment to establish climate change as a real global problem that has to be addressed. Several international conferences had been taking place during the past year [85, 34]. Moreover, a 17 years old environmental activist teenager had been declared "Time Person of the Year" by Time journal [36]. Consequently, climate change's debate is here to stay and governments will be forced to take measures to revert the actual situation.

The main producer of CO_2 emissions on a global scale is the electricity generation industry [80]. Electricity is produced under the demand of their main consumers, residential and company buildings. The ideal solution for this big problem is the use of green energies. However, many countries are not prepared for this big change yet. Hence, it is important to promote a transitory solution to reduce CO_2 emissions while the transition from non-green energies to green energies is achieved.

Taking into account this information, it seems that IoT technology can be helpful to design a system that makes use of the data provided and reduce the impact that humans have when they consume different types of energies. Therefore, this thesis aims to research an IoT architecture that allows having a well defined distributed system that works together intending to reduce gas emissions and promote humans to make efficient energy use.

1.1 Hypothesis and objectives

At present, it is possible to find a great variety of distributed systems in the IoT field of study. Many of them with solid architecture. Even so, the increase of the use of homes smart devices has supposed a new challenge to IoT researches that now they can use the data provided by the sensor to extract knowledge and behaviors and control the house in a smart way. However, a well designed and distributed architecture is needed to achieve the goals and have an impact on both users' experience and society.

Therefore, the following hypothesis is selected as the basis for this Ph.D. (Doctor of Philosophy) thesis:

Hypothesis

Design of an architectonic model for IoT applications that includes distributed hardware components and artificial intelligence models for knowledge acquisition that can facilitate the users' experience and contribute to the climate change fight.

To validate this hypothesis several objectives have to be addressed. These objectives are explained below:

- Research in data collection from Wireless Sensor Networks (WSN) mainly for short distance environments. At the same time, research in sensors that allow us to collect the appropriate data effectively and reducing electricity consumption.
- Research in different artificial intelligence models and techniques that allow us to study the data and extract from them the knowledge and different patters from the users' behaviors. At the same time, data cleaning and preprocessing techniques will be evaluated to extract the most from the data.
- Research on different types of IoT architecture in general and for data collection and analysis in particular. It will be focused on systems that allow integrating different entities that work as only one to obtain the platform objective.
- Establish several case studies that help in the climate change fight thanks to their contribution to reducing the consumption of non-green energies while they help users to reduce cost and/or improve their life quality.

1.2 Research methodology

Throughout the development of this Ph.D. thesis, the Action Research (AR) methodology [74] has been used. This methodology has been widely used in other similar software projects.

AR focus on the resolution of an existing problem-based on a hypothesis. Once the purpose of the research is defined, the next step is to collect information related to the research hypothesis so a deep analysis is performed to design the best proposal that obtains a solution for the studied problem or challenge. After that, the designed solution is tested with cases study. These tests serve to evaluate if the hypothesis was right or if the designed proposal is useful for the hypothesis. If the proposal did not support the hypothesis the AR methodology allows repeating the process iteratively until the hypothesis is accepted or refuted.

In consequence, this methodology can be defined as a cyclic method that has the following phases or steps:

- **Problem definition**: identification of the problems and their variables to obtain the research hypothesis and the research objectives.
- **State of the art revision**: a study of previous researches and study of the basic and fundamental concepts and techniques related to the research hypothesis.
- **Analysis and design of a proposal**: a deep analysis of the state of the art to define a proposal that aims to prove the hypothesis.
- **Case studies definition**: a definition of one or several case studies that aim to test the designed proposal.
- **Testing and result extraction**: the case studies are executed and the results are obtained for its latter analysis.

- **Results analysis and discussion**: the results obtained are evaluated and explained in detail to know the reason for themselves.
- **Conclusions definition**: conclusions are evaluated in order to accept the proposal and/or the hypothesis or refute the proposal and/or the proposal. After this step, the cyclic can be restarted.

The use of this research methodology allows the researchers to proof their study with real case studies so the study can be easily transferred to the society. Furthermore, this methodology also aims to communicate the results obtained from the research through journal or conference publications. This last statement is quite important since the aim of every research is to transfer the knowledge obtained to the rest of the scientific community.

1.3 Thesis structure

Once the hypothesis is defined it has to be studied. This study is shown in the next chapters of the present manuscript. Its structure is defined below.

- **Chapter 2. Background**: this chapter contains the art related to the proposed research hypothesis. It contains a deep study of different IoT environments and technologies. Also, the study about artificial intelligence techniques, models and concepts are studied in this chapter. This subsection will be essential in order to extract knowledge from the data and perform useful decisions or actions for the system. Furthermore, a study about currently distributed architectures in IoT environments is studied.
- **Chapter 3. List of journal articles**: the third chapter of the Ph.D. thesis contains the articles used for this thesis in the modality of a compendium of articles. First, a subsection with the established relationship between the articles is presented. After that, the original articles are included following by a Spanish summary for every one of them. This summary contains the research objectives, the used methodology, the results explanation, and the conclusion extracted from the article.
- **Chapter 4. Conclusions**: finally, the last chapter of this Ph.D. thesis includes the conclusions extracted from the development of the research work developed during this doctoral thesis.

Chapter 2

Background

This chapter contains the study of the previous works and knowledge concerning the research hypothesis of this manuscript. The chapter is divided into three main sections: IoT environments, intelligent computing algorithms, and multi-agent systems.

The first section is dedicated to IoT environments. It will explain the concepts of IoT technology as well as the different kinds of environments in which this technology can be applied. Also, it is analyzed the different types of sensors networks and all the theoretical concepts and ideas related to this research area.

The second section speaks about the different types of intelligent algorithms used to resolve the research hypothesis. It contains information about machine learning and artificial intelligence techniques. Furthermore, the more important algorithms or techniques are explained in deep.

The last section includes information about multi-agent systems and their features. The theory about this type of system will be explained in deep as well as some of the most important applications and implementations of the multi-agent system.

2.1 IoT environments

Sensors have been capturing data for decades in different environments, but, especially in industrial environments; where sensors have been used, for example, to measure some values at a manufacturing plant between others. Although, during the last decade IoT technology had gained an important relevance at a worldwide level.

Without any doubt, that relevance is due to the decrease in the sensors' price. As explained in [40] and as shown in 2.1 the price of the sensors during the past years has suffered a big drop in the last years. This fall is closely linked with three different factors:

- The increase of companies dedicated to the IoT area and companies that are expanding their products and services with this technology.
- The constant optimization of IoT sensors regarding energy consumption, range area, size, and efficiency.
- The facility that manufacturers offer to their clients. Increasingly companies are offering plug and play sensors that facilities the use of them for non-expert users.

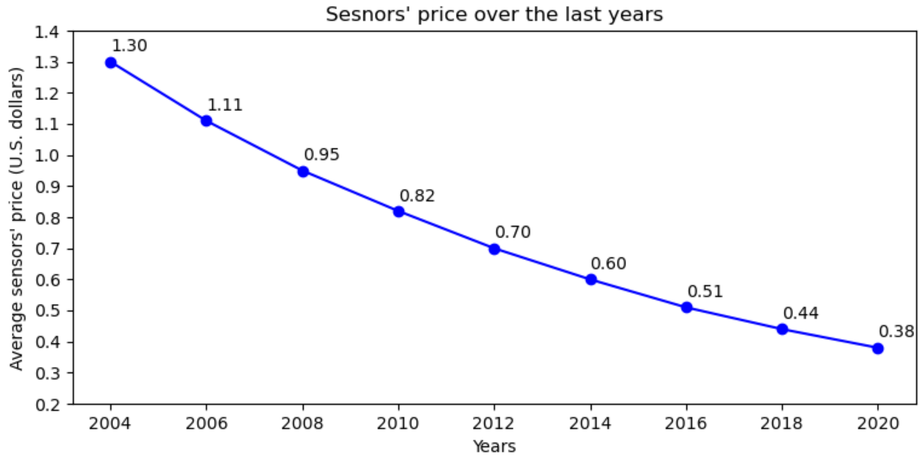

FIGURE 2.1: Sensors' price over the last years.

Consequently, the IoT concept and other related to it have emerged between society and the media. However, for many of them, this seems like an abstract concept. Therefore, it is necessary to include a proper definition of IoT. Since its first appearance, IoT has been defined in many different ways. Nevertheless, almost all the definitions share the same basic idea: IoT defines an interaction between the physical and digital world to achieve a common goal by working together [66, 72]. The communication between these two worlds is provided by actuators and sensors. These hardware elements have computing and networking capacities that allow the communications between them and/or between the digital world. Also, the computing and networking capacities allow to know and change the state of the elements [3, 47, 81].

One of the main characteristics of IoT technology is the ability to measure the data form the real world. However, IoT also includes some problems or challenges related to this feature and with others [19]. These kinds of problems or limitations have to be taken into account when designing or configuring IoT solutions. They are listed below:

- **Constrained sensors**: although IoT sensors manufacturers are improving their sensors, these are still limited in some aspects. Limited battery power, bandwidth, and hardware capability have to be taken into account when configuring an IoT environment. For many scenarios, a balance between these limitations has to be achieved to record useful and valuable data.
- **Time problems**: an IoT infrastructure can be spread over different geographical locations. Hence, it has to be very clear if the data recorded by those sensors are using the local time or the Coordinated Universal Time (UTC). Furthermore, the sensors may have synchronization problems with their internal clock due to a bad initial configuration or a communication mistake.
- **Space problems**: the locations in which the sensors are located may affect their accuracy level. Temperature and elevations have a great impact on sensors' behavior. Also, remote locations may have weaker network access, affecting the quality of the data. Even the country in which the sensor is located has to be taken into account for political and privacy reasons; some European countries have very specific laws to regularize the use of sensors' data.

- **Data volume**: IoT scenarios may suppose a problem to many companies or organizations that starts using this technology. This technology usually generates big amounts of data so companies that are not prepared for this scenario may have problems with the storage of the raw data. Because of this data growths exponential during the first years of the IoT infrastructure. Also, this big amount of data may cause computational problems when trying to extract the knowledge hidden behind them with advanced computer sciences techniques.

These limitations should be taken into account when a new IoT environment is being configured in every one of the applications of this technology.

2.1.1 IoT applications

IoT is able to touch every one of the aspect of human lives. IoT applications are found in a great number of environments and scenarios. In this subsection, an overview of the most important applications of IoT are addresed.

Smart-homes and smart-buildings

Smart-building and smart-homes, also know as home and building automation, have suffered a great development over the last years. This growth was motivated by the decrease in prices in the IoT industry and the creation of plug and play devices. The main applications are related to energy efficiency, energy-saving, and home security [50, 48, 49]. These applications allow promoting the monitorization and automation of the homes and buildings. However, other applications are also gaining significance like healthcare [45], but it will be discussed in another subsection. What is important to remark about these applications is that smart-buildings and smart-homes are moving from luxury, comfort, and security solutions to other types of applications connected between them that help users in their normal life and that even create new market opportunities.

Smart-cities

Smart-cities are complex ecosystems in which sensors are spread all over a city or in specific neighbors. The main objective of these environments is to increase the comfort and quality of life in cities. They try to respond to the necessities of citizens, institutions, companies, public authorities, and local governments in different areas. Some of these areas or applications could be healthcare [23], security [55], energy optimization [60, 6], public services [67, 30], and environmental [10] care among others. For those purposes IoT plays an important role in allowing to collect the data and events that happen in the city and putting it at citizens' disposal. The solutions provided by these kinds of infrastructures could be as complex and connected as desired. In addition, IoT sensors could be located in mobile objects which increase the possibilities of IoT solutions.

Smart-grids

Smart-grid is the term applied to an intelligent electric grid that includes different operational systems, including smart-meters, smart-appliances, sources of green energy, and energy-efficient resources. These systems brigs new opportunities for the society allowing them to implement new applications regarding the electric field of study [26]. This field of study is possible thanks to the Power Line Communications (PLC) that permit the transport data over existing electrical cables. With this technology system that smart-metering and energy consumption reporting is possible. Also, a more complex system that uses that data to optimize the use of energy in cities and buildings is possible. Nonetheless, the use of PLC technology indeed depends on different factors, like the country, frequency band, etc. Therefore, it is still too much to investigate in this field of study.

Industrial IoT

Industrial IoT (IIoT) defines the use of IoT in fields like transports, logistics, manufacturing, mining, aviation, utilities, and all kind of industries [27, 61]. IIoT is used to measure and sensor data from the machines and components of the different industries. Nevertheless, the importance of having real-time data in some of these industries is still a challenge. Since in many of these industries, like aviation or industrial machines, they require strict deadlines so, the precision of milliseconds or less to avoid serious consequences or catastrophic problems is required. Another big deal that IIoT has to resolve is that many of the machines on a factory have their specific protocol; so, it is quite difficult to make sensors of different machines communicate between them. As a consequence, many governments and privates companies are investing their efforts, facilities, and money to obtain a more competitive IIoT.

Smart-farming

Smart-farming is one of the areas in which IoT has been introduced less but on the other hand, is one of the fields in which have more applications. With the new tendency of living in medium and big cities, the primary sector must replace itself with a modern farming system. This important renovation is closely linked to the use of IoT which can help to perform solutions for weather monitorization, watering precision, fertilization and pesticide precision, cattle monitoring [8], precision farming, fleet management among others. The sensors and real-time data help to develop these useful solutions for farmers to reduce resources and optimize production. For this purpose, communication technologies are key. Farms usually take up big field areas, therefore, long-range communication protocols should be a must to resolve this problem.

Smart-health

Smart-health uses networked and IoT technology to improve services in the health sector. This IoT field is one of the most important and interesting since its results are directed applied to society. It makes use of mobile or portable devices, data connectivity, measures from sensors, big data, and machine learning analysis to provide their solutions to medical staff and patients. The solutions could provide remote patient monitoring [51, 54], fall detection [62, 78], decissión support systems [89, 65], virtual analysis [84], illness detection [16], etc. These solutions could help to improve and modernize health services. However, the inconsistent and immature technology in health services [83] difficult the development of these solutions. Furthermore, medical staff usually see these services as an enemy instead as help to improve their job. Another important issue is the restriction to medical data due to

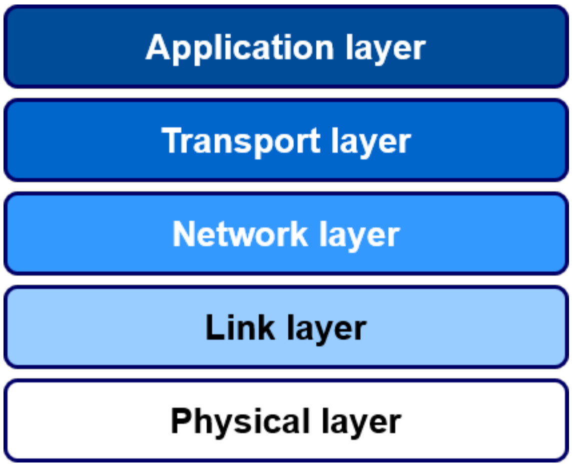

FIGURE 2.2: The OSI model's stack.

privacy issues; with the appropriate data is impossible to achieve an effective solution for this sector.

2.1.2 IoT protocols

Communications networks operate following the principles of the Open Systems Interconnection model, also known as the OSI model. OSI model divides the communications into five different layers of a stack. There is an important principle that the bottom layers of the stack not need to know about the layers above. Figure 2.2 shows the OSI model's stack.

The physical layer is extremely related to the device's electrical engineering. Due to it, this section will not analyze this layer since its main goal is to analyze the different protocols related to data transaction. The link layer is referred to as the connectivity; the network layer is the Internet Protocol (IP). The transport layer transmits data over long distances using TCP (Transmission Control Protocol) or UDP (User Datagram Protocol). Finally, the Application layer deals with data messaging or communication.

There are several protocols related to every one of these layers [3, 81, 25]. However, to determine the more appropriate one for a study or environment is important to take into account how the system is going to send data depending on the battery power and computational resources of the electronic devices as well as the requirements for that delivery of data. Therefore the network protocol depends on the type of device and its environment.

An important component in almost all IoT system is the gateway. It could be defined as a network node that connects two separate networks that use also different protocols. Therefore, the gateway mission is to translate from one protocol to the other. It usually translates from the device protocol to the IP.

Now the most used IoT protocols will be explained to analyze the best options for the proposed system.

Bluetooth Low Energy

Bluetooth Low Energy (BLE) or Bluetooth Smart is the newer implementation of the classic and well know Bluetooth. It is specially designed for low power devices that require a less frequent data exchange. BLE devices can be connected between them and exchange data. If a BLE device acts as a sender in a connected it is defined as a master; meanwhile, if it acts as a receiver it is defined as a slave. A master can have several slaves connected while a slave is only connected to one master. Typically a gateway transmits the data received from the BLE nodes to the appropriate format for the Internet.

6LoWPAN

IPv6 over Low-power Wireless Personal Area Networks also knows by its abbreviation 6LoWPANs defines one of the options for the link layer in the OSI model. The communications use IPv6 transmission over lossy and low-power networks. Due to those characteristics of the networks, it is interesting to apply some kind of encryption to the message in one or more of the OSI layers. The link (6LoWPAN) and network (IPv6) layers are connected through an edge router that allows exchanging data between the devices inside the same 6LoWPAN network and exchange data between the Internet and the devices inside a 6LoWPAN network between other functions. 6LoWPAN networks are connected between them using IP-based routers which makes it easy to establish connections between them without the need for a gateway. Finally, the elements inside one of these networks can be defined as a router, who send data to other devices, or host, who pick and share data.

ZigBee

ZigBee is a protocol that not only belongs to one layer of the OSI's stack but it covers different layers, from network to application. One of its most important characteristics is the security mechanisms that it incorporates. It transfers data in small low power ratios; therefore, its range is small but it can travel long distances by transferring data to intermediate ZigBee devices in the network. Also, data rates are low, in consequence, the battery of the devices tends to last a long time. In a Zigbee network, there can be three different types of devices: a coordinator device, router devices, and end devices. The coordinator initiates the network; there can be only one in a network. A router device can be in touch with the coordinator or with other router devices and it works as an intermediary in the routing of messages. And an end device can only communicate with the coordinator of the network. The network protocol used in ZigBee is Ad hoc On-Demand Distant Vector (AODV) which finds the desire destination by broadcasting to all the neighbors and spreading that broadcast also in the neighbors. Furthermore, a ZigBee network usually includes a gateway to connect the network into the IP routing protocol.

NFC

NFC is Near Field Communication protocol, a protocol that allows two NFC devices to communicate between them when they are extremely close (around 4 cm). It offers low speeds and a simple and quick setup. The communication between the devices of the network is based on electromagnetic induction and the data exchange is done over radio frequency band 13.56 MHz. In the NFC network, there are two different types of devices, full NFC devices, and NFC tags. Full NFC devices can operate exchange information, can act like smart cards, can read information stored in inexpensive NFC tags. On the other hand, NCF tags are usually read-only and they do not need a battery since the full NFC devices create the radiofrequency field. Unpowered NFC tags are extremely cheap. However, NFC tags can also be written but for that purpose, they should have a power supply. In this kind of network usually, the full NFC devices act as a gateway translating the message to the Internet.

Sigfox

Sigfox is a protocol developed by a French company that allows implementing a low-power and a long-range network. It is supposed to be used in devices that do not require a continuous update. The message can travel up to 40 kilometres from a node to a base station. Furthermore, Sigfox devices can be cheap since their low power requirements and complexity. These characteristics make it possible to use it for a great variety of purposes.

LoRaWAN

Equivalently, as Sigfox the Longe Range Wireless Area Network or LoRaWAN is a protocol designed for longe range network, low bandwidth, and low-frequency rates. It is used to communication devices to a network server through a LoRa gateway. Also, the devices may be divided into different classes depending on the type of communication required by the IoT application. A great difference with Sigfox is that it is open source so no license is needed for a LoRaWAN implementation [57].

Wi-Fi

A Wi-Fi Local Area Network (WLAN) is any kind of network that uses the IEEE 802.11 specifications. It is a global technology used by many IoT devices. To use Wi-Fi these devices need to incorporate any kind of network interface controller. The packet of data is sending using the Ethernet style. Therefore the delivery is not guaranteed. In the same way, usually, Wi-Fi devices are connected to an access point connected to an Ethernet network with Internet access. The use of Wi-Fi technology is spread all over the world, however, IoT-WiFi devices tend to use a lot of energy resources due to constant communications. Nevertheless, new standards with lower consumption are being implemented for IoT scenarios.

Cellular

Cellular or also referred to as 4G or LTE are communications protocols that operate over radio waves. Both 4G and LTE are IP-based networking technologies with huge data rates (up to 300 Mbits/s). One of the main advantages of these technologies is that they handle perfectly devices that change from one network to another. Still, the main disadvantage is the enormous use of energy consumption compared to other protocols. As a consequence, a new category, LTE Category 0 has been designed for IoT devices with lower data rates and bandwidth ranges.

MQTT

MQTT or Message Queue Telemetry Trasport is a data messaging protocol located in the application layer of the OSI's model and that operates over IP and TCP protocols. It is one of the most common protocols in IoT devices. For that reason it is incorporated in all the Silicon Valley made IoT platforms. MQTT is specially designed for low power rates and small bandwidth communications; something that fits with the most IoT devices.

Every MQTT network has at least 3 main entities or devices: a publisher, a broker, and a subscriber. Regarding the name of the components, it is clear that the MQTT protocol uses the publish/subscribe architecture. In this architecture, the publisher sends the data to a specific topic of the broker replacing the previous data. Next, the broker sends the data to all the subscribers of the topic. Therefore, a publisher does not have to ware about the subscriber at all since the broker makes as an intermediary. This is a great advantage of MQTT since both publishers and subscribers could be disconnected without putting in risk the network.

An important feature of MQTT is that natively it is an unencrypted protocol. However, it operates over TCP, hence, TLS/SSL encryption can be used. Security is an important issue for all IoT implementations.

HTTP

The Hyper-Text Transport Protocol (HTTP) is a protocol that follows the RESTful principles and that operates in the application layer of OSI's stack over TCP and IP. It has been used for several IoT implementations due to its reliability when sending data and its easy implementation and disponibility all over the world. However, it seems not to be the best IoT protocol due to that HTTP is a text-based protocol wich increment the size of the message and the power and complexity needs for the IoT devices.

CoAP

Constrained Application Protocol (CoAP) is a protocol that operates in the application layer and over UDP and IP protocols. It has been designed for low resources devices, like IoT devices. It uses a client/server communication architecture but over the UDP protocol which reduces the communications between client and server; the datagrams inside the UDP contain all the relevant information to establish a connection between client and server without previous connections. However, reliability is not guaranteed and the receiver of the message should take that into account to handle these circumstances.

As well as MQTT, CoAP is unencrypted but the use of Datagram Transport Layer Security (DTLS) when using UDP allows to encrypt the communications.

DDS

DDS or Data Distribution Service is a protocol that operates in the transport layer and that follows the principles of peer-to-peer communications. In a DDS network, the nodes use a variation of the publish/subscribe model in which nodes announce the data that they are publishing and the data they want to subscribe to. Thus, any node can be a publisher, a subscriber, or both.

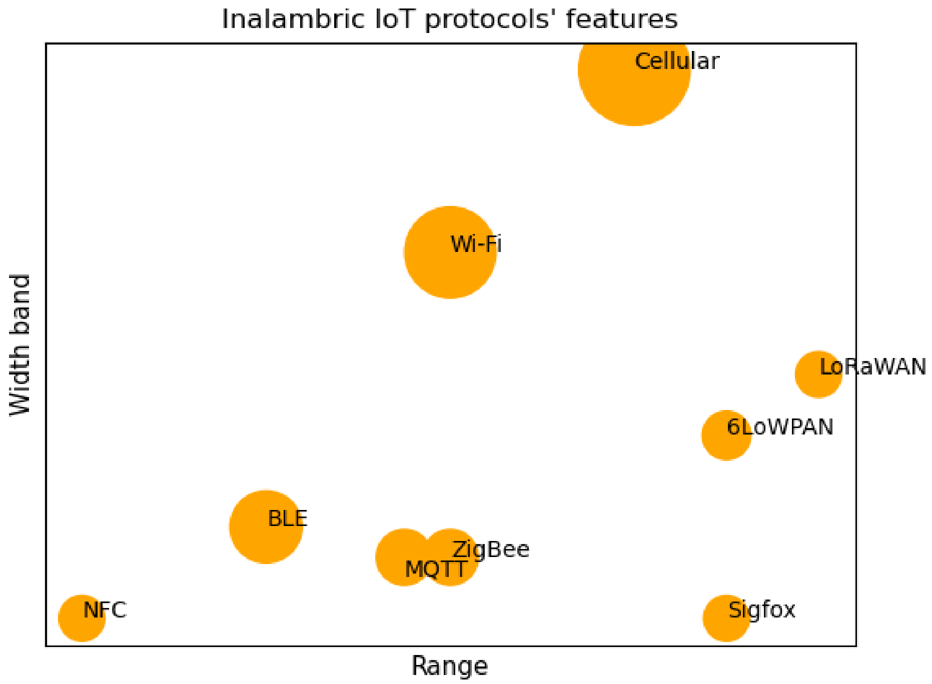

FIGURE 2.3: Inalambric IoT protocols' features.

Figure 2.3 illustrates some of the protocols mentioned before with the range and width band features represented by the graph's axis and the power consumption represented by the diameter of every protocol, as bigger the diameter as bigger is the power consumption.

2.2 Intelligent algorithms

One of the most important aspects of an IoT platform is how to use or interpret the data collected by the physical sensors. Hence, the correct selection of the algorithm or algorithms to extract the knowledge hidden in the raw data is a crucial step for the correct implementation of an IoT platform. These algorithms are the key to an IoT solution; they allow us to forecast the circumstances of the system in a near future, to detect anomalies, to identify objects or instances of the system and to automatize several circumstances of a system between other actions.

Therefore, it is important to define in this section the different kinds of intelligent algorithms that can be applied to an IoT environment. The section will be divided into three subsections. The first one presents to machine learning techniques. The second one addresses the principles of recommendation systems. And finally, the third discusses control systems.

2.2.1 Machine learning algorithms

Machine learning has been defined in many different ways, however, they all agree that it is a subfield of study in the computer science area. It gives computers the capacity to learn dynamically from data. This field of study tries to imitate the behavior of a brain that can learn and take action taking into account previous experiences. In machine learning techniques the brain is the algorithm and the previous actions are the previous data.

The most common example to illustrate machine learning algorithms is the email example. It consists of a spam filter that tries to identify spam emails using previous examples of classified emails. Hence, if the new email is similar to the spam emails, it will be classified as spam. If not, it will be classified as non-spam. With every iteration, the algorithm can increase their results and establish a better difference between spam and no-spam emails. The previously classified examples comfort the training set and the new email to classified is an instance. The performance of the machine learning algorithms can be evaluated by several performance measures [38, 58].

The use of machine learning algorithms in contrast to traditional techniques extracts the knowledge hidden between the raw data and offers solutions much shorter, easier to maintain, and probably with better results. The use of Machine Learning (ML) is extremely useful when the dataset has a lot of examples.

There are multiple ways to classify different ML algorithms. Nevertheless, the most common is to classify them by the kind of supervision they receive during the training process [87]. In this subsection four different types will be presented:

- **Supervised learning**: in this learning type the ML algorithms used label data to obtain their knowledge. Thus, the instances of the training data have an attribute that indicates is class or label. This attribute should be the result of the algorithm's output when a new instance is classified. Algorithms include in this type can perform classification and regression tasks.
- **Unsupervised learning**: in this case the data used for the training process is unlabeled. As a result, the algorithm output will not indicate a label or class. Alternatively, these kinds of ML algorithms offer different kinds of solutions like clustering, dimensionality reduction, and rule learning.
- **Semisupervised learning**: this type of learning uses a lot of unlabeled training data and a little bit of labeled data. They usually combine or use several algorithms of both previous types, supervised and unsupervised.
- **Reinforcement learning**: it is a completely different kind of learning. Here an agent can learn the best policy for a specific situation and environment. Every time the agent performs an action it receives a reward (positive or negative). Hence, the reward determines if the action is the correct one or not. As a result, the agent's policy is updated to get the most reward over time. This type of learning is having a lot of research interest nowadays by big computer sciences companies.

Notwithstanding, all these kinds of ML strategies deal withs some problems and limitations [68, 59, 53]. These limitations are common to every ML system and are extremely related to the quality of the datasets used to performance the model of the algorithms. These limitations are defined below:

- **Quantity of data**: ML models need a big amount of data to increase their results on a specific task. The number of training examples will be determined by the complexity of the problem to resolve, as bigger the complexity is as bigger the size of the data should be.

- **Nonrepresentative data**: to achieve a better solution the data that conforms to the training data should be representative of the future events that the system will deal with. Otherwise, the results with the unknow data will not represent the results obtained with the training data.

- **Poor-quality data**: sometimes the datasets includes a lot of errors, like missing values, extrem values, noise. These errors leads to a poor model definition since the algorithm is unable to find the hiddend patters in the data. An efficient but hard task to reduce these errors is to clean up the data.

- **Irrelevant features**: many datasets include irrelevant features that does not apport anything to the final decision. In fact, these features can reduce the effectiveness in computing the cost and quality of the results. So, a good solution for this limitation is to select the most useful features for the training process, applied dimensionality reduction or even creating new features with new data.

- **Overfit the model**: overfitting is a process in which a model stands out in the training process but it does not generalize the knowledge learned with unknow data. It means that the model is overtrained. At the same time, this problem is usually related to the quality and quantity of the dataset since the ML algorithm can infer knowledge from data that is not representative. A common solution for this problem is regularization, in which ML engineers can establish the values of the hyperparameters of the ML algorithms.

- **Underfit the model**: underfitting is the opposite of overfitting. It usually means that the model is to simple and provide general solutions without learning the knowledge hidden in the data.

Another important issue when a ML system is being developed is to configure correctly the different subsets of the dataset. Three different subsets can be defined: train, validation, and test. Instead of using all the instances in the dataset for the training process and testing the solution on a real or production environment, the best solution to avoid undesired errors is to divide the dataset into two main subsets, train, and test. The train set will be used for the training process and the test subset is used to test the provided solution with unknown data. If the results obtained during the test decreased significantly compared to the results of the training process, it means that the model may have suffered overfitting. As it was explained the hyperparameters have to be tunned; but, to avoid selecting the best hyperparameters for the test dataset, the train set is divided into train and validation sets usually using the cross-validation technique. The validation set allows to select the best hyperparameters for the ML algorithm. Once these hyperparameters are selected the solution can be tested with the test dataset. The whole process is illustrated in Figure 2.4.

Once presented a summary of ML, it is time to introduce the ML algorithms used in the articles used for this Ph.D. thesis. In the following subsections RIPPER, PART,

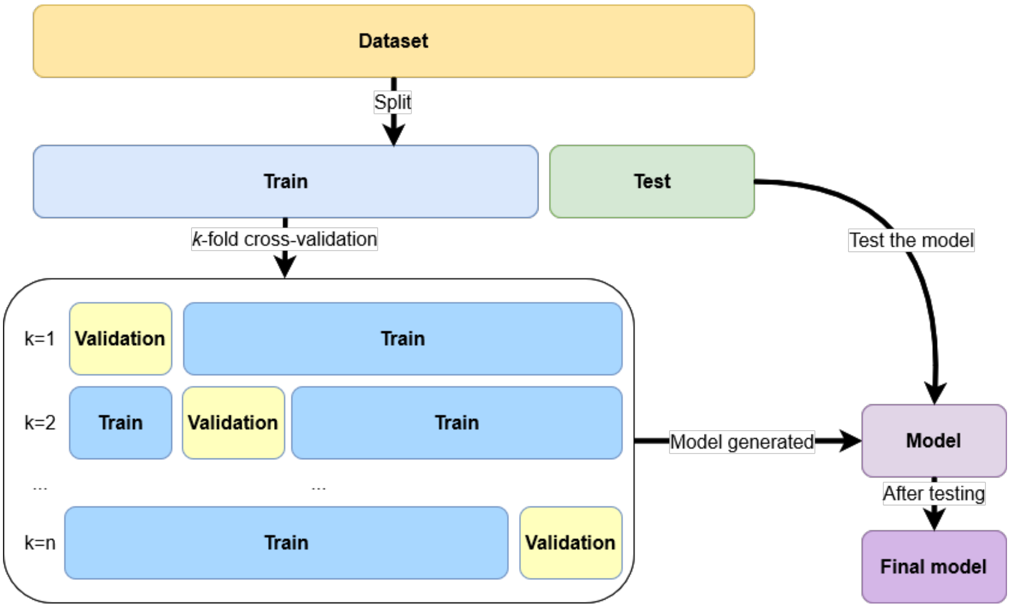

FIGURE 2.4: Dataset split process.

C4.5, RandomForest, RandomTree, k-NN, kStart, bayesian networks, and neural networks will be explained.

RIPPER

The Repeated Incremental Pruning Produce Error Reduction (RIPPER) is a rule-based ML algorithm proposed by Cohen [21]. It is an evolution of the IREP (Incremental Reduced Error Pruning) [35]. In brief, the IREP algorithm creates rules in a growing process adding new conditions until the acquired a 100% percent accuracy. The conditions added are the ones with the best information gain. Once the growing step is finished the pruning process starts. The prune follows an equation that in RIPPER algorithm it is replaced with Equation 2.1:

$$f_p(R_i, PrunePos, PruenNeg) = \frac{p-n}{p+n} \tag{2.1}$$

where R_i is the rule to prune, $PrunePos$ is the subset of positive instances used for the pruning process, $PruenNeg$ is the subset of negative instances used for the pruning process and p and n are the positive and negative instances represented by the rule R_i in the previous subsets.

In the IREP algorithm, the growing and pruning processes are repeated until the error rate is greater or equal to 50%, there are no more positive instances or the description length of the ruleset and examples is n bits larger than the smallest description length obtained so far. However, in the RIPPER algorithm, n is equal to 64. Additionally, once the ruleset is defined, the RIPPER algorithm generates two rules from every rule in the set; it applies to every one of them the growing and the pruning process to minimize the error in the ruleset and obtain the best rule.

PART

The PART algorithm was proposed by Frank and Witten [33] and it is a rule-based ML algorithm that combines C4.5 and RIPPER algorithms to define the rules. The PART algorithm is called with this term since it uses partial decision trees. From every one of the partial decision trees, a rule is extracted. The rule is obtained from the tree's leaf with more convergence; the rest of the tree is discarded. The rules are extracted following the rules below.

1. Several subsets are obtained using the C4.5 methodology.
2. From every subset, a partial decision tree is build using the entropy value (Equation 2.2).

$$H(X) = -\sum_i p(x_i) \log_2 p(x_i) \tag{2.2}$$

   where X is an event and $p(x_i)$ is the probability that event X belongs to one of the types defined in the subset.

3. At the moment that an intermediate node has a leaf in all its sons, the growing process is finished and the pruning process starts. The prune follows the same principles of the C4.5 algorithm. Once a node is not pruned the pruning process is stopped obtaining the final partial tree. From the partial tree, the rule is obtained.

C4.5

The C4.5 algorithm is a decision tree ML algorithm [70]. It is an evolution of the ID3 algorithm, which as well as the C4.5 was proposed by Quinlan [71]. The C4.5 algorithm builds the tree using two main concepts a gain function (Equation 2.3) and a gain rate function (Equation 2.4).

$$G(X,B) = H(X) - \sum_{i=0}^{n} \frac{|x_i|}{|X|} H(x_i) \tag{2.3}$$

$$P(X,B) = -\sum_{i=0}^{n} \frac{|x_i|}{|X|} \log\left(\frac{|x_i|}{|X|}\right) \tag{2.4}$$

where B represents a test to separate the nodes of the event X in $x_0, ..., x_n$, $|x_i|$ represents the number of elements in the node x_i and $|X|$ represents the number of elements in the event X.

Several tests are proposed in every branch construction and the best one is selected using Equation 2.5. Once the growing process is finished, the prune is done using the error rate of the tree and the subtrees. The prune decides when to replace a node by a subtree or a leaf or when to leave the node intact. The whole process is detailed in [52].

$$\frac{G(X,B)}{P(X,B)} \tag{2.5}$$

Random Forest

The Random Forest ML algorithm is a classification algorithm proposed by Breiman [12]. It is inspired by the Bagging algorithms [11] and the bootstrapping techniques. The Random Forest creates several random trees from random variables. The random forest algorithm improves the Bagging algorithm by reducing the variance; this reduction is achieved by reducing the correlation between the different trees in the forest. The process of creation and growth of the different trees in the forest is described below.

1. A subset, Z_i, is extracted from the train set, Z, using the bootstrapping technique.
2. For every subset, Z_i, a random tree, T_i, is created. The tree is created by repeating the following steps:
   (a) m random variables are selected form the total number of variables.
   (b) The best of the m variables is selected as the new node.
   (c) From this new node, two new son nodes are selected by repeating the previous two steps.

After the desired number of random trees is created, the Random Forest algorithm classifies new instances applying the majority vote policy from the results obtained from the random trees.

Random Tree

The Random Tree is an algorithm derived from the Random Forest algorithm. As well as the Random Forest it a ML classification algorithm and blend the concept of Bagging and bootstrapping. The construction of a Random Tree was explained in the steps (a), (b), and (c) in section 2.2.1. After the tree is obtained the classification task is trivial, it just has to follow the correct path in the obtained Random Tree.

REPTree

The REPTree (Reduced-Error Pruning) algorithm is a ML learning algorithm that classifies instances by creating a "fast" tree. To obtain the "fast" tree the algorithm used the numeric variables in the first levels of the tree. The tree is obtained as follows.

1. A test using the instances in the training set is done. The node will be selected using the gain function (Equation 2.3).
2. After the test is performed the selected node is divided into different subsets. These two sets are repeating for every new subset.
3. Once the creating and growing process is finished, the prune is performed using the backfitting algorithm. This algorithm allows to reduce the error during the pruning process.

k-Nearest Neighbors

The *k*-Nearest Neighbors algorithm is a ML algorithm that bases its knowledge in the informatión provided by the instances in the dataset. It is an instance-based learner proposed in [2]. The algorithm is known by its abbreviation, *k*-NN. the algorithm uses the instances in the dataset as vectors placed in a *n*-dimensional space, where *n* is the number of attributes or variables of an instance. Every instance has an associated class; hence, the *k*-NN is a supervised learning algorithm.

The algorithm can be explained in two simple steps:

1. The algorithm bases its knowledge to compare how similar the instances are between them. Therefore, the first step of the *k*-NN is to calculate the distance between the new instance to classify, a, and the rest of the instances of the dataset, Z. Equation 2.6 represents the generic form to calculate distances between instances.

$$d(a,z) = d(z,a) = \left(\sum_{i=1}^{n} |a_i - z_i|^p \right)^{\frac{1}{p}} \tag{2.6}$$

   where a_i and z_i are the vector's values of the instances a and z (where z belongs to Z) respectively; p is a parameter greater than 1 and it determinates the type of distance. If $p = 1$, it is the Manhattan distance; if $p = 2$, it is the euclidean distance; if $p \geq 3$, it is the Minkowski distance of p's grade.

2. After all the distances between a and Z's instances are calculated, the algorithm classifies a taking into account the class of the k closest instance to a. The class selected for a is usually the most common one between those k instances.

*k*Star

The *k*Start algorithm is also an instance-based learner used to resolve supervised learning problems. It was proposed by Cleary and Trigg [20]. As well as the *k*-NN, it uses a measure to compare instances between them; it uses entropy, which allows to measure the complexity to transform one instance into another one. The entire process is described below:

1. To classify an instance, a, every possible transformation from that instance to the rest of the dataset, Z, has to be calculated. The set of the transformation is defined as P.

2. Calculate the distance between a and the rest of instances in Z (Equation 2.7).

$$K^*(z|a) = -\log_2 P^*(z|a) \tag{2.7}$$

$$P^*(z|a) = \sum_{t \in P : t(a) = z} p(t) \tag{2.8}$$

   where $P^*(z|a)$ is the sum of probabilities, t, that transform the instance a in z.

3. Finally, the class of a is determined by the highest probability that it is of one of the classes, c_i, of the dataset. These probabilities are calculated with Equation 2.9.

$$P^*(c_i|a) = \sum_{x \in c_i} P^*(z|a) \tag{2.9}$$

Bayesian networks

A Bayesian network is a ML classification algorithm that tries to predict the class of an unknown instance using probabilities [9]. A Bayesian network is a directed acyclic graph in which the nodes are the different variables or attributes, U, of a dataset and a set of probabilities defined by Equation 2.10.

$$P(u|pa(u))|u \in U \tag{2.10}$$

where $pa(u)$ is the set of parents of u in the grap.

Hence, the Bayesian network classifier calcules the class y of an unknown instance x with $argmax_y P(y|x)$ where $P(y|x)$ is defined by Equation 2.11.

$$P(y|x) = \frac{P(u)}{P(x)} \propto P(U) = \prod_{u \in U} P(u|pa(u)) \tag{2.11}$$

It is important to mention that this algorithm does not support datasets with continuous variables and/or missing values. So, to use this algorithm with these kinds of datasets some preprocessing has to be done.

Neural network

Since the first appearance of the perceptron in 1958 by Rosenblatt [75] neural networks have suffered a great evolution and several types of them exist nowadays: multilayer perceptron, Convolutional Neural Networks (CNN) [56], Recurrent Neural Networks (RNN) [77], Radial Basis Function networks (RBF) [13]. Several of these types have demonstrated to have a great interest in scientific research in the last years [39, 82, 17, 18]. However, this section will be focused on the multilayer perceptron, since it is one of the several ML algorithms used in this Ph.D. thesis.

The multilayer perceptron is formed by an input layer, an output layer, and one or more hidden layers. In these layers, there are neurons (perceptrons) that are connected forwards between them from layer to layer. The activation functions activated the neurons when they received the information from the previous layer. Furthermore, the activation functions also take into account the *bias* that is applied to every layer.

These *bias* as well as the weights of the network are modified by the training algorithm used by the network, the backpropagation algorithm [76]. This algorithm tries to adjust the output of the network to the desired output by modifying the weights and *bias* of the network. The backpropagation algorithm is a basic algorithm for almost every neural network. The whole algorithm's process is described in detail in [76].

2.2.2 Recommendation system algorithms

In many technological infrastructures, users produce or navigate over big amounts of data. These big amounts of data impede users to normally obtain or see the most relevant information or data for them. Due to this situation users usually get frustrated about a specific technology or platform. Notwithstanding, recommendation systems can allow users to obtain more relevant information/data for them.

Recommender systems can be defined as a decicissión making algorithm for users in platforms or infrastructures with enormous information. Recommender systems can advise users especially at the beginning of their experience with the new platform. At present, three main types of recommendation can be defined: Collaborative Filtering (CF), Content-Based filtering (CB), and Hybrid Filtering (HF). In some of these types, some subtypes can be defined as well. The different types of recommendation systems are explained in the next subsections.

Nevertheless, before explaining the different types of recommendation systems it is important to discuss some problems that these kinds of systems usually have. Hence, these problems are explained below:

- **Cold start problem**: it is very common that when a new user or product appears in the system, the recommendation system does not have any information or data about them. Some systems ask for general information when a user signs up in a platform or use the description and/or attributes of the product to recommend actions to the users.
- **Data sparsity**: users tend to not rate products in the platforms hence, the user-item rating matrix tends to be very sparse. This reduces the effectiveness of the recommendation system. A good solution is to apply a dimensionality reduction over this matrix.
- **Grey-sheep problem**: many users usually rate items with extreme values in a given interval. These kinds of users may not be very representative to the recommendation task. So the correct recommendation technique has to be applied to deal with these kinds of users.
- **Synonymy**: many platforms have similar objects that differ in small features or that are the same ones but produced by a different company. To deal with these products and do not recommend the same or similar products it is important to select the right recommendation algorithm.
- **Shilling attacks**: sometimes users rate their products with hight marks and rate other users' products with low rates to stand out over the rest of users. Furthermore, many companies pay other users or build bots to rate their products. To resolve this problem is important to analyze the behavior of the platforms' users.

Once the recommendation systems' problems are mentioned it is time to explain the already mentioned types of recommendation systems.

Collaborative filtering

CF technique uses a user-item matrix to obtain the recommendations. This matrix store the preferences of a user for all or some of the items on the platform. CF uses the matrix to relate similar users with similar preferences by calculating the similarity between them. Such users build a community named neighborhood. A user gets recommendations from items positively rated by other users of her/him neighborhood. The user can even receive users' recommendations from his/her neighborhood or the closest neighborhoods, if the platform allows it. CF can be divided into two categories [46]: memory-based and model-based.

Memory-based CF This category is based on the information stored in the user-item matrix to get the recommendations. The recommendation can be obtained following two different approaches, user-based and item-based. The user-based technique calculates the similarity between users by comparing the ratings on the same item. Then it computes the predicted rating for a specific unrated item by the active user as a weighted average of the ratings that the similar users give to that specific item. On the other hand, the item-based technique gets predictions by calculating the similarity between items. It uses all the rated item by the active user and calculates the most similar to a specific item. Therefore, the prediction is made by taking a weighted average of the calculated similar items. Similarity can be calculated from different ways, however, the two most popular measures are correlation and cosine.

Model-based CF This technique use ML algorithms and data mining techniques to build a model that can generate recommendations. All these models and techniques analyze the user-item matrix to identify the relations hidden in the data. Some of the algorithms used for this type of CF are association rules, clustering, decision tree, regression, neural networks, and Bayesian classifiers between others. The model-based CF resolves the sparsity problem usually associated with many recommendation systems.

Content-based filtering

CB filtering uses the information of the item to generate new recommendations to a user. It uses the items positively evaluated by the user to get the recommendations. This technique finds the most similar items by using techniques like Term Frequency Inverse Document Frequency (TF/IDF) or ML algorithms like decision trees, Bayesian classifiers, or neural networks [46]. This technique can adjust itself to the changes that the user made in her/his profile or interests.

Hybrid filtering

The HF techniques make use of both previous techniques to obtain a better recommendation system with more accurate and effective recommendations for the user. The idea of this type of filtering is that a combination of algorithms will increase the satisfaction of users with the provided recommendations. Also, both models can suppress the debilities of the other obtaining a stronger model. The hybridization of the models can be done in any of the following ways: separate implementation of the models and a combination of the results, using a CB filtering in a CF approach or vice versa, creating a model that uses both filtering techniques [46].

Other approaches

Some authors believe that in the specific case of an IoT platform other types of recommendations system have to be considered. This subsection will describe briefly two types proposed by Felfernig et al. [31].

Knowledge-based approach This approach is not based on ratings or features. It is a completely different approach in which users have a list of requirements. Consequently, the items or actions that want to be recommended have to past those requirements. To establish this type of recommendation the system has to have information about the user.

Utility-based approach The recommendations are based on how much useful are them taking into account the utility established by the user. The recommendations with a higher utility raking are proposed to the user.

2.2.3 Control systems

In some cases, algorithms do not need to have previous data or information about the system or users; they just need to know the current state of the system to take the most appropriate action. Control systems work this way and they have demonstrated to be the perfect solution for many IoT implementations.

A control system regulates the behavior of other more complex systems or devices using control loops. Control systems have been used for decades, especially in the industry sector to control processes or machines. The idea behind a control system is simple it uses the feedback that the control system provides to compare the output of the control with the desired value and apply the difference as a control signal to equalize the output with the desired value.

However, there are several types of control systems and not all of them use the feedback. This is the case of the open-loop control, which do not use the feedback and only apply a setpoint to a system for a specific time. The rest of the systems that use the feedback to change the signal produced by the control systems can be defined as closed-loop control. There are different types of closed-loop control.

Logic control

Logic control is still used in many industries in microcontrollers and/or Programmable Logic Controllers (PLCs) [42]. In the past, it was implemented using relays and cam timers. Logic controllers respond to states' changes in sensors and switches and perform the correct output for the system.

On-off control

On-off control uses feedback to change between two opposite states like on and off. The feedback is used to switch abruptly between the states. It compares the output with the desired value and depending on the difference between these two values it decides to maintain the output or change it [32].

Linear control

Linear controls use negative feedback to maintain the measured value at the desired value. The characteristics of this type of control are described for several types of linear controls.

Proportional control This type of control applies a correction to the measured value that is proportional to the difference between the setpoint and the measured value [37]. Proportional controllers modulate the manipulated variable to avoid instability provides by abrupt changes. However, this type of control always has a residual error that prevents the system to get the desired value.

Proportional-integred control To avoid proportional control's residual error, the PI (Proportional-Integral) control was proposed. It uses a proportional term and an integral term to eliminate the residual error by integrating the error over time [86].

Poportional-integred-derivative control PID (PI-Derivative) controllers introduce a derivative term to improve the PI controllers and eliminate the oscillations produced by this type of controllers. PID's controls produce a more stable output [5].

Fuzzy control

Fuzzy control is based on the fuzzy set theory proposed by Zadeh [90]. In this famous theory Zadeh established that an element x can belong to a set A with a value between 0 or 1; unlike in other proposes in where x can only belong to a set A with a value of 0 (it does not belong to A) or 1 (it belongs to A). A common example of fuzzy logic is the age example: a woman is 26 years old; for some people, she is still young but for others, she is an adult. This example shows that the woman does not belong to the "young" set with a value of 1 and neither do the "adult" set.

Those sets are defined as fuzzy sets. The fuzzy sets have elements inside of them; an element belongs to a fuzzy set if the membership function for that element has a positive value. An element may belong to several elements at the same time. Hence, a fuzzy set, A, can be defined as explained in Equation 2.12.

$$A = (x, \mu_A(x)) : x \in X \tag{2.12}$$

where x is an element of a set X and μ_A is the degree of membership for the fuzzy set A and has a value of [0, 1].

As can be seen, the concepts of fuzzy set and membership functions are closely related since the definition of the membership functions defined the fuzzy sets. The membership functions are conformed by fuzzy numbers. Depending on the type of fuzzy number different membership functions can be defined.

The triangular fuzzy number is the first type. A triangular fuzzy, A, is defined by three points as showed in Equation 2.13. With a triangular fuzzy number, its corresponding membership function is defined by Equation 2.14.

$$A = (a_1, a_2, a_3) \tag{2.13}$$

$$\mu_A(x) = \begin{cases} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ \frac{a_3-x}{a_3-a_2}, & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases} \tag{2.14}$$

Additionally, the trapezoidal fuzzy number can be used to define a trapezoidal fuzzy function. A trapezoidal fuzzy number, A, is defined in 2.15. The membership function of that fuzzy number is obtained using Equation 2.16.

$$A = (a_1, a_2, a_3, a_4) \tag{2.15}$$

$$\mu_A(x) = \begin{cases} 0, & x < a_1 \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leq x \leq a_2 \\ 1, & a_2 \leq x \leq a_3 \\ \frac{a_4-x}{a_4-a_3}, & a_3 \leq x \leq a_4 \\ 0, & x > a_4 \end{cases} \tag{2.16}$$

Finally, there is another type of fuzzy number, the bell shape fuzzy number. Its function is defined as follows in Equation 2.17.

$$\mu_f(x) = e^{\frac{-(x-m_f)^2}{2\delta_f^2}} \tag{2.17}$$

where m_f is the mean of the function and δ_f is the standard deviation.

In fuzzy logic, two main concepts have great importance in the process. Those concepts are fuzzification and defuzzification and they are explained below.

On the one hand, fuzzification is the process that transforms the value of a specific variable to a fuzzy value using the membership functions defined for that variable. The definition of the membership functions is not trivial, indeed, there are several methods to infer the membership functions [41]. These methods are listed here.

- **Intuition**: it is based on the human's knowledge of the problem. Usually, an expert uses its understanding and intelligence on the problem to define the membership functions.
- **Inference**: it is based on the knowledge that can be extracted from the set. Therefore, the membership functions are formed using deductive reasoning.
- **Rank order**: this method is normally used for pairwise comparisons and from this, the order of the variables defines the membership functions.
- **Angular fuzzy set**: it is used for linguistic variables and it uses angles to define the membership functions. The membership functions can be obtained with, $\mu_t(\theta) = \cos\theta \tan\theta$, where θ in the angle defined on the unit circle and t is the horizontal projection of the radial vector.

- **Neural networks**: it used a NN to obtain different groups for a set. These groups form several membership functions for a specific variable.
- **Genetic algorithms**: it works similarly to the NN method. In this case, it uses a genetic algorithm to conform to the best membership functions for the problem.
- **Inductive reasoning**: this method tries to generate membership functions by minimizing the entropy in the membership functions. This method is used in a big amount of static data.

On the other hand, defuzzification turns a fuzzy variable to a non-fuzzy variable. This process is used when the output of the fuzzy system is obtained. The different methods used to defuzzification the output of the system are explained briefly below [41].

- **Max-membership principle**: it uses the value with the highest membership value.
- **Centroid method**: it is the common method and it uses the centroid of the membership function.
- **Weighted average method**: it is only used with symmetric membership functions. In this method, every membership function is weighted using the value with the highest membership value.
- **Mean-max membership**: this method is similar to the max-membership principle but in this case, the extremes of the range of values or the values that share the maximum membership value are used for the defuzzification process.
- **Centre of sums**: it uses the weighted area of the sum (intersection) of the membership functions to determine the output.
- **Centre of the largest area**: if a membership function has two or more convex zones the weighted area of the largest one is used to calculate the output.

The concepts of fuzzification and defuzzification are used in many fuzzy control systems. There are different types of fuzzy systems, like neural fuzzy systems [14, 69], piecewise multiaffine systems [64, 29], Mamdani fuzzy systems, and Takagi-Sugeno fuzzy systems. Nonetheless, the last two types are the most common and used ones. Hence, in this section, we will focus on the explanation of the Mamdani and Takagi-Sugeno controllers.

These two fuzzy controllers are quite similar between them. Both of them use fuzzy sets an determine the output using rules and fuzzification process [63]. However, Mamdani uses the defuzzification process while Takagi-Sugeno applies a predefined function with the fuzzy values to obtain the output. The rules of the Mamdani system follow the definition expressed in Equation 2.18. On the other hand, Takagi-Sugeno systems' rules can be defined as shown in Equation 2.19.

$$R_i: \text{ If } x_1 \text{ is } A_{i1} \dots \text{ and } x_n \text{ is } A_{in} \text{ then } u \text{ is } B_i, \qquad i = 1, 2, \dots, K \tag{2.18}$$

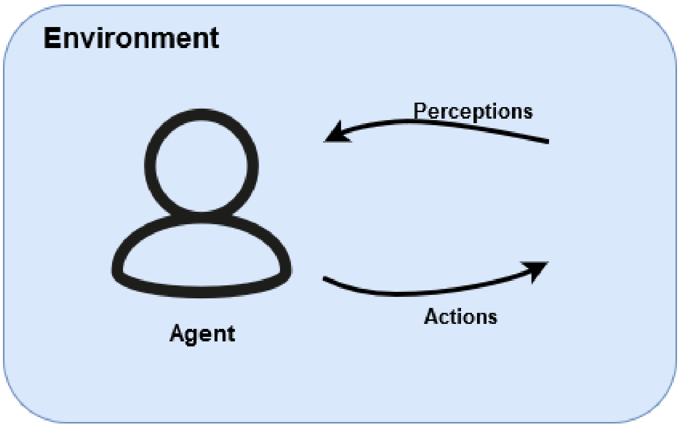

FIGURE 2.5: Agent's actions and perceptions in an environment.

where x denotes a fuzzy variable, A_i denotes a fuzzy set of that variable, u is the output fuzzy variable and B_i denotes a fuzzy set of the output variable.

$$R_i: \text{ If } x_1 \text{ is } A_{i1} \ldots \text{ and } x_n \text{ is } A_{in} \text{ then } u = f(x_1, \ldots, x_n), \qquad i = 1, 2, \ldots, K \quad (2.19)$$

where $f(x_1, \ldots, x_n)$ is a function that determinates the output. Different rules can have different functions.

2.3 Multi-agent systems

An agent can be defined as a physical or software entity that can interact with its environment and that has its behavior. Figure 2.5 shows the interactions between an agent and its environment. Agents have been present for decades in society since a robot that can interact with the environment or a crawler that can collect data from the Internet. In this sense, it is normal to assume that agent theory has been applied to IoT environments in the past. It has been applied [4, 73, 88, 15]. It seems natural to apply the agent theory to the IoT ecosystem since it usually has a great number of sensors and/or actuators that can be intelligent controlled thanks to the advances of the AI field. In consequence, in this section, the agent and multi-agent systems will be analyzed.

An agent can be defined in many different ways but every definition shares the same idea that is represented by the features of an agent [28].

- **Adaptability**: the agent can improve and learn with experience.
- **Autonomy**: the agent can respond to the events taking into account its knowledge and experience.
- **Collaborative behavior**: the agent can collaborate with other agents to achieve a common goal.
- **Rationality**: the agent tries to achieve its personal goals.
- **Proactive**: it can receive and attend requests.

- **Initiative**: it feels the events of the environment and response taking into account their goals or aims.
- **Mobility**: the agent can act in a different system of the same net.
- **Benevolence**: the agent does not have contradictory goals.
- **Presence**: it can be active for long periods.
- **Character**: the agent has personality, it can change its behavior or ask for instructions/permissions to other agents or entities.
- **Flexibility**: its actions can change in execution time.

Agents are usually classified taking into account their features and the information that they have. According to [28] the most extended classification describes four different types of agents. The first type is the most simple one, simple reflex agents. These agents just perform an action related to a perception of the environment. The second type is called internal state reflex agents. In this type, the agents also make use of other information (their internal state, the environment evolution, how previous actions affect the environment) to respond to the perceptions of the environment. The third type is the goal-based agents; these agents combine the information that they have about their goals and the possible actions to select the best action to achieve their goals. And finally, but not least, the utility-based agents. These agents related a utility value obtained with a function to every possible action; the best action is the one with the highest value since the utility is a measure that has to be maximized.

When several agents are presented in a system and they interact not only with the environment but also between them, they conform a Multi-Agent System (MAS). A MAS allows agents to develop social skills; they can establish communications, share information, and work together to solve their aims and the global aim of the system. Allow with this feature, MASs also have other features that make them a great solution for IoT environments; they are listed below [79].

- **Flexibility**: it allows the MAS to change agist agents' and environments' alterations.
- **Adaptability**: it makes it easy to change agents' behavior or actions.
- **Scalability**: it is the ability to add new agents to the system.
- **Leanness**: it establishes the difference between agents but without incrementing the number of agents' categories.
- **Resilience**: this feature guarantees that the system accomplishes its aim even if an agent fails or is corrupted.

MASs not only are used in IoT environments as mentioned before but also in deep learning and machine learning studies. Recently, researchers from OpenAI have used a MAS in which agents learned and collaborated between them to learn to play hide and seek [7]. A great example to learn how MASs work when mixed them with AI algorithms.

Chapter 3

List of journal articles

The current chapter shows the articles used for this thesis in the modality of a compendium of articles. It shows three articles published in three different scientific international journals indexed in the Journals Citation Reports (JCR), which means that the articles have an impact factor. The chapter is divided as follows. First, a subsection discusses the coherence and relationship between the three articles within the hypothesis and line of research of the Ph.D. thesis in Spanish[1]. Thereafter, the original articles are presented as well as a summary in Spanish[1].

3.1 Coherence and relationship between articles

En esta sección se describe la coherencia y relación que existe entre los artículos y en relación con la hipótesis de investigación plateada en la sección 1.1. Como ya se ha mencionado anteriormente se trata de un total de tres artículos de investigación científicos publicados en revistas internacionales con factor de impacto, es decir, indexadas en el JCR. Todas ellas siguen la línea de investigación de la hipótesis. A continuación, se enumeran las publicaciones acompañadas por un resumen muy breve:

- ***Dealing with Demand in Electric Grids with an Adaptive Consumption Management Platform***: presenta una arquitectura multiagente para viviendas inteligentes con el objetivo de gestionar la demanda de la energía eléctrica mediante un novedoso sistema de identificación de dispositivos electrónicos.
- ***Multi-Agent Recommendation System for Electrical Energy Optimization and Cost Saving in Smart Homes***: presenta una arquitectura multiagente capaz de obtener los patrones de uso de dispositivos electrónicos en una vivienda inteligente para ofrecer recomendaciones que distribuyan el consumo y ofrezcan un ahorro económico a los usuarios.
- ***Central Heating Cost Optimization for Smart-Homes with Fuzzy Logic and a Multi-Agent Architecture***: presenta una arquitectura multiagente capaz de obtener datos de sensores distribuidos en una vivienda y utilizar esos datos para determinar el estado del sistema de calefacción central de la vivienda mediante el uso de un sistema de control borroso que reduce el consumo energético y el impacto de este en el medio ambiente.

[1] According to the requirements of the Ph.D. school of the University of Salamanca when a Ph.D. thesis is presented in a compedium of article modality and the articles are not written in Spanish several Spanish summaries have to be included in the doctoral manuscript. See http://posgrado.usal.es/TESIS NUEVA 2012/Formato_Tesis_compendio.pdf (accessed date: April 21, 2020).

Durante las últimas décadas y promovido por el abaratamiento del material tecnológico los sensores y en general las redes de sensores se han vuelto más importantes y usadas incluso por usuarios no expertos. La irrupción de dispositivos de medición *plug and play* (enchufar, conectar y usar) ha supuesto el primer paso para muchos ciudadanos en su inicialización en el mundo tecnológico y sobre todo en el mundo de la domótica. Con esta tecnología los usuarios pueden saber exactamente lo que ocurre en su casa incluso cuando no están en ella. Los datos medidos y recolectados por estos sensores son de gran utilidad pues contienen todos información relevante que puede ser de gran utilidad para otros propósitos.

Sin embargo, en ocasiones es complicado conformar una red de sensores ya que existen diferentes protocolos de comunicación que dificultan las tareas. Este problema hace que en ocasiones no se pueda diseñar fácilmente un sistema que utilice la información de sensores de diferentes fabricantes. Además, el poder utilizar los datos de diferentes sensores ayuda en la construcción de más complejos sistemas que puedan extraer toda la información y conocimiento de estos para poder aplicarla con un propósito concreto.

De esta forma y teniendo en cuenta la hipótesis de investigación planteada, se hace necesario el investigar en una arquitectura para la obtención de datos de sensores y que a su vez permita extraer el conocimiento de estos para poder extraer el conocimiento necesario que permita mejorar la vida de los usuarios y contribuir a la lucha contra el cambio climático. En el caso de esta tesis doctoral la arquitectura está basada en un sistema de agentes o sistema multiagente que es capaz de obtener los datos medidos por los sensores y/o incluso actuar sobre ellos, analizar esos datos mediante diversos algoritmos de aprendizaje automático o inteligencia artificial para extraer conocimiento que es brindado al usuario para que tome acciones o automatizar estas acciones.

Consecuentemente, los trabajos presentados presentan una solución para este problema y siguen la hipótesis de investigación. Todos ellos presentan una arquitectura multiagente similar y que realiza más o menos las mismas acciones. La arquitectura se encuentra dividida en diversos módulos que permiten agrupar a agentes de funciones similares a del mismo tipo. En todos los trabajos existe un agente de control encargado de gestionar el sistema multiagente y de inicializar el resto de los agentes. Del mismo modo, el módulo de dispositivos está presente en todos los trabajos permitiendo establecer conexiones con los dispositivos y/o sensores en ambos sentidos (recolección de datos y actuación). Del mismo modo, en todos ellos existe un módulo que, aunque recibe distintos nombres tiene una misma funcionalidad, la extracción de conocimiento de los datos a través de diversas técnicas de inteligencia artificial. Además, en uno de los estudios se propone un nuevo módulo que se encargará de recoger información de internet mediante el uso de arañas web, este módulo servirá para evitar usar sensores para obtener información que ya está disponible en la web o para obtener datos no medibles a través de ningún sensor.

Con esta información queda claro que las arquitecturas mostradas en los tres artículos muestran semejanzas entre ellas y por lo tanto existe coherencia entre las propuestas. Además, esta coherencia se ve reforzada por los casos de estudio planteados en los artículos. En dos de ellos se pretende ofrecer un sistema capaz de gestionar la demanda de electricidad en las viviendas, uno de ellos mediante acción directa sobre los dispositivos electrónicos conectados y el otro mediante un sistema de recomendaciones e incentivos para que sea el/los usuario/s del sistema los que realicen la acción si así lo desean. Con estos casos de estudio se pretende principalmente distribuir el consumo de energía eléctrica y por lo tanto disminuir la producción de ésta en ciertos momentos del día lo que conlleva a una menor emisión de gases contaminantes. El tercer artículo presenta un caso de estudio distinto pero relacionado con el consumo energético y la reducción de gases contaminantes. En este sentido, el artículo trata de optimizar el uso de un sistema de calefacción central mediante un sistema de control borroso y los datos recogidos por una red de sensores; con este control inteligente se reduce el consumo del combustible de la calefacción haciendo que por la tanto haya menor combustión y reduciendo la demanda de combustibles fósiles.

En resumen, esta tesis doctoral presentada en la modalidad de compendio de artículos reúne a tres artículos científicos en los que se muestra el diseño de una arquitectura multiagente aplicada a tres casos de estudio bien diferenciados que ponen de manifiesto las características del sistema propuesto. Como se verá en las siguientes secciones los artículos tiene coherencia y relación entre si así junto la hipótesis planteada.

3.2 Dealing with Demand in Electric Grids with an Adaptive Consumption Management Platform

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Research Article

Dealing with Demand in Electric Grids with an Adaptive Consumption Management Platform

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The control of consumption in homes and workplaces is an increasingly important aspect if we consider the growing popularity of smart cities, the increasing use of renewable energies, and the policies of the European Union on using energy in an efficient and clean way. These factors make it necessary to have a system that is capable of predicting what devices are connected to an electrical network. For demand management, the system must also be able to control the power supply to these devices. To this end, we propose the use of a multiagent system that includes agents with advanced reasoning and learning capacities. More specifically, the agents incorporate a case-based reasoning system and machine learning techniques. Besides, the multiagent system includes agents that are specialized in the management of the data acquired and the electrical devices. The aim is to adjust the consumption of electricity in networks to the electrical demand, and this will be done by acting automatically on the detected devices. The proposed system provides promising results; it is capable of predicting what devices are connected to the power grid at a high success rate. The accuracy of the system makes it possible to act according to the device preferences established in the system. This allows for adjusting the consumption to the current demand situation, without the risk of important home appliances being switched off.

1. Introduction

As De Baets et al. [1] report in their paper, European Union member countries made an agreement in October of 2014 in which they set a number of goals for 2030. These goals are related to reducing pollution and obtaining cleaner and more efficient energy. This means that the use of renewable energies should increase in the next years. However, such changes also imply certain challenges; one of them is the adjustment of electrical production to demand. That is why consumption management plays a very crucial role in electric networks and it is becoming an important facet in Smart Grids. The sources of production are very diverse and they are distributed geographically, so it is more complicated to keep an electric network in stable conditions. For these reasons, it is necessary to create a system that will allow for managing consumption automatically, adjusting the generated energy to the requirements of each moment, since the management of short-term production is not feasible. The need for an automatic consumption management system has been reflected in the variety of devices that have been proposed in recent years for the analysis of consumption in electrical networks. We live in an information age where data is highly valuable because of the knowledge that can be extracted from it. For example, a system can obtain the consumption data of a house and analyze it in order to detect behaviour patterns and identify the devices that are connected to that house's electric network. To be able to manage the data of a measurement device a multiagent system has to be implemented.

Up until now several studies addressing this topic have been published. They all focus on identifying the devices connected to an electric network by employing a range of techniques based on NonIntrusive Load Monitoring (NILM); the majority of them are improved versions of standard algorithms. While NILM techniques are used in other works, we use a variety of measuring devices in our proposal in order to extract the consumption data from each line connected to an electric network, and this simplifies the identification of electrical appliances and optimizes the system's performance.

For this reason, we propose a distributed system which will be able to connect with the different measurement systems and obtain the consumption data read by them. By analyzing and extracting important characteristics from the data provided by these measurement systems, the system will be capable of identifying the devices or appliances connected to the electric network. Simultaneously, the system will be able to act on each of the lines connected to the measuring devices.

Furthermore, the proposed system makes use of multiagent technology which provides the distributed architecture with agents who carry out different and specific tasks in the final system. The multiagent system allows creating autonomous entities that work in a coordinated way, providing features such as mobility, dynamic behaviour (the system is capable of creating agents dynamically; this feature makes it possible to modify the goals and behaviour of the system), federation of services, and high-level communication through the transparent management of message queues. This architecture makes it possible to perform different tasks in a coordinated way, improving the system's learning and adaptation capacities. There are numerous agents with different roles; one of the agents, for example, is in charge of communicating with the measuring devices and the acquirement of measurement data. There is also an agent that extracts the home appliances' activation periods from the data obtained by a different agent and another that extracts the main characteristics of activation periods. In addition, one of the agents identifies the home appliances that are connected to the gird. Finally, we have an agent who is responsible for acting on the different lines connected to the measuring systems. These agents act on smart-meter lines or smart plugs in order to interrupt the power supply to these devices; in this way demand can be managed.

The system will identify home appliances by using different supervised machine learning algorithms. To verify the proposal, the system will use several algorithms based on decision rules, decision trees, neural networks, and algorithms based on the Bayes theorem and case-based learning. These methods are tested with a dataset that has been created for the purposes of this study. In order to create the dataset, the principles of the fingerprint algorithm were followed. Fingerprint methods make use of the distances between the maximus of a sound since at these points the sound is purer. When creating the dataset, the maximus of activation periods have been used to extract some of their characteristics and to identify the different algorithms. This allows us to obtain knowledge about the behaviour of the devices. This knowledge is stored on a database in order to subsequently apply advanced reasoning and learning techniques to it.

The article is divided into the following sections. In the background section, we describe some of the studies related to this line of research. The proposed system is outlined in the architecture section. The case study section focuses on particular situations that have been considered during the research. In the results section, the system's performance will be described and analyzed. The last section draws conclusions on the different technological solutions that we had considered for our system; furthermore we discuss future lines of work related to the proposed study.

2. Background

This section is focused on literature that is related to the aims of the present research. All the related works make use of techniques based on NonIntrusive Load Monitoring, described by Hart [12] and by Zoha et al. [13]. Below, the most noteworthy works have been described.

In the year 2014, Belley et al. [2] had already used a smart meter to obtain a house's consumption data. The authors made use of the activation periods of appliances that were in the house. In this study, the authors used the equality between the cases stored in the database and the appliances they analyzed. This methodology entails a high computational cost due to the process of comparing an element with each of the instances stored in the database. In [3] the same authors proposed an improved version of their system using the same algorithm for the identification of devices; however, in the new proposal the system was capable of identifying erratic behaviours related to possible cognitive problems experienced by the users.

Other authors like Lin et al. [4] proposed a new strategy for NILM systems. They suggested that devices should be identified using quadratic programming rules. The results of this research proved that this methodology is effective. The work of De Baets et al. [1] proposed two new algorithms applied to NILM techniques for the identification of devices in electronic networks. The two new methods were as follows: a modified version of the chi-squared goodness-of-fit test and an event detection method based on cepstrum smoothing. Besides, the authors explained that both methods can be optimized using surrogate-based optimization.

Other lines of research focus on improving NILM techniques. The researchers Tang et al. [5] suggested that the state of the building must be taken into account; it can be either occupied or unoccupied. Thus, a system that is capable of considering these two situations will not operate when there are no people in the building. On the contrary, when the building is occupied the system will decide to identify the connected devices in the household. This methodology allows for improving the accuracy of classifiers and reducing computational costs at times when the building is not occupied.

The study conducted by Brown et al. [6] also considers the state of the building. In this work, ultrawideband radar technology was used to determine whether a building is occupied or not. This was done by comparing its results with the data that the system receives from the power monitoring system. Apart from establishing the state of the building, this technique also detects the devices connected to the grid. In addition, this methodology examines the users' behaviour.

The research conducted by Liang et al. in [7] is focused on the construction of a new platform that would provide a better understanding of electrical consumption patterns and that would successfully identify the devices connected to the electrical network. For this purpose, the different activation periods of the devices were analyzed and a number of mathematical programming and pattern recognition techniques were applied to unbundle the load.

A similar task is tackled in the study presented by Lee et al. [8]. In this case, the article leverages already existing methods for measuring and representing the characteristics of electricity consumption. Moreover, the article considers signal processing as a method of identifying the devices connected to the network by means of disaggregation and filtering techniques.

There are also researches that focus on slightly different aspects, such as electrical demand forecasts for a few days ahead. Examples of works that address this issue are Chen et al. [9] and Chen and Tan [10]. In the first work, daily demand is predicted for each hour using a hybrid clustering algorithm. The second one fulfils the same function but it uses a hybrid algorithm based on support vector regression. Both techniques render great results.

Finally, it is important to list an open source tool that implements several NILM techniques. This tool is called NILMTK (NonIntrusive Load Monitoring ToolKit). It has been developed by Batra et al. [11]. This tool is designed to employ several techniques and shows the results rendered by each of them. It also includes public datasets.

The studies presented above make use of NILM techniques or use a new method to identify the devices connected to an electric network. However, none of them consider the use of smart devices which will be present in our future homes and buildings, and these can measure the consumption of home appliances. In our article, we also propose a new method for the identification of electronic appliances connected to the grid. This new technique makes use of a combination of characteristics of the fingerprint algorithm and NILM techniques. Hence, this proposal sets forth a new methodology for the analysis of data that allows for identifying the devices connected to electric networks. In conclusion, this section summarizes the novel aspects of the work and the main contributions of the work: (a) a management platform that allows for adapting consumption in a network. (b) The identification of household appliances using NILM techniques and their integration with fingerprint algorithm principles. (c) The use of smart meters and relevant communication protocols for obtaining consumption data and switch household appliances on/off in order to adapt consumption. In order to clearly show the features of this proposal, we include a comparison between the proposal and the state of the art (Table 1).

3. Proposed Architecture

The adaptive consumption management system for satisfying demand in electrical networks has to work with different measuring devices in order to read information from them and act accordingly. Information is extracted for the purpose of processing and extracting the knowledge contained in it. The system needs this knowledge in order to identify the household appliances connected to the electric network.

The system works according to the principles of NILM techniques. The NonIntrusive Load Monitoring or NILM systems use a technique that disintegrates the data extracted from meters. Meters are located outside of homes; this is where the name nonintrusive comes form. So, according to a definition proposed by Hart [12], the consumption of a network is composed of the consumption of all the devices connected to it; therefore the goal is to identify as many devices as possible.

In mathematical terms, we could say that, in an instant of time t, the energy is consumed by all the devices n_i, connected to an electric network N in the instant t, as formulated by Zoha et al. [13]:

$$N(t) = n_1(t) + n_2(t) + \cdots + n_n(t). \quad (1)$$

The appliances that are connected to a network are identified by their activation period. Usually, every device has a singular activation period that makes it distinguishable from the rest. So, it can be said that these activation periods are like a signature or a fingerprint; a similar idea is proposed in the work of Haitsma and Kalker [14].

However, we should stress that not all devices behave in the same way; as explained by Kaustav in [15] this makes their identification and distinction easier. Some groups of appliances have a more continuous performance in time than others. Other devices can only have two possible states—on or off. Some appliances, such as a microwave, have a more variable behaviour; this is related to their program or the role they are performing. However, there are also many appliances that have almost infinite behavioural patterns; this depends on the role they perform and on a specific moment in time, such as an LED printer.

Commonly, systems based on NILM techniques can be divided into three successive stages, consisting of three modules: a data acquisition module, a feature extraction module, and finally a learning module. The NILM process is illustrated in Figure 1.

(i) *Data Acquisition.* In this stage, the system obtains the data that allow identifying the different behaviours in an electric network; a meter system is used for this purpose.

(ii) *Feature Extraction.* In this module, the system extracts the connected devices and differentiates between active and inactive devices. That is, it is capable of detecting and extracting the activation periods of household appliances. Diverse techniques are used to extract activation periods; one of them is event-based extraction. These so-called events are the on/off transactions of the different devices. On the contrary, extraction that is not based on events uses sample times to determine whether an appliance is active.

(iii) *System Learning.* This stage consists of training and learning. Learning can be supervised or unsupervised. The systems with supervised learning need a labelled dataset in order to learn and identify devices correctly. Moreover, these systems can also be identified as on-line or off-line systems.

Consequently, to achieve the aim of this work, the system is operated by the different agents. Agents carry out all the subprocesses in the global system. The agents that form part of the system can be divided into two large groups, as shown in Figure 2. These two groups are environmental agents and processing agents.

TABLE 1: Comparison between the proposal and previous work.

	Belley et al. [2]	Belley et al. [3]	Lin et al. [4]	De Baets et al. [1]	Tang et al. [5]	Brown et al. [6]	Liang et al. [7]	Lee et al. [8]	Chen et al. [9]	Chen and Tan [10]	Batra et al. [11]	Our proposal
Use NILM techniques								X			X	X
New method	X		X	X			X		X	X		X
Improve a method		X										
Consider the state of the building					X	X						
Consumption prediction									X	X		
Toolkit											X	
Uses smart devices												X
Adaptive consumption												X

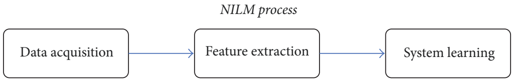

Figure 1: NILM process.

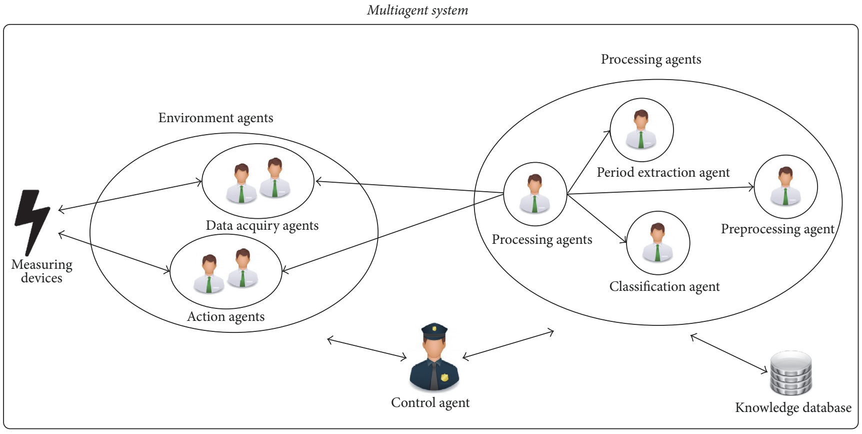

Figure 2: Proposed multiagent system architecture.

(i) *Environmental Agents*. These agents communicate with the measuring systems that are connected to the global system. Their task is to obtain data and work with the measuring system. The agents that acquire data have to communicate with the meters through the required protocols, in order to obtain them, whereas the agents acting on the meters are responsible for turning on/off the different lines of the measuring devices. By acting on the smart meter and the smart plug it is possible to manage demand according to requirements. For efficient demand management, it is necessary to identify the connected devices beforehand. This identification is done in the processing agents organization. In order to determine the order of priority in which these devices have to be switched off, the agent has a prioritized list of how important a device is for daily use and it proceeds to the interruption of supply according to these preferences, until the demand is adjusted.

(ii) *Processing Agents*. They are in charge of the internal processing of information. They carry out a number of actions, such as the pretreatment of data. They are responsible for all the important actions in the system. The processing agent controls the rest of the agents in the same group. The period extraction agent extracts activation periods from the raw data it receives. This agent will extract the consumption values of every activation period, in a way that there are as many groups with consumption values as there are activation periods. These activation periods are detected when the consumption changes in a considerable way. In Figure 3 we can see the agent will extract four activation periods. The preprocessing agent is in charge of extracting the necessary information for identifying the appliances. The extracted features are outlined below.

(a) Mean (m): this characteristic indicates the mean of the consumption values for each activation period; therefore it is the arithmetic mean of consumption of a device in its activation periods:

$$m = \frac{\sum_{t=0}^{n} w(t)}{n}, \quad (2)$$

where $w(t)$ is the set of consumption values in the instant of time t and n indicates the total time instants that compound the activation period.

(b) Maximum (m_x): this value indicates the device's highest consumption value during the activation period:

$$m_x = \max W, \quad (3)$$

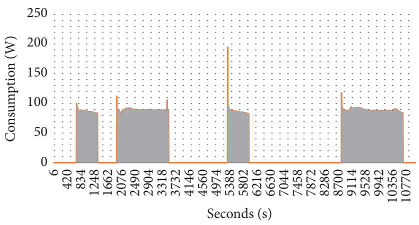

Figure 3: Line connected to a fridge.

where W is the set of consumption values of the activation period.

(c) Minimum (m_n): this feature indicates the minimum consumption value in the activation period of an appliance:

$$m_n = \min W, \quad (4)$$

where W is the set of consumption values of the activation period.

(d) First step (s_1): this value indicates the difference between the first value of the activation period ($w(0)$) and the maximum value (m_x). This "leap" is taken into account:

$$s_1 = m_x - w(0). \quad (5)$$

(e) Second step (s_2): in this case, the value represents the difference between the maximum value of consumption (m_x) and the last value of the period ($w(n)$), so that the second "leap" is also taken into account:

$$s_2 = m_x - w(n). \quad (6)$$

(f) Time (T): it refers to the time during which the device has been active, that is, switched on:

$$T = t(n) - t(0), \quad (7)$$

where $t(n)$ is the final instant of the activation period and $t(0)$ is the initial instant.

The classification agent is in charge of determining what kind of devices it is dealing with. This agent is able to predict what kind of a device exhibits the determined features. In this case, to identify the appliance, case-based reasoning is applied. There are several algorithms that agents can execute (some of them are defined in [16–20]); the process that is followed to determine which of them renders better results will be described in the Results.

Once we obtain a model that is capable of identifying home appliances with a certain level of accuracy, this model will be included in the case-based reasoning system. Every one of those cases will contain all of the features explained before. So, the cases will have the following structure:

$$C = \{m, m_x, m_n, s_1, s_2, T, class\}. \quad (8)$$

The nomenclature of a case is composed of the following values: mean, maximum, minimum, first step, second step, time, and the tag *class* which refers to the device that is represented by the characteristics of C. Thus, the CBR (case-based reasoning) will go through a phase in which it will recover the composed model. The CBR also has a reutilization phase where the recovered model will be used to classify new cases. If the model correctly classifies a new case in the review stage, we move on to the learning stage in which the new case is added to the database. If the user decides it has been incorrectly classified, the model is reconstructed taking into account the new instance added to the database.

(i) Control agent: it is in charge of monitoring the rest of the agents in the system that are found in any of the groups described previously.

The agents from different groups communicate with each other in order to achieve a common goal in the system. This communication between agents is illustrated in Figure 2.

As explained before, the accuracy of several machine learning methods in the identification of appliances was tested. These methods are data mining algorithms based on decision rules, decision trees, case-based learning, neural networks, and the Bayes theorem.

These algorithms can be combined with the fingerprint algorithm for the identification of home appliances. The fingerprint algorithm is used to identify music/songs by their sound wave. Wang [21] and Haitsma and Kalker [14] talk about this in their works. This technique is based on the calculation of hidden Markov models; however the main idea of this technique is the use of distances between the maxims of a sound, since at these points the sound is purer and there is less ambient noise. By finding maximum values and calculating the distances between them, the algorithm can compare these values with the ones stored in a database in order to identify a song; the system then provides the user with an answer containing all the information on the predicted song.

In this way, the relative sound wave maximums allow the algorithm to form a single fingerprint that would be contrasted with those stored in the system database. This algorithm can therefore be used to identify the appliances that are connected to a network once the periods of activation of the consumption network are extracted. The idea is quite similar; the maximums of these activation periods are used to identify the device. However, there is a possibility that difficulties occur in the extraction of relative maxims that contain information; this is because some devices have a continuous or constant activation. Other devices have a variable performance which is what makes them less predictable than others. All this suggests that the task of collating those "fingerprints" with records in the database would be complicated. We therefore have to study and analyze whether using the fingerprint algorithm is practical for this study.

4. Case Studies

For the case study consumption data from different buildings and different users and therefore from different lines of several electric networks were obtained.

Nowadays, there is a great variety of tools that allow measuring the amount of consumed energy in a particular electric network or by a specific appliance that is connected to that network.

Before the study of these technologies, it is important to clarify how they will be integrated in the intelligent system. The first aspect to consider is that this measuring system must offer information in real time; that is to say, the proposed system must be able to communicate with the measuring devices using some kind of protocol that establishes a connection between them. This will allow the intelligent system to communicate with the measuring system, extract information from it, and send it at specific moments.

The intelligent system must be able to manage the information it receives, and this information must regard the consumption of the electric grid or on the consumption of a particular electronic device. This is very important since the extraction of information is necessary for identifying the connected electronic device(s).

Another important feature that this intelligent system must possess is the ability to turn on/off the different devices connected to an electrical grid. Considering the total amount of consumption in a network, at times it may be advisable to turn off devices that are not being used but that continue to consume electricity. That is, the intelligent system must be able to act on the devices using the required communication protocol.

The following measuring and/or actuator devices make communication with the system possible thanks to specialized agents developed for each of them.

(i) *Smart Meter.* Intelligent meters or smart meters are used to measure consumption levels in a home, but in a more detailed and precise way than a traditional electric meter. In addition, these types of counters are capable of communicating the data that they read through some type of a protocol (usually a standard protocol) and in this way consumption can be monitored at all times. If necessary they can interrupt the power supply from a number of lines without interrupting electricity provided by the rest of the lines. This feature allows for the automatic management of demand, suited to the energy needs.

In this study, the German-made "EMH LZQJ XC" smart meter has been used. This device is manufactured by the "EMH metering" company. This smart meter has all of the functions that have been described in the previous paragraph and for this reason it can easily be integrated with any intelligent system. In Figure 4, we can see one particular model.

This model, in particular, communicates through a protocol that uses "TCP/IP" type connections. So, the information stored and managed by this meter can be accessed remotely. It is common for these meters to use standard communication protocols, and specifically the presented model uses the IEC 62056 protocol. Moreover, this smart-meter model has already been installed in many homes in Germany.

Figure 4: Smart-meter LZQJ XC.

(ii) *Smart Plugs.* Smart plugs can be plugged into a standard wall socket and the consumption of any electronic device that is plugged into it can be controlled. Figure 5 shows an example of a smart plug.

These devices allow controlling consumption remotely and in real time. We can operate these devices either through the official developer applications or through third-party APIs that allow establishing a connection with smart plugs.

In this way, smart plugs allow users to obtain consumption data remotely and in real time. It is essential for the intelligent system proposed in this article to be provided with the necessary information. It also allows acting on the devices connected to them, allowing the intelligent system to switch them off or on when necessary or convenient.

With these devices, the necessary information can be extracted and consumption data can be obtained for different electrical devices. To carry out this study ten different home appliances have been used; we have extracted sufficient samples from them to form a dataset. This dataset has been used to test supervised machine learning algorithms and helped us create a classification model that will enable us to identify the behaviour of future appliances. The following devices have been selected to validate the proposed system: a refrigerator, a water pump, a television, a dishwasher, an electric gas heater, a washing machine, a kettle, a freezer, a microwave, and an LED printer. Figure 6 shows an example of the distribution of different devices in a house.

The activation periods of some of these appliances are illustrated on the graphs found in the appendix, where it can be seen that in all cases the appliances have waveform characteristics. Once the characteristics of each activation period are extracted, the identification of devices is, a priori, performed easily. However, given that the behaviour of some of the appliances varies depending on their use over time, identifying them may be more complicated.

Figure 5: Edimax smart plug.

5. Results

This section will analyze the function of the agent organizations illustrated in Figure 2. Furthermore, it will examine the architecture's capability to acquire data from the devices and manage demand. Also, it will evaluate the performance of the processing organization in identifying devices connected to smart plugs. This automatic identification performed by the processing organization is necessary due to the dynamic variations in smart plugs.

The first step is the monitoring and control of the actuators. Firstly, in order to obtain consumption data, we must communicate with the different measurement systems that provide it. To do this, it is necessary to establish a connection with the meters through the specific protocols belonging to each of the meters. In Figure 7, you can see an example of how communication is established with the smart meter to obtain real-time information on energy consumption. Figure 8 shows a fragment of the response to the request for real-time consumption data. The real-time consumption information is located in row seven. Relevant data is then extracted from this information and it is used by the system.

The system uses the same communication protocol to manage the smart meter (Figure 7), thus communication allows for both, the acquirement of data and its management. This scheme is followed in order to reduce energy consumption whenever this is necessary, by acting on the different lines.

The second step is the evaluation of the processing organization. This organization includes the Automatic Device Identification System which uses an algorithm to classify different measuring devices. To choose the most accurate classifier, several supervised machine learning algorithms have been tested and their performance was compared. The following classifiers were used: RIPPER algorithm, PART, C4.5, RandomForest, RandomTree, REPTree, k-NN, KStart, Bayesian networks, and neural networks. These algorithms are provided by the machine learning library Weka. Different databases were used when comparing the algorithms, each database varied in the number of classes and each had one hundred instances per class. Tests have been performed with datasets of four, seven, and ten classes, respectively. Each of the classes is associated with a type of appliance, so that the instances belonging to the same class belong to different models of the same appliance. In order to evaluate the functioning of the identification system, the classifiers were included in the case-based reasoning system's reuse stage and the performance of each of them was analyzed in order to assess the effectiveness of the fingerprint algorithm in the detection of household appliances. After verifying the different algorithms and their classification accuracy, the final system makes use of a dataset of ten classes and one thousand instances, one hundred for each of the classes.

The created dataset has the same characteristics as those described in the architecture section. At the time of tests and experiments, this dataset will help to determine which algorithms offer better results and are the most suitable for the device identification system in a power grid.

In this part of the article we are going to describe the process that we followed to verify and create the final model. Initially a dataset was created, and it contained a total of 400 instances divided among four classes, each containing 100 instances. Therefore, the four classes in the dataset are balanced and represent four different appliances: a refrigerator, a water pump, a television, and a dishwasher. Tests were performed with this dataset, using the 10-fold cross validation method with each of the algorithms mentioned above.

Table 2 shows the results of the tests that were performed on the dataset.

As we can observe, all the proposed algorithms, with the exception of neural networks, offer excellent results. Moreover, the algorithms that work best are the algorithms whose behaviour is based on decision rules: rule algorithms and tree algorithms.

From these results, we can infer that all algorithms render very good results, but we wanted to see how these algorithms would behave if they had to identify more classes. So, three more appliances were introduced to the dataset: a washing machine, a kettle, and a gas heater. For each of these devices 100 new instances were introduced.

Again, we submitted the algorithms to a series of tests with the objective of seeing with what precision they classified the seven appliances. After validating the different models shown in Table 2, we could see that the algorithms that provided the best outcomes were those based on rules. Specifically, the RandomForest algorithm offered the best results and its validation is shown in Table 2, although this time with lower success rate, which is logical since the number of classes and instances has increased. However, if we look at the results of neural networks, their success rate has increased considerably in the second case, from around 0.89 to about 0.925. The improvement in the performance of this algorithm can be caused by a greater number of instances and classes and this leads the weights and the bias assigned to each of the simple neurons to adjust better to the characteristics of the problem. Furthermore, we decided to check if by adding three more appliances—a freezer, a microwave, and an LED printer—the neural network would exhibit further improvement. We also wanted to check if the accuracy of the rest of the classifiers

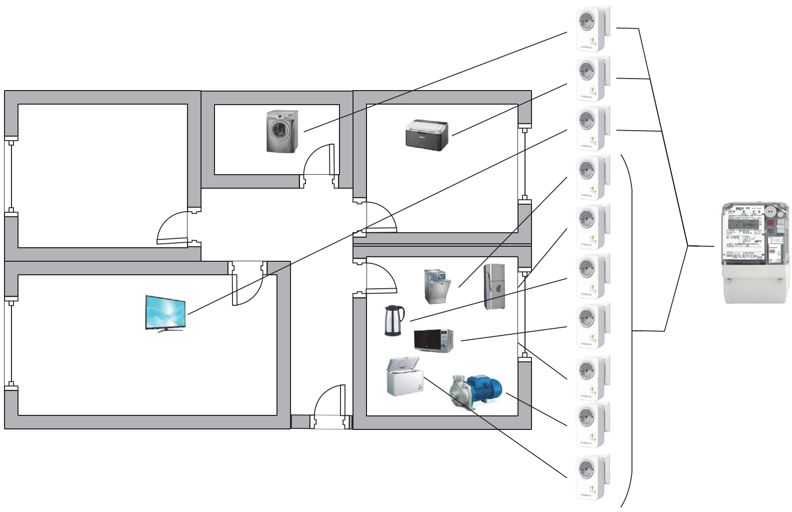

FIGURE 6: Distribution of the smart meter and smart plug in a house.

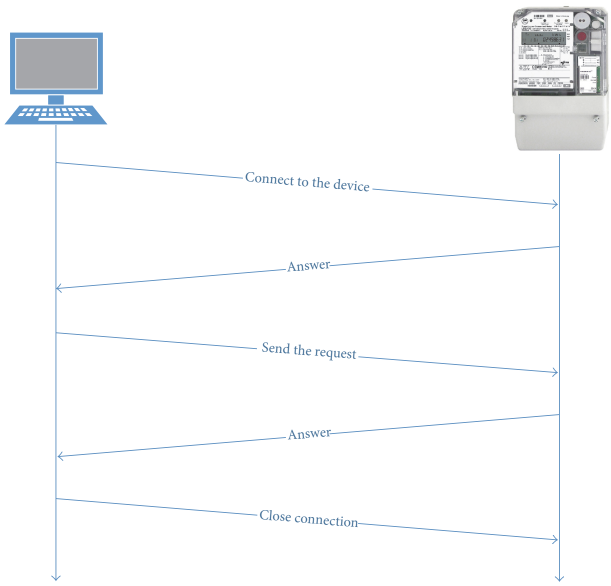

FIGURE 7: Smart-meter communication sequence.

Table 2: Datasets results.

Algorithm	Four classes' dataset		Seven classes' dataset		Ten classes' dataset	
	Accuracy	Kappa	Accuracy	Kappa	Accuracy	Kappa
RIPPER	0.9775	0.97	0.967143	0.9617	0.928	0.92
PART	0.9875	0.9833	0.975714	0.9717	0.959	0.9544
C4.5	0.9875	0.9833	0.974286	0.97	0.958	0.9533
RandomForest	0.9925	0.99	0.987143	0.985	0.98	0.9778
RandomTree	0.975	0.9667	0.977143	0.9733	0.96	0.9556
REPTree	0.99	0.9867	0.978571	0.975	0.945	0.9389
k-NN	0.97	0.96	0.967143	0.9617	0.952	0.9467
kStart	0.9575	0.9633	0.972857	0.9683	0.966	0.9622
Bayesian networks	0.9575	0.9434	0.94	0.93	0.927	0.9189
Neural networks	0.8875	0.85	0.924286	0.9117	0.853	0.8367

```
/EMH4\@01LZQJL0014F
F.F(00000000)
0.0.0(05439342)
0.0.9(1EMH0005439342)
0.9.1(0111147)
0.9.2(0170320)
1.2.1(000.188*kW)
1.2.2(000.000*kW)
1.2.3(000.000*kW)
1.6.1(0.102*kW)(0170314103000)
1.6.2(0.000*kW)(0000000000000)
1.6.3(0.000*kW)(0000000000000)
1.8.0(00016.722*kWh)
1.8.1(00016.722*kWh)
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Figure 8: Smart-meter response.

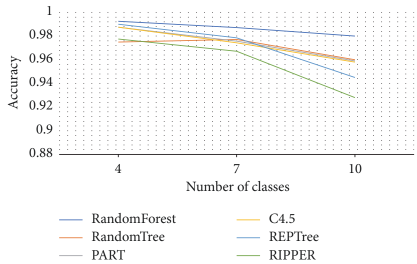

Figure 9: Results of rule-based classifiers in different test.

continued to decline as new appliances were introduced to the dataset. The results of this validation are shown in Table 2.

Interestingly, what we observe in Table 2 is that the accuracy of neural networks lowers significantly with three more classes. The performance of the other algorithms also decreased but to a lesser extent. For the third time, the algorithms that have the greatest accuracy are those that formulate decision rules, specifically RandomForest, which has an accuracy of 98%.

Good results are rendered by techniques that use decision rules and decision trees. We can therefore infer that this kind of algorithms performs well when determining what electronic devices are connected to an electrical network. For this reason, the graph in Figure 9 compares them on the basis of each of the experiments in which they had been tested.

From the graph, we can conclude that all these techniques have very similar behaviour; when the number of instances and classes increases the precision of the classifiers decreases. However, the RandomTree algorithm is an exception because its accuracy increased in the second test, which contained seven classes. Although RandomForest gave outstanding results, it is clear that all the rule-based classifiers performed very well and can be used to predict what devices are connected to an electrical network.

This statement could be confirmed with an ROC analysis. Various techniques can be used to carry out this analysis: the area under the ROC curve or the distance to the point

Table 3: ROC analysis of the best algorithms.

Algorithm	Distance to point (0, 1)	Area under the ROC curve
RIPPER	0.0724	0.98
PART	0.0413	0.987
C4.5	0.0423	0.984
RandomForest	0.02	0.998
RandomTree	0.0402	0.978
REPTree	0.0553	0.988

(false positive rate, sensitivity) of each classifier to the point (0, 1); this technique is explained by Fawcett [22]. The second technique has been selected because it allows distinguishing the different classifiers better. In Figure 10, the points of each classifier were represented in a two-dimensional space.

At first sight, the results we see here for the tested algorithms are the same that we saw in the previous plots and tables. However, they are nearer to the point (0, 1). To verify this, we illustrate the results in Table 3, with the distance of each of the points, as shown in the graph in Figure 10, as well as the area under the ROC curve of each algorithm.

In these types of analyses, the distance is closest to 0 and the area under the ROC curve is the closest to 1. In cases where a classifier has these values, it could be considered

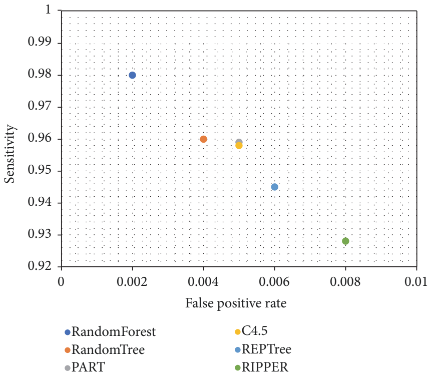

Figure 10: Rank positions (false positive rate, sensitivity) of classifiers.

Table 4: Attribute selection results.

Attribute	Info gain	Correlation
Mean	2.565	0.261
Maximum	2.333	0.248
Minimum	1.005	0.198
First step	2.21	0.289
Second step	2.197	0.289
Time	1.889	0.178

the most suitable classifier for that problem. In the analyzed algorithms, the two values obtained are very close to the objective values, so it can be said that the methods employed are very well coupled to the problem that arises.

However, there is no doubt that the success of these classifiers in the conducted experiments is largely due to the great quality of the dataset. The performance of instances and especially the selection of attributes from the dataset cause the difference in results when executing the machine learning algorithms, as we can see in the tables and the previous plot. For this reason, it would be worthwhile if we made an attribute selection with different techniques, in order to see which of these characteristics are more important when classifying a new instance.

To carry out these studies two different techniques have been used—the info gain and the correlation of attributes in connection with the class. Table 4 and Figure 11 show a comparison of the two techniques mentioned before. The results of these analyses have been normalized with the variable scaling formula, in order to make a clearer comparison between the results of the two techniques.

As can be seen in Figure 11, in the two techniques the most important characteristics that have to be considered in an algorithms' classification of instance are the mean, the maximum value, the first step, and the second one. The

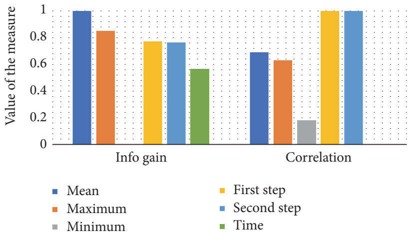

Figure 11: Results of attribute selection with normalized results.

minimum value and time are less important than the other attributes in the classifiers' classification task; however, they are the main reason for which the accuracy of the tested techniques is so high.

6. Conclusions

This work presented the developed adaptive consumption management system, capable of identifying devices connected to an electrical network. In cases where the production of energy is scarce or when excessive energy is being consumed, the user can choose to disconnect some of the devices that are not necessary, in homes, offices, and so forth.

The proposed system has a multiagent architecture, where different types of agents are in charge of carrying out different functions in the process. The agent system also includes the use of case-based reasoning systems.

Different techniques and methods have been studied in order to consider the possibility of implementing them in the proposed system. Above all, we examined the different machine learning techniques that were the most appropriate for the type of problem presented in this work. Specifically, the Results demonstrates that there is a variety of algorithms that offers a more satisfactory behaviour, and for this reason any of these techniques could be used in the proposed system.

Moreover, the work studied the performance of existing devices developed for measuring electrical networks, as well as the home appliances connected to the network itself. The system presented in this work has been developed to act and communicate with two types of devices—smart meters and smart plugs. Thus, the system can obtain data from each of them.

Accordingly, the objectives set forth in the Proposed Architecture have been achieved. The designed platform adapts the consumption of electricity in the networks by interacting with intelligent devices. The purpose of the proposed method is the extraction of knowledge from the electrical network, which allows us to obtain a network's consumption data. It employs NILM techniques to identify the connected household appliances. Subsequently, a method based on the principles of the fingerprint algorithm is used to form a dataset with the identified devices. This dataset allows obtaining excellent results in adapting the electrical

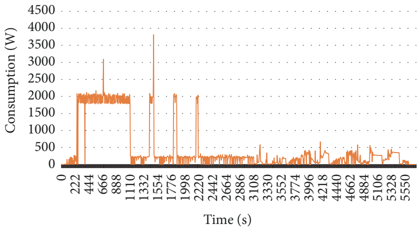

Figure 12: Washing machine activation period.

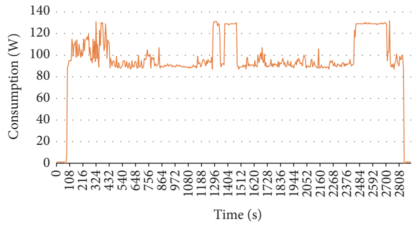

Figure 14: TV activation period.

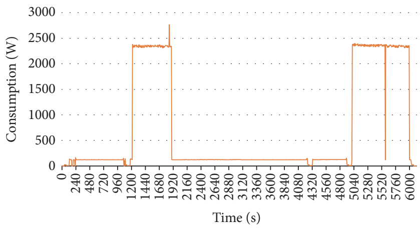

Figure 13: Dishwasher activation period.

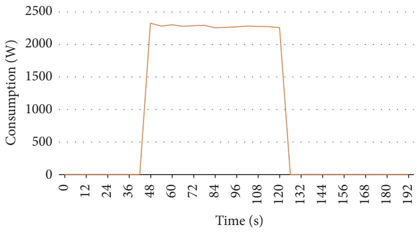

Figure 15: Kettle activation period.

consumption of the devices. Thus, the proposed platform uses a new method that leverages modern technologies for the control of the consumption in the network.

Making our system more effective is an important goal for the coming years. Therefore, future lines of research will include improving the system by adding more devices and appliances to it. This would allow identifying new devices and make the system more complete. The more the appliances in the system's database are, the more robust the system will be.

In addition, a new technique could be added for extracting the activation periods of the devices connected to the network. Some techniques allow withdrawing activation periods, as proposed by Serrà and Arcos [23]. Thus, the effectiveness of this type of techniques for the extraction of patterns in time series could also be verified in a future work.

Security is another aspect that certainly should be considered. The communications established between meters and the system connected to them could be provided with security. The reason for which this improvement is crucial is that transmitted information can be considered important and the privacy of users' data must be guaranteed in intelligent systems.

Appendix

In this appendix we introduce the activation periods of the different devices used in the study (see Figures 12–21).

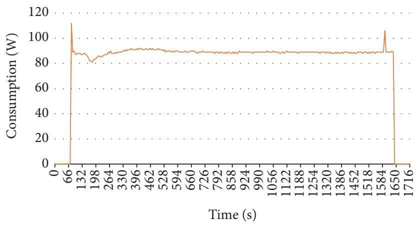

Figure 16: Fridge activation period.

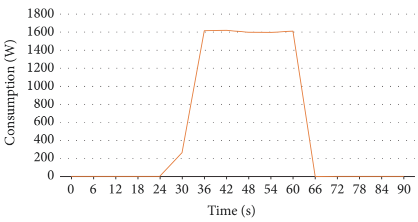

Figure 17: Microwave activation period.

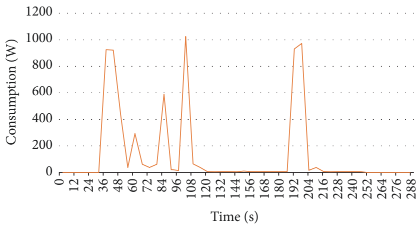

FIGURE 18: LED printer activation period.

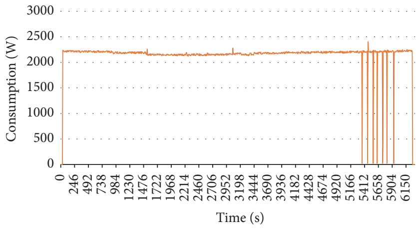

FIGURE 19: Electrical boiler activation period.

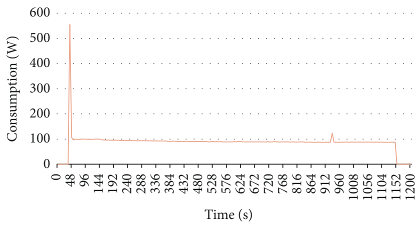

FIGURE 20: Freezer activation period.

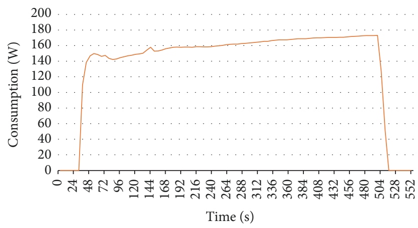

FIGURE 21: Water pump activation period.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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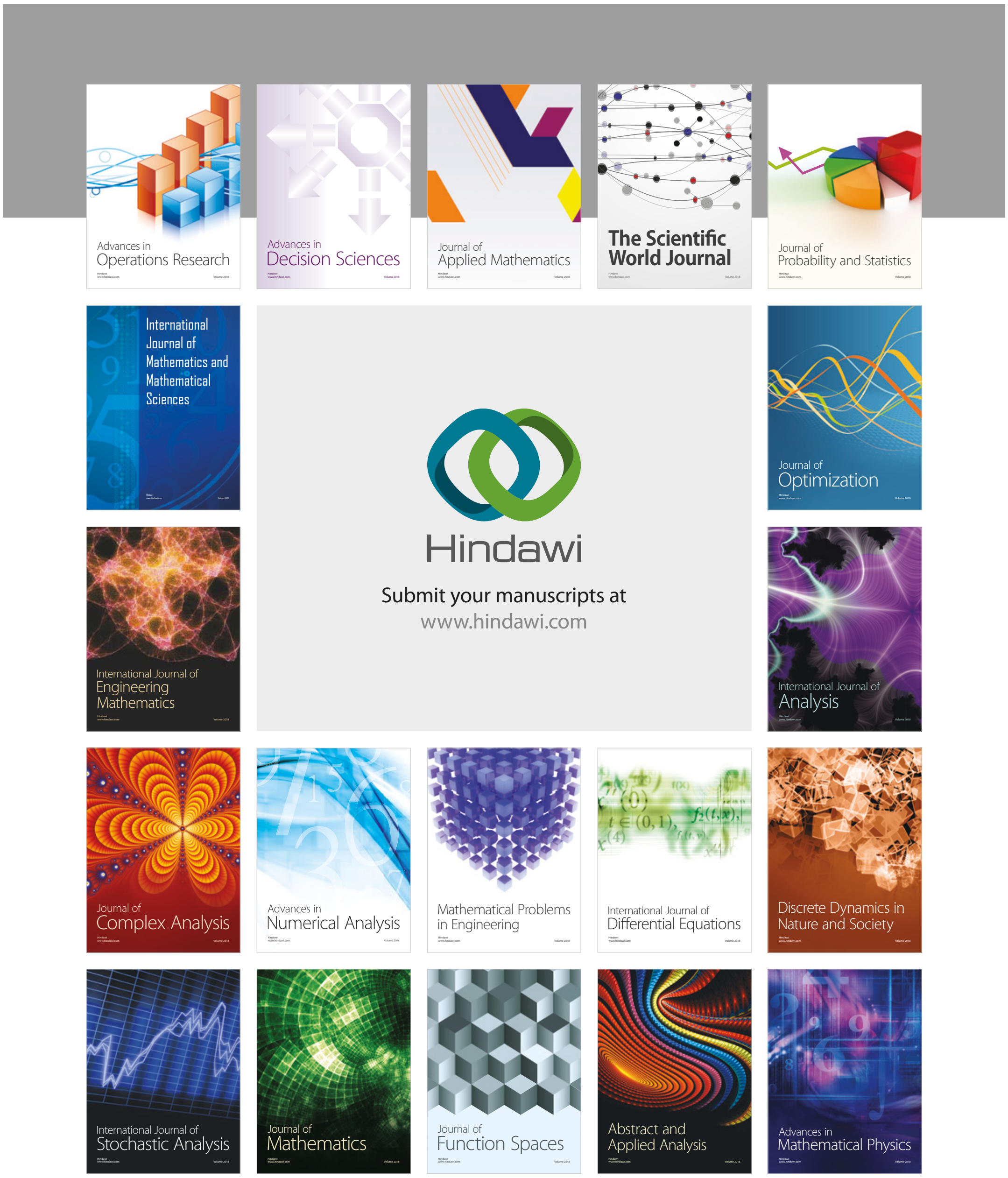
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International Journal of Stochastic Analysis
Journal of Mathematics
Journal of Function Spaces
Abstract and Applied Analysis
Advances in Mathematical Physics

3.2.1 Summary in Spanish

Esta subsección muestra un resumen en castellano de los aspectos más relevantes del artículo científico titulado "*Dealing with Demand in Electric Grids with an Adaptive Consumption Management Platform*" que en castellano se podría traducir a "Gestionando la Demanda en Redes Eléctricas Inteligentes con una Plataforma de Gestión de Consumo Adaptativo".

Research objectives

Durante los últimos años la Unión Europea ha empezado a promover políticas e iniciativas referentes a la reducción de la contaminación ambiental y al uso de energías más eficientes y respetuosas con el medio ambiente. En este sentido es de especial interés el poder obtener un sistema que sea capaz de gestionar de forma inteligente el consumo de energía para adaptarlo a las circunstancias de las redes eléctricas, así como a la producción de energía. Por otro lado, la reciente aparición de dispositivos inteligentes que permiten analizar el consumo en las redes eléctricas puede ser de gran ayuda para la obtención de tal sistema. Con los datos que proporcionan estos dispositivos se pueden extraer patrones de comportamiento de los usuarios e incluso identificar los dispositivos electrónicos conectados a la red.

Así pues, se propone la creación de un sistema distribuido basado en agentes que permita la obtención de datos de estos dispositivos de medición inteligentes y que a su vez brinde información sobre los dispositivos conectados en una red eléctrica determinada. Es decir, el sistema multiagente es capaz de obtener los datos, preprocesarlos para obtener la información útil, realizar una clasificación de los dispositivos conectados y realizar acciones sobre los mismos. Por otro lado, se propone un nuevo método para facilitar la identificación de los dispositivos electrónicos presentes en la red.

En consecuencia, los objetivos de investigación presentes en el artículo son los siguientes:

- Investigación sobre los diversos dispositivos de medición inteligentes para redes eléctricas, así como las opciones que se pueden realizar sobre ellos.
- Investigación en técnicas de inteligencia artificial para la identificación de dispositivos electrónicos con el objetivo de la definición de una nueva metodología para este tipo de problemas.
- Creación de un sistema multiagente que permita recopilar datos de los dispositivos de medición inteligentes, procesar la información recopilada para extraer el conocimiento que esconde y tomar acciones de nuevo sobre los dispositivos presentes en la red eléctrica con el objetivo de reducir el consumo en la red.

Methodology

La metodología utilizada durante la elaboración de este artículo científico es la misma que se ha explicado en la sección 1.2. No obstante, en esta subsección se explicarán cada uno de los pasos o aspectos relevantes tenidos en cuenta durante el proceso de investigación. Para ilustrar este proceso vamos a utilizar algunos de los pasos de la metodología AR.

- **Revisión del estado del arte**: como en toda investigación se hace necesario conocer las principales técnicas y estudios realizados en el ámbito de la investigación. Concretamente el estudio se centra en diferentes sistemas de gestión de la demanda. Como se constata en el artículo casi todos los estudios hacen uso de las técnicas NILM (del inglés *NonIntrusive Load Monitoring*, monitorización de carga no intrusiva). El término NILM establece que el consumo de una red eléctrica es igual al consumo de todos los dispositivos conectados a dicha red. Sin embargo, revisando la literatura se observa que existen algoritmos utilizados en otros ámbitos de investigación que pueden resultar de interés para el artículo. Mas concretamente el algoritmo *fingerprint* utilizado frecuentemente para el reconocimiento de canciones.

  Además, se observa que los estudios analizados no hacen uso de un sistema distribuido basado en agentes. Por lo que se hace necesario obtener una nueva propuesta en la que se haga uso de los sistemas multiagentes para resolver un problema típico de la técnica NILM, pero con un nuevo método.

- **Análisis y diseño de la propuesta**: en vista al estudio realizando durante el estudio de trabajos previos está claro que es necesario la propuesta de un sistema multiagente que sea capaz de obtener información de los electrodomésticos y obtener una identificación de estos. Para realizar esta identificación se siguen las etapas del proceso NILM: adquisición de los datos, extracción de características y el sistema de aprendizaje. Con el objetivo de conseguir que estas tres fases se realicen simultáneamente pero que a la vez colaboren entre si para conseguir el objetivo final del sistema se propone una arquitectura multiagente. De esta forma, el sistema propuesto cuenta con un agente de "control" y dos grandes grupos de agentes, el grupo de agentes del entorno y el de procesamiento. El primero de los grupos se encargará de obtener los datos con los agentes de "obtención de datos" y de actuar sobre los dispositivos (encenderlos o apagarlos) con los agentes de "acción". El otro grupo contará con los agentes de procesamiento uno de ellos encargado de extraer los periodos de activación de los electrodomésticos, el agente "extracción de periodo"; otro agente encargado del preprocesamiento y de la extracción de características, el agente "preprocesamiento"; y el agente de "clasificación" que determinará el tipo de electrodoméstico. Esta arquitectura en combinación con la adaptación del algoritmo *fingerprint* con el cual conseguiremos extraer ciertas características de los periodos para posteriormente realizar una clasificación nos permitirá identificar y actuar sobre los dispositivos deseados.

- **Definición del caso de estudio**: para realizar el caso de estudio es necesario utilizar dispositivos inteligentes de medición que nos permitan obtener los datos de consumo de la red eléctrica y que además permitan actuar sobre los dispositivos. En este sentido se han utilizado un *smart-meter* de la compañía "*EMH metering*" y enchufes inteligentes de la marca "Edimax". Además, para la verificación de la propuesta se han recolectado datos de 10 tipos diferentes de dispositivos y se han diseñado 3 experimentos en los que se van aumentando el número de dispositivos progresivamente. Por otro lado, también se prueban diferentes tipos de algoritmos de clasificación para probar cuál de ellos obtiene mejores resultados.

Results

Tras probar el caso de estudio diseñado para probar la validez de la propuesta realizada en este artículo científico es necesario comprobar los resultados obtenidos. En este sentido, se analizarán la respuesta tanto de la plataforma planteada como de cada una de sus tareas. Como ya se ha mencionado antes existe un grupo de agentes de entorno que recuperan información de los dispositivos de medición inteligente y actúan sobre ellos. Este grupo de agentes funcionan a la perfección y permiten recuperar el consumo en tiempo real. Esta información es la que se utilizara en el otro grupo de la arquitectura multiagente.

Este segundo grupo se encarga de extraer los periodos de activación de los electrodomésticos y de extraer las principales características de los mismos para conformar la instancia a clasificar. No obstante, y como se ha mencionado anteriormente, se han diseñado diferentes experimentos con el objetivo de determinar cuál de los métodos de inteligencia artificial era el más eficiente. Los algoritmos estudiados son los siguientes: RIPPER, PART, C4.5, *RandomForest*, *RandomTree*, *REPTree*, k-NN, *KStart*, redes bayesianas y redes neuronales. Cada uno de estos algoritmos fue evaluado en los diferentes experimentos utilizando la técnica de validación cruzada (en inglés *k-fold cross validation*) con una $k = 10$. Durante todos los experimentos se observa que el algoritmos que siempre ofrece un mejor resultado es el *RandomForest*; sin embargo, también se observa que los algoritmos basado en reglas obtienen un muy buen desempeño para la resolución de este problema.

No obstante, la obtención de tan buenos resultados también se debe a como se ha confeccionado el conjunto de datos utilizado para los experimentos demostrando que casi todos sus atributos tienen una gran relevancia a la hora de determinar la clasificación entre las diferentes clases de electrodomésticos o dispositivos que existen en el conjunto de datos.

Conclusions

Durante la elaboración de este artículo científico se ha construido y diseñado una arquitectura multiagente en la cual los diferentes agentes actúan de forma coordinada para obtener la meta del sistema, coordinar la demanda eléctrica mediante la actuación sobre diferentes dispositivos electrónicos. Por otro lado, la nueva metodología para la identificación de dispositivos en redes eléctricas ha demostrado ser eficiente y capaz de identificarlos correctamente con altos porcentajes de precisión.

También, tras finalizar esta investigación se han propuesto nuevas líneas de investigación a desarrollar. Una de ellas sería la incorporación de nuevos dispositivos a nuestro conjunto de datos para de esta forma comprobar la eficacia del algoritmo utilizado y ver si aún es el más eficiente. Por otro lado, existen otro tipo de técnicas que permiten extraer los periodos de activación de los electrodomésticos y que deberían de ser estudiadas. Así mismo, sería necesario reformar y securizar las comunicaciones entre los dispositivos de medición y la plataforma para evitar posibles ataques que pongan en riesgo la información de consumo de los usuarios del sistema.

3.3 Multi-Agent Recommendation System for Electrical Energy Optimization and Cost Saving in Smart Homes

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Multi-Agent Recommendation System for Electrical Energy Optimization and Cost Saving in Smart Homes

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Abstract: The European Union Establishes that for the next few years, a cleaner and more efficient energy system should be used. In order to achieve this, this work proposes an energy optimization method that facilitates the achievement of these objectives. Existing technologies allow us to create a system that optimizes the use of energy in homes and offers some type of benefit to its residents. Specifically, this study has developed a recommendation system based on a multiagent system that allows to obtain consumption data from electronic devices in a home, obtain information on electricity prices from the Internet, and provide recommendations based on consumption patterns of users and electricity prices. In this way, the system recommends new hours in which to use the appliances, offering the economic benefit that it would propose recommendations for the user. In this way, it is possible to distribute and optimize the use of energy in homes and reduce the peaks in electricity consumption. The system provides encouraging results in order to resolve the problem proposed by the European Union by optimizing the use of energy among different hours of the day and saving money for the customer.

Keywords: data acquisition; data processing; electricity; energy optimization; Internet of Things; money saving; multiagent; recommendation system; smart home

1. Introduction

The European Union established in October of 2014 a series of requirements that should be complete by the year 2030. The reduction of pollution and the use of cleaner and more efficient energies mark the goals during this period, according to De Baest et al. [1]. In order to achieve these objectives, the use of energy optimization techniques plays a very important role. The general aim of energy optimization is to reduce energy consumption and therefore reduce the consumption of resources needed to produce that energy. Further, another way to optimize the use of energy is to distribute the use of energy throughout different hours of the day. In this way, peaks where there is a higher consumption of energy can be eliminated or reduced. To apply techniques of this type is elementary to obtain and modify the patterns of use of users.

More recently, the European Union has implemented a new Energy Performance in Buildings Directive (EPBD) (EU) 2018/844 [2]. This plan intends to increase efficiency in the European buildings sector. It includes steps to guarantee more efficient energy systems and to renovate buildings into smart buildings.

The data that are generated in homes could be useful in order to make effective use of the electrical energy consumed in the houses. Smart homes are the ideal situation in order to collect the consumption generated by their electronic devices. However, there is a different type of devices that allows us to achieve the consumption of the electrical appliances and other devices without the need to make a great investment to transform homes in smart homes.

With this information, a data mining program can extract the behavior and rules that a resident follows during the day related to their home appliances. There are a lot of works that try to identify the electronic appliances in a home in order to predict the future use of the device by a user; for examples, see Brown et al. [3], Chen et al. [4], and Tang et al. [5]. The main objective of these investigations is to use energy efficiently. By making this consumption identification, the authors are trying to distribute the use of electric energy along the different hours of a day. This method expects to reduce the maximums of consumption among other moments in the day. Therefore, electrical consumption could be more uniform during the daytime.

When a system tries to make consumption in a house uniform, it finds the best way to achieve a global goal, the effective use of energy. However, during this process, the customer is often forgotten. The client plays an important role in the process, so the system should include an incentive that promotesachieving a local goal to the client which could be useful to reach the global one. For example, in many countries, the price of electricity is modified every hour. Consequently, a good local aim could be to minimize the bill of the customer.

As a result, we propose a system in which we take into account the data generated by the electronic devices, a local aim related to how we can reduce the bill of the costumer and the global goal of distributing the use of electrical energy. In our system, the data have an enormous value, because the entire system is going to be based on recorded and storage data. By using the consumption data, we could be able to develop a recommendation system that suggests little changes to the client on their daily routine that can help to minimize their bill and to achieve a more distributed consumption from a global perspective. We verify the system with a Spanish case of study, which we think is a good case of study in order to verify the efficiency of the proposed system and the research carried out. In order to implement the proposed case of study, we should recollect the data related to the electricity prices. This information is usually stored and provided by several web pages. For this reason, our system includes a crawler that gathers and stores all the relevant information from the webs. In addition, our proposed system uses virtual agent architecture. This is a type of distributed infrastructure that allows agents to work together and in a parallel and coordinated way to achieve a common goal. This architecture allows us to make a more adaptive system in case we want to update the proposal with new features or just in case we want to modify an existing one.

The article is divided into the following sections. In the background section, we describe some of the studies related to this line of research. The proposed system is outlined in the architecture section. The case study section focuses on particular situations that have been considered during the research. In the results section, the system's performance is described and analyzed. The last section draws conclusions on the different technological solutions that we considered for our system; furthermore, we discuss future lines of work related to the proposed study.

2. Background

Firstly, we are going to make a brief introduction about the different types of recommendations systems in order to know which technique fits better with the problem we want to resolve. According to some state-of-the-art reviews about recommendation systems, like Isinkaye et al. [6] and Shah et al. [7], there are three kinds. The most famous are content-based filtering (CB) and collaborative filtering (CF). The third one is hybrid filtering (HF). CB recommendation systems try to find similar items or similar users or whatever it is that we are recommending. This technique finds one object similar to another one if both share some features and characteristics in common. Basically, the similarity is established by comparing their features. Thus, an object is recommended if the user has seen, ranked, etc. a similar one. The recommendation systems based on CF recommend items that have been seen, bought or positive-ranked by users with similar preferences to the target one. This technique categorizes two different items as similar if a great number of users, similar to the original one, buy or rate the two items. The users are seen as similar if they share a great number of preferences. In this case, they are seen as close users. Finally, the HF technique is used in recommendation systems that want to avoid the problems and limitations that CF and CB usually have. It uses the best of both techniques in order to provide more accurate and effective recommendations.

Hybrid filtering, however, according to Felfernig et al. [8], assumes that in the special case of the Internet of Things (IoT) recommendation systems, there are two more types of recommendation systems. In the case of knowledge-based recommendations, the recommended system is not based in rankings or features. In this case, the users have a series of requirements. Thus, if items or actions want to be recommended, they have to pass these rules. To do that, the system has to have information about the user. The other technique for IoT recommendations is the utility-based. In this case, when we want to recommend an item, an action, etc. we have to evaluate it based on the utility established by the user or the system. Therefore, these are all the possibilities related to recommendations for IoT and smart environments.

IoT deployments in home environments are proven by several studies. This way, the implementation of smart systems in houses can benefit the residents. From the point of view of health-related benefits, smart homes contribute to providing confort to the final user, because of the way that they perform operational efficiency, monitoring and management, and consultancy (Czaja [9]). Smart homes also provide environmental benefits. The actual threats about climate change and volatility in energy prices have increased interest in smart devices and systems. These technologies allow to reduce energy consumption, which is important according to what the European Union has established (De Baest et al. [1]). Smart systems can monitor the information on energy description, control the consumption patterns, and achieve efficiency and optimization and consultancy (Zhou et al. [10], El-hawary [11]). According to Elkhorchani an Grayaa [12] and Aye and Fujiwara [13], energy control can eliminate carbon emissions and be used as a first step in the way to use renewable energy sources. This assumption is more long-term, while the economic benefit is obtained more quickly. Smart home technologies reduce expenses on energy consumption. However, users do not usually see them as useful as they could be because they do not think they are going to recover the return of the investment (Balta-Ozkan et al. [14]). Nevertheless, Khedekar et al. [15] said that smart home technologies are going to be more affordable in the near future.

This benefit should be taken into account when a researcher develops a new smart home system. Therefore, Longe et al. [16] proposed a daily maximum energy scheduling (DMES) algorithm that reduces by10% the amount of the monthly electrical bill. The algorithm accomplishes all the benefits exposed in the previous paragraph. They assume that people are distributed across several income classes, so based on income classes, it establishes a consumption limit that homes appliances connected to home network can consume. In order to optimize daily consumption in a home, the DMES algorithm uses mixed integer linear programming. The results of the study show that smart meters that include the proposed algorithm optimize energy consumption for residents and for utility providers. In this research, they deploy an algorithm that is installed in a smart meter. Smart meters are smart home devices that are not yet installed in all houses and are also expensive. For this reason, clients could be reticent to use this smart system.

Other researchers, such as Li et al. [17], have worked on a multiagent system that allows to improve and optimize the energy usage of smart homes. Every electrical device is configured as a virtual agent. These agents work simultaneously and together to reduce consumption while ensuring user comfort, energy costs, and peak energy savings. The investigation permits communication, interaction, and negotiation between energy sources and appliances in order to achieve energy efficiency and a minimum electrical bill.

Lin and Chen [18] developed a new home electric energy saving system. The system makes use of different smart devices, smart meters, smart plugs, smartphones, and database servers. The system even allows a user to monitor the electrical devices remotely. The consumed data are also used to identify the devices using the SVM (support vector machine) algorithm. The system can also control the state of the appliances remotely, so these actions could be used to save energy and reduce consumption. The system uses two monitoring devices, smart meters and smart plugs. As we said before, smart meters are expensive devices whose use is not widespread. Thus, for better deployment of the system, smart plugs can be used as the only smart devices that can monitor consumption information.

Other systems also try to make use of an intelligent home control system, for example, the one proposed by Bian et al. [19]. In this research article, the authors have developed a new temporary home gateway in an Android phone in order to reduce the working hours of a traditional gateway. This new temporary gateway is only used when the mobile enters the home network. They also developed an intelligent control system based on the users' behavior. This control system is able to shut down unused devices. With this functionality, the system is able to reduce cost and save energy. With this functionality, they also reduce the information that is sent between the different elements in the home network.

Sharifi and Moghouli [20] propose a scheduling control system that can reduce cost in bills and that also tries to reduce peaks in energy consumption. Therefore, they use real-time cost pricing. They based their system on a fuzzy decision system. Researchers Khalid et al. [21] also proposed a similar fuzzy system. In this study, a fuzzy control system is capable of reducing consumption peaks as well as reducing the cost of energy for home residents. They also classify electronic devices using their pattern of behavior. By using the fuzzy control and the classification, they can schedule the use of the devices.

On the other hand, some researchers do not automatize the system. They leave the power of decision to the user. This is the case of the study presented by Wright et al. [22]. According to the article, they present a policy of " know" and "care". The user consumption information is obtained from the use of a smart meter. With this information, the system is capable of estimating the energy price. This price and the estimated carbon dioxide emissions are shown to the users in order to apply the policy of "know" and "care". Thus, in this case, the system tries to reduce the demand for energy during peak hours. This goal tries to makes energy more efficient.

Taking into account all the previous works, in this paper, we present a new smart home electric energy saving system. We have developed a new recommendation system that works in a multiagent architecture. The recommendations are based on knowledge and utility. The recommendation system used historical consumption and price data. Historical and recent data are taken into account when the system makes its recommendations. Furthermore, in order to make recommendations, the system takes into account the type of appliances. In conclusion, the main objective of this research article was to reduce the user bill and obtain a more distributed use of energy with the use of recommendations. By doing this, the client is still the one who controls the electricity system. This is important because the users could have a more reliable relationship with the presented system. This way, the proposal satisfies the IoT benefits. In order to make the proposal more clear, a comparison between it and previous works is presented in Table 1.

Table 1. Comparison between the proposal and previous works.

	[16]	[17]	[18]	[19]	[20]	[21]	[22]	Our Proposal
Follow IoT benefits	✓	✓	✓	✓	✓	✓	✓	✓
Use multi-agent system		✓						✓
Use previous data		✓	✓	✓	✓	✓	✓	✓
Use prices data					✓			✓
Use economic smart devices				✓				✓
Reduce bill	✓	✓	✓	✓	✓	✓	✓	✓
Reduce energy use in peak hours		✓			✓	✓	✓	✓
Automatize control	✓	✓	✓	✓	✓	✓		
Users in control							✓	✓
Do not limitate devices use							✓	✓
Recommendation system								✓

3. Proposed System

As discussed in the previous section, the main contribution of the paper is the multiagent recommendation system. Multiagent technology provides a distributed architecture in which different agents carry out different and specific tasks at the same time. Equally important is the characteristic that agents work in a coordinated way to achieve a common goal. The main advantages of the multiagent system are the mobility, the dynamic behavior, and the high level of communications through the transparent management of the message queues. Hence, the system will have different agents. Every agent will perform a different job but needed for the rest of the agents. The multiagent system is based on a Python library [23]. With the use of this software, we implement the different agents in a central system. By doing this, the system will be installed more easily in smart homes. The agents will be connected between them, and some of them (as we will describe so on) will be connected with a network of smart devices or web pages through the specific protocol. Therefore, in the proposed system, the multiagent system is centralized, but each agent can establish communication with external elements. The architecture developed for the research is shown in Figure 1. In order to clarify, we explain it in detail.

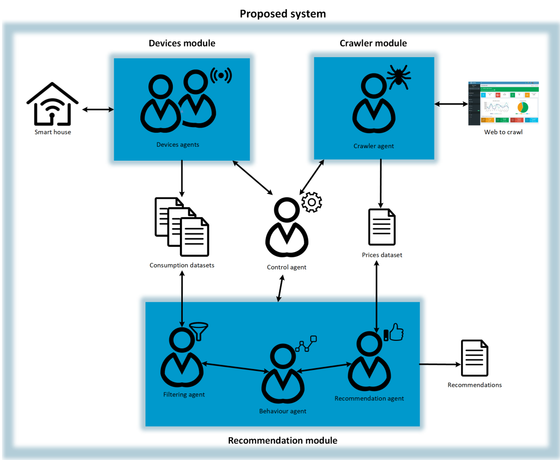

Figure 1. Architecture of the proposed multiagent system.

As can be seen in the previous figure, there are three main modules in the presented system. Every one of them plays an important role in the system because they all depend on one another to work in a proper way. Nevertheless, there is another important agent, which is in charge of controlling the system and the interactions between the modules. Therefore, the control agent and the three different modules are explained in the following paragraphs.

- Control agent: It is the agent that controls the rest of the agents and determines when to initialize them. When the rest of the agents are initialized, they execute their actions in order to achieve their personal goals and also the global goal of the system.
- Device agents: These agents communicate with the smart devices inside the house. The devices are connected to the global system via the specific protocol. In this article, we propose to use a low-cost device, namely, a smart plug. This can be easily installed in every normal plug of the house. The communication between the agents and the smart plug can be performed via the specific protocol. There will be as many device agents as electronic appliances we want to control. The use of virtual agents allows us to increase or reduce the number of agents with no apparent effort. Every agent only connects to a single appliance. The agents proceed in the following way. Firstly, they connect with the specific physical device. When the agent receives the answer from the device, it requests the consumption data every six seconds. This window of time can be modified, but we recommend to use this value in order to obtain good results and to reduce the number of communications between the agents and the devices. The consumption data are stored in a text file. There is a text file for every device agent and, therefore, for every appliance.
- Crawler module: This module contains the crawler agent which connects to a web page. This web page contains information about the prices of electricity for the current day. Consequently, the software included in the agent selects the relevant information from the web page. This relevant information consists of the prices and the corresponding hours of the extracted prices. Thus, the agent requests the information located on the web page. When the agent obtains this information, it extracts and stores the relevant data into a text file. This text file includes all the historical information about electricity prices. This agent performs these actions every twenty-four hours, once a day.
- Recommendation module: This module contains three different types of agents that interact between them and make use of the data recollected by the modules previously explained. Every one of these agents implements a specific action. Hence, we explain them thereupon.

  - Filtering agent: Its function is to filter and apply changes to the data in order to obtain a more quality dataset. The actions that this agent can take into account are extracting some extra features that can be taken into account when doing the recommendations. The actions include transforming the data that can be stored in the text file, extracting the day of the week as of the measurement date, and determining when an appliance is active or not.
  - Behavior agent: This agent is the one that has to determine when a device is used more and when it consumes more electricity. It interacts with the filtering agent. This agent uses the information provided by the previous one in order to extract the different patterns of use of every appliance. It extracts the use of every device every hour, and it also obtains the use during every weekday. This is important because these two patterns are used when the system provides recommendations, as we will explain soon. This agent not only extracts the historical use of the devices but, also, the last month of use, something we call temporal use. We consider this information really relevant because the use of appliances can change in time, and the most recent use is what best represents the user. For this reason, we weigh the historical and temporal use. The weighted formula is represented in Equation (1):

$$\forall d_i \in D = \{d_1, d_2, \ldots, d_n\} \rightarrow U_w(d_i) = \sum_{j=0}^{m} U_h(d_{i_j}) \cdot \alpha + U_t(d_{i_j}) \cdot \beta, \quad (1)$$

where d_i is an electrical device, D represents the devices as a whole, U_w is the weighted use. It is calculated from the historical use, U_h, and the temporal use, U_t, j represents the historical and temporal use for every daily hour or weekday. Finally, α and β the weight elements. In our case, we estimated the values of 0.8 and 1.2, respectively.

Therefore, with the use of Equation (1), we increase the importance of temporal use and decrease the value of the historical one. This equation is applied for hours patterns and weekdays patters. This way, the behavior agent extracts the way users use their connected devices.

– Recommendation agent: It is in charge of making and providing recommendations to the client. The first action that this agent uses is to recollect the user behavior provided by the behavior agent. This information, along with the prices dataset, is used to decide which the best recommendations to suggest are. The process that every device follows in order to make the recommendations is illustrated in Figure 2. The agent divides the appliances into different types, namely, no recommendation type, short-term recommendation type, and long-term recommendation (this will be explained in more detail in the next section). The no recommendation type will not produce any recommendation, because its consumption is not related to human use or it has a more restricted use. The short-term recommendation type refers to a device with a restricted use, although it can be changed slightly. On the other hand, the long-term recommendation type is applied to devices that can be used in any day period.

  Once the appliance is classified as a long- or short-term classification type one, the agent proceeds to make energy and money-saving recommendations for the device's use. As explained before, the system takes into account the weekday. Thus, if the device is more used in the current day, the system will provide recommendations for that. If not, the system will not recommend anything in order to not overload the users with too many recommendations which may not be useful for the user during the current day. In the same way, when the agent provides recommendations about the electrical appliance, the number of recommendations is limited. Consequently, the recommendations supplied will be the most efficient and the ones that optimize the final goal more, to reduce the consumer bill and to distribute the use of electrical energy. For short-term recommendations, the system suggests variating the consumption to the closest and cheapest active hour (which means that the user is probably in the house). With this strategy, the system tries to distribute consumption along proximate hours and to save money. However, for long-term recommendations, the system suggests variating the consumption to the cheapest active hour, allowing to distribute the use of energy and to achieve a better financial saving.

  According to what we have been saying before, the proposed recommendation system makes use of two techniques mentioned by Felfernig et al. [8]. These techniques are knowledge-based (KBR) and utility-based (UBR) recommendations. The KBR is used when we obtain the patterns of use of the different devices. With this information, we can predict when it is more likely that the users are going to use the appliance, so we can suggest small changes in their usage. These recommendations are accompanied by an incentive, what the user can save with this small change. Therefore, with this incentive, we make use of UBR.

Consequently, all the modules and all the agents interact between them and are in continuous communication. Hence, we illustrate the communications and the iterations between agents in Figure 3. There, it can be seen how the control agent initializes the rest of the agents and how specialized agents interact between themselves and achieve their personal goals. The full process is represented in Figure 3.

On the whole, the system presented in this section makes use of a distributed architecture based on virtual organizations of agents in order to provide recommendations, generated by a KBR and UBR recommendation system, that minimize the monthly electricity bill in the short-term and that generate a more distributed use of energy, without maximum peaks, in order to use electrical energy in a more efficient way.

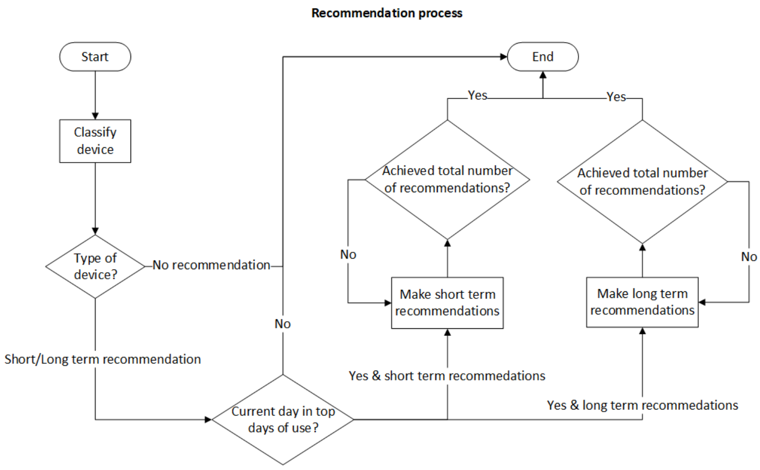

Figure 2. Recommendation process followed for every electric device.

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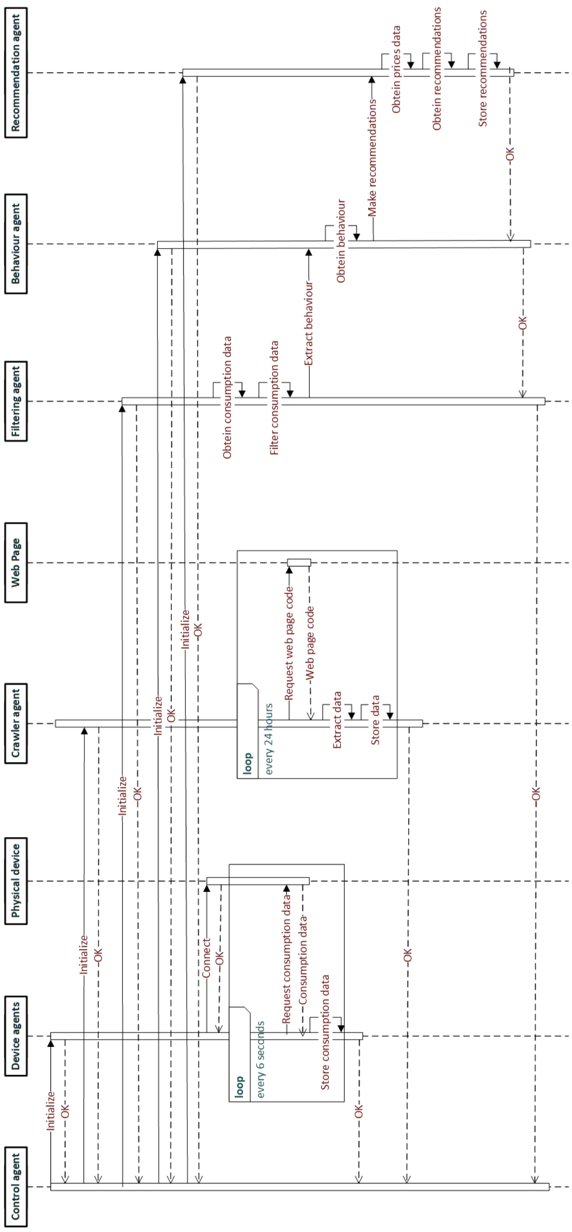

Figure 3. Communication and interactions between agents.

4. Case Study

In this section, we are going to present the different characteristics and specifications that have been taken into account to evaluate the multiagent recommendation system proposed in this article. Firstly, we are going to talk about the smart devices that are going to be installed in the house. We explain how can we recollect the consumption information from them and what other possibilities they can offer. Secondly, we explain the consumption dataset used to evaluate the recommendation system and the considerations we have taken into account to achieve better results. Thirdly, we explain how we obtain the prices dataset and what information it stores.

In our proposal, we pretend to create a low-cost system but without sacrificing certain aspects which we consider relevant for the proper performance and possible extension of the system. Therefore, the smart device that we have selected has to allow us to achieve these requirements. The requirements are as follows: In the first place and most importantly, the measuring devices must offer consumption information in real time. Consequently, the global system has to be connected continuously to the smart device using some protocol so the data can be stored and processed by the multiagent system. Secondly, the measuring devices have to be installed in the house without disturbing the client. This requirement is important because of the reticence of users to adopt this type of intelligent systems. Taking this into consideration, we decided that "plug and play" devices are the ones that best fit this requirement. Lastly, we considered that for future improvements to system, the smart devices should be allowed to turn on/off the electrical appliances connected to the electrical grid. This will allow the system to turn off some devices when there is no one at home and turn them on when the clients arrive home in order to save energy and reduce consumption. However, this requirement is being taken into account for future versions of the system proposed in this article so that the current investment in intelligent devices is not in vain.

For these reasons, we consider that smart plugs are the devices that have the best quality–price relation and accomplish all the requirements. These devices have an easy implantation in the house. They just have to be plugged in a normal wall socket and the electronic appliances connected to them will be monitored. Furthermore, the devices provide information about the consumption of the appliances connected to them. Usually, these data are transmitted by a specific protocol that is implemented by official developer applications or through third-party APIs (application programming interface) that allow the establishment of a connection with the smart plugs. As a result, through this direct connection with the device, some smart plugs allow the controlling of the state (on/off) of the electronic devices through commands sent to the smart plug. Hence, for the deployment of this study, we have installed smart plugs that implement all these functionalities—in particular, the Edimax smart plug, which is illustrated in Figure 4.

Figure 4. EDIMAX Smart Plug Switch SP-2101W.

This smart plug uses the "TCP/IP" protocol described by Forouzan and Fegan [24] in their work. Therefore, it makes use of WiFi technology in order to establish the connection. It uses IEEE 802.11b/g/n (see Sendra et al. [25] for more information) as standard wireless. In consequence, our system makes use of the work elaborated by Wendler [26], who has elaborated a Python API to control the Edimax smart plugs. With the use of this API, we can obtain real-time data and also control the state of the electronic appliances among other actions. Thus, in our study case, we make use of this software to implement the connectivity between the multiagent recommendation system and the measuring devices.

Thus, with this software, the devices agents are to connect to the different appliances allocated in the house. For each appliance, a device agent is generated. This agent establishes the connection through the IP address and the credentials. After the connection is established, the agent requests the current consumption of the device every six seconds. These data are stored in a text file with the weekday and the time of the request. Therefore this file contains as many records as requests done by the device agent. Once more, there is a text file for every electrical appliance in the house. Therefore, this information will form one of the datasets used for recommendations.

However, during this case study, we used an existing consumption dataset in order to verify our system with a proved dataset. Therefore, in this instance, we tested our system in order to demonstrate that the theory explained in the previous version works in the right way. Moreover, we used a well-knowing dataset so other researchers can test and improve the proposed system in this work. The last statement is what we consider more important in order to use an existing dataset. That is the continuous evolution of sciences thanks to the researchers' community. For this study, we used electrical consumption data from the United Kingdom. We used the dataset created by Kelly and Knottenbelt [27]—the UK-DALE dataset.

UK-DALE (domestic appliance-level electricity) is a dataset that has records from five different homes. The measure from the houses has different periods of time. The one with the longest period is "House 1", with more than two years of active consumption records. During this time, the use of 52 electrical appliances was stored. Most of them were active for almost the entirety of those two years. Therefore, with only "House 1", we have a lot of records in order to extract the behavior of the users. Consequently, we used these data for the case study. In particular, we used the data that were stored every 6 s (the dataset offers 6 s, 1 s, and 16 kHz data).

These data contain records with the data-time in "Unix epoch time" format, and the consumption for this time is in Watts. In order to attain a piece of more visual information, we transformed the "Unix epoch time" format into a "YYYY-mm-dd HH:MM:SS" format. We also obtained the weekday for this date. As we explained before, these actions are carried out by the filtering agent in the recommendation module. Once the system filters the data, the behavior agent extracts the patterns of use for every device. In this process, it is important to mention that two electronic devices of the UK-DALE dataset have to been taken out of the study because they do not have the expected structure. These appliances are the ones labeled as "breadmaker" and "kitchen_lamp2". Therefore, the system is now working with 50 electronic appliances. The patterns of use of the different devices are shown in Figures 5 and 6. Figure 5 compares the hourly use of the different devices between each other. Figure 6 represents the hourly use of devices analyzed individually.

Hence, with the information provided by these two images, we can assume some requirements in order to improve the efficiency of the proposed system. In Figure 5, we can appreciate that there are some devices that do not change their behavior at all. These appliances can be identified as nonhuman action devices. The other type is human action devices. This classification is better understood with an example. For instance, a fridge or a boiler are electronic devices that in normal situations are continuously connected to the electric grid. Their electric consumption is not very related with the human because they will consume energy while they are connected to the grid. Consequently, it can be understood that they are nonhuman action devices. However, in many cases, these devices are the ones that consume more energy, but their behavior is not related to the user's behavior. Thus, these devices do not require recommendations. Human action devices are the opposite, like a TV. The TV only consumes energy when the client turns on the device.

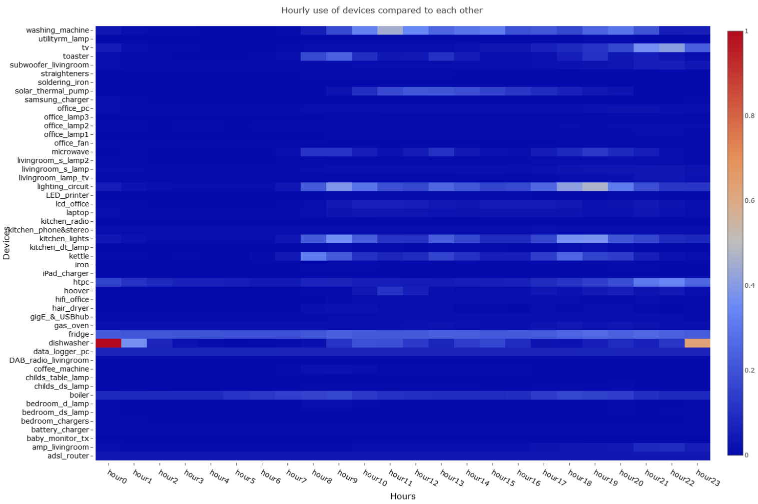

Figure 5. Hourly use of devices compared to each other.

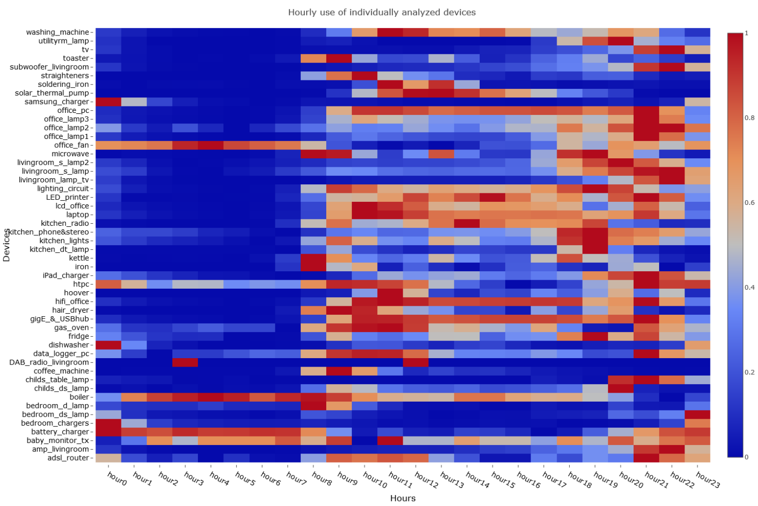

Figure 6. Hourly use of individually analyzed devices.

In Figure 6, we see how appliances are used. It is important to know how devices are used in order to obtain better recommendations. Therefore, there are some devices that have a more variable use, like the washing machine. The washing machine can be used at different hours. This means that the client can turn on the washing machine at 7 p.m. or at 9 a.m. We classify these devices as "long-term recommendation". Furthermore, in the case of the washing machine, it is important to assure that the suggested hour in which the device's use is recommended is an active hour as well as the hour in which the device finishes its performance. This requirement prevents future complaints of the system's users. Alternatively, there are other kinds of appliances of a more restricted use. Devices like lights are only used when the client is forced to turn them on. These devices are labeled as "no recommendation". However, there are other kinds of restricted devices that can suffer a little change in their normal use—for example, a laptop. These devices can be used a little bit earlier or a little bit later depending on the electricity price. These types of devices are classified as "short-term recommendation". Nevertheless, some of the recommendations related to "short-term recommendation" devices could be rejected by the users due to them not wanting to change their normal use. However, we wanted to provide these recommendations to the final users in case they change their mind and then follow the recommendations or just so that they decide to do another thing. For example, if the system recommends using the microwave one hour later, the user could decide to prepare another meal that does not involve the microwave. Another example is that if the user has turned on the TV while doing another activity, thanks to the proper recommendation, he/she could decide to turn it off in order to save some money since he/she is not paying too much attention to the TV. Consequently, we consider that this kind of "short-term" recommendation has to be offered to the user. The assumed requirements from Figures 5 and 6 are illustrated in Table 2.

Hence, with this decision table, the recommendation agent can follow the recommendations properly. However, to do it, it also needs an electric prices dataset. In this case study, we are going to work with the Spanish electric market. In the Spanish case of study, it is important to mention that there are three different rates. The first one is the normal rate. This rate is hired by almost all citizens in Spain. It has lower prices during the night and higher prices during the evening. The second rate is the hourly discrimination rate. This rate has higher prices between the morning and the afternoon. The lower prices are during the night and during the early morning. This type of rate is usually hired by people who are habitually active during the night because they rest during the day because of their jobs. Just as a side note, in Spain, there is a third rate, the rate for electric vehicles. It has similar prices to the hourly discrimination rate. Consequently, in order to test the proposed system, we do so with a dataset that contains the daily prices for the normal rate.

As we mentioned previously, there are several web pages that offer public information about the prices of electricity during the different hours of the day. We considered it was important to extract the data from a web page that could offer to the possibility of extracting the three different kinds of rates. Thus, for future implementations, we only have to apply little changes to the crawler software. For this study, we extracted data from the following URL, https://tarifaluzhora.es/. A capture of this web page can be seen in Figure 7. We have marked the data that we had to extract in blue.

The crawler agent collects these data. For future use, we store the data with the structure that is represented in Equation (2). The distribution of these data in the normal rate is shown in Figure 8. As we explained before, the rate has lower prices during the night and higher prices in the evening.

$$\forall i \in D = \{i_1, i_2, \ldots, i_n\}, i = \begin{cases} data \\ weekday \\ hour0 \\ \vdots \\ hour23 \end{cases}, \quad (2)$$

where i represents every one of the instances in the prices dataset, D. For each instance, the date and weekday are stored as well as the prices for every hour of the day in €/kWh.

Table 2. Devices used in the case study and their labels.

Device	Type	Recommendation Type
adsl_router	Nonhuman action	No recommendation
boiler	Nonhuman action	No recommendation
data_logger_pc	Nonhuman action	No recommendation
fridge	Nonhuman action	No recommendation
gas_oven	Nonhuman action	No recommendation
htpc	Nonhuman action	No recommendation
kitchen_phone&stereo	Nonhuman action	No recommendation
solar_thermal_pump	Nonhuman action	No recommendation
kitchen_lights	Human action	No recommendation
livingroom_s_lamp	Human action	No recommendation
kitchen_dt_lamp	Human action	No recommendation
beedroom_ds_lamp	Human action	No recommendation
lighting_circuit	Human action	No recommendation
livingroom_s_lamp2	Human action	No recommendation
livingroom_lamp_tv	Human action	No recommendation
kitchen_lamp2	Human action	No recommendation
utilityrm_lamp	Human action	No recommendation
bedroom_d_lamp	Human action	No recommendation
childs_table_lamp	Human action	No recommendation
childs_ds_lamp	Human action	No recommendation
office_lamp1	Human action	No recommendation
office_lamp2	Human action	No recommendation
office_lamp3	Human action	No recommendation
iPad_charger	Human action	Short-term recommendation
samsung_charger	Human action	Short-term recommendation
bedroom_chargers	Human action	Short-term recommendation
battery_charger	Human action	Short-term recommendation
hifi_office	Human action	Short-term recommendation
amp_livingroom	Human action	Short-term recommendation
subwoofer_livingroom	Human action	Short-term recommendation
kitchen_phone&stereo	Human action	Short-term recommendation
office_fan	Human action	Short-term recommendation
DAB_radio_livingroom	Human action	Short-term recommendation
kitchen_radio	Human action	Short-term recommendation
baby_monitor_tx	Human action	Short-term recommendation
tv	Human action	Short-term recommendation
lcd_office	Human action	Short-term recommendation
laptop	Human action	Short-term recommendation
htpc	Human action	Short-term recommendation
data_logger_pc	Human action	Short-term recommendation
office_pc	Human action	Short-term recommendation
gas_oven	Human action	Short-term recommendation
coffee_machine	Human action	Short-term recommendation
kettle	Human action	Short-term recommendation
toaster	Human action	Short-term recommendation
microwave	Human action	Short-term recommendation
washing_machine	Human action	Long-term recommendation
dishwasher	Human action	Long-term recommendation
soldering_iron	Human action	Long-term recommendation
hoover	Human action	Long-term recommendation
iron	Human action	Long-term recommendation
gigE_&_USBhub	Human action	Long-term recommendation
LED_printer	Human action	Long-term recommendation
straighteners	Human action	Long-term recommendation
hair_dryer	Human action	Long-term recommendation

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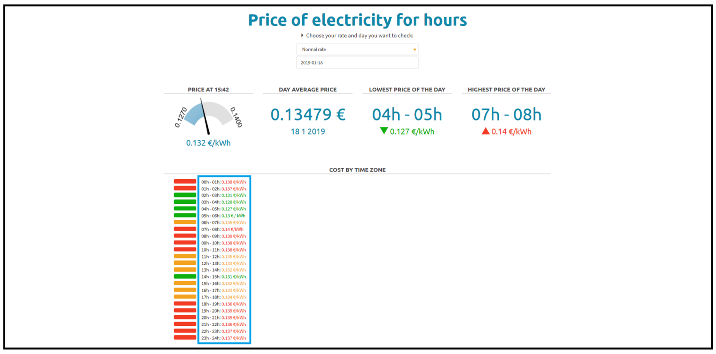

Figure 7. Web page used for the prices dataset.

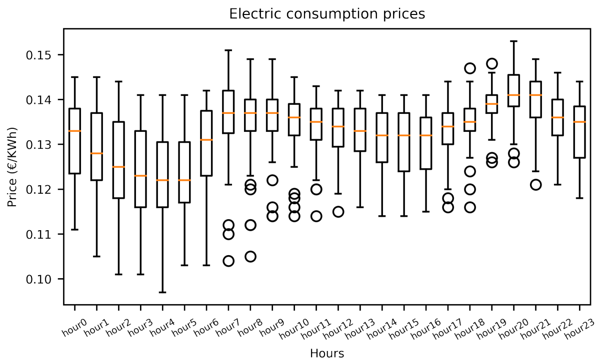

Figure 8. Distribution of the prices dataset.

5. Results

In this section, we explain the results provided by the different modules of agents that have been described in Section 3. Just to remember, there are three different modules, "devices module", "crawler module", and "recommendation module". First, we explain the results of the "devices module" and then the rest.

As we explained before, we connected the devices agent with the different smart plugs using the software library elaborated by Wendler [26]. We tested this module with six different EDIMAX Smart Plug Switch SP-2101W. Hence, we tested the module with a maximum of six devices agents deployed at the same time. We reviewed different electronic devices. These are a microwave, a washing machine, a TV, a fan, a laptop, a router, a desktop computer, a computer monitor, an alarm clock radio, and a desktop lamp. These devices are located in an apartment of around 120 m^2. The distribution of the flat is represented in Figure 9. The house has ten rooms, and the appliances were distributed all over the household. We tested the module with different combinations of devices. The system has not shown debilities with any of these combinations. We verified every one of them throughout a day. We have to keep in mind that the agent consults the consumption of the device every six seconds. Consequently, the agent obtains 14,400 registers for a single device in one day. Hence, 86,400 registers are collected in a single day in the case that the combination contemplates six devices. As we mentioned, the behavior of the different devices agents is as expected. Therefore, we concluded that the "devices module" is performed correctly.

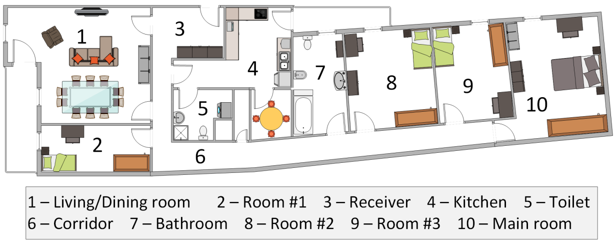

Figure 9. Plane of the house where the "devices module" is tested.

The software implemented for the "crawler module" also works perfectly. In order to assess this agent, we tested it for 72 days. As explained, the agent obtains the consumption prices once a day. In our case, we decided to extract this information at 00:01:00 hours. Hence, this agent was deployed for more than 1,728 hours without causing any problems. During this process, we obtained a dataset which is going to be used by the "recommendation module".

Finally, we are going to discuss the "recommendation module". This module is the main contribution of this work. As we explained, this module tries to optimize the electrical bill of the customer. With this action, the system also tries to distribute the electrical consumption in the house. These are the two mains objectives of the proposed system. Consequently, we discuss each of them individually.

In the first term, we analyze the different simulations that were developed in order to test the system. Once the system is finished, we have to test it, so we established different situations related to the answer that the user can have to the recommendations provided by the system. It is important to mention that we limited the maximum number of recommendations per device to three. Therefore, we considered four situations, the "Optimistic", the "Neutral", the "Probable", and the "Pessimistic". The "Optimistic" is the less probable simulation because users are usually reticent to change their habits. The "Neutral" is a probable simulation but still needs a user that is not very restricted. The "Probable" simulation is the one that we considered where normal users could follow after the installation of the multiagent recommendation system in their homes. The "Pessimistic" simulation is related to the behavior followed by a restricted user. In all these simulations, we determine a percentage of the consumption consumed in the original hour that we know is going to be consumed in the recommended hour. Hence, for each situation, there is an associated percentage. In Table 3, we determined the percentage for every simulation. For example, in the "Optimistic" situation, we determined that a tenth of the normal consumption in the original hour is going to be consumed in the recommended hour. We explain this process in Figure 10. In these simulations, we simulated the recommended system for a month. Thus, we can offer the quantity of money that the user can save in a month and how the consumption can change in the case that the user continued with the recommended consumption and the rate of acceptance that we estimated. For the simulation, we used the consumption prices collected with the "crawler module" and the data consumption from the UK-DALE dataset ([27]). Using this dataset, other researchers can improve this work.

We determined these percentages because it is well known that the usually recommended system has a low rate of acceptance, so we also considered low percentage for running the simulations.

Table 3. Different simulations and their percentages.

Simulation/Situation	Percentage
Optimistic	1/10
Neutral	1/20
Probable	1/40
Pessimistic	1/50

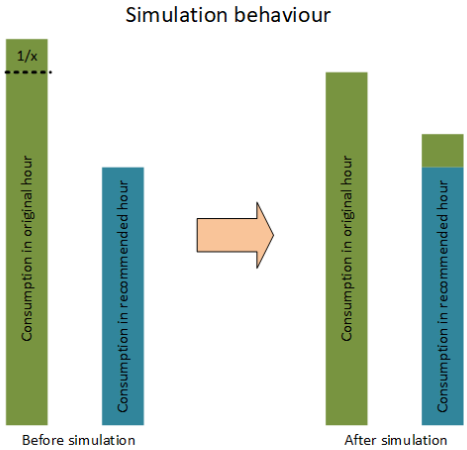

Figure 10. Simulation behavior.

Consequently, we ran the four different simulations and we estimated what the client could save. With every simulation, we could achieve the median value that the user could save in a month. Therefore, first, we estimated these values with the mean consumption every hour. The savings in the different situations are illustrated in Figure 11 and in Table 4. Table 4 also shows the total consumption in kWh during the simulation month. It can be observed that the most optimistic situation is the one that also saves more money. The other simulations' saving decreases proportionally. Further, in Table 5 we represent the return on investment (ROI). We considered that in this case of study, it is important to show in which moment the user receives a real economic benefit. As can be shown in the table, the return on investment is a very long period of achievement. This is due to the great number of electronic devices that the system monitored (32 devices). Therefore, we considered that in a normal home, the number of devices will be reduced significantly. However, in future lines of investigation, we will discuss the possibility of providing recommendations based on potential financial saving, so the number of monitored devices will decrease as well. Furthermore, we will study the possibility of introducing new smart plugs, which will be cheaper than the original one, to the system.

Thus, with these representations, we demonstrated that the proposed system in this article provides an incentive to the user of the system, an economic incentive. By using this strategy, more users will respond in a positive way to the recommendations that the system generates, although, as we mentioned before, this goal is not the only one that our work intends to accomplish. By using these recommendations and their incentives, we tried to distribute the use of energy so there are fewer peaks in their consumption.

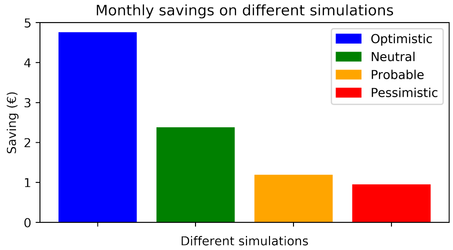

Figure 11. Savings on the different situation.

Table 4. Different simulations and their saves.

Simulation/Situation	Save (€)	Total consumption (kWh)
Optimistic	4.76	433.208
Neutral	2.38	433.208
Probable	1.19	433.208
Pessimistic	0.95	433.208

Table 5. Return on investment (ROI).

Simulation/Situation	Save (€)	Price of smart plug (€)	No. of smart plugs	ROI (years)
Optimistic	4.76	25.89	32	14.50
Neutral	2.38	25.89	32	29.01
Probable	1.19	25.89	32	58.01
Pessimistic	0.95	25.89	32	72.67

Then, if we compare the different simulations determined before and we determine how the consumption change in the case that the user follows the recommendations provided by the system, we see how the recommendations affect and modify the user's electrical behavior. In order to make these results more clear, we prepared a visualization of how the consumption change in every simulation compared to the original pattern of consumption. It is represented in Figure 12. There, we can see that the "Optimistic" is the one that changes more with regards to the "original consumption". This simulation generates a lot of peaks in the consumption line. This type of answer is not what we are looking for with the execution of this project. However, Figure 12 represents the new behavior of a single user, so even if this answer is not as good as expected, it will not have a big repercussion in the consumption of a huge community of users. Even if some users of this community implement this response, it could be good because it can distribute the energy consumption inside the community. The "Neutral" is similar to the "original consumption". As we can see, it reduces some peaks in the original behavior, and it modifies and generates a few peaks in order to reduce the electric bill. It seems that this type of simulation does not change the user pattern behavior a lot; hence, it could be a good answer for a user who wants to save some money at the end of the month. Once again, this behavior helps to distribute the use of energy during the day in the house where the system is installed and in a major scale in the community.

The other two situations, "Probable" and "Pessimistic", have a very similar behavior between them and the "original consumption'.' These are the behaviors that represent the most common answer for all users. Of course, they generate savings for the clients and also distribute the energy and reduce energy consumption peaks. It can be seen that during the morning and the afternoon/evening, they soften the peaks. Further, during midday, they reduce the peak produced at meal time. However, during the last hour of the day, they produce a little peak in order to save some energy in the previous hours. These two behaviors can change the energy consumption distribution in a community if they are employed by a large amount of users. Consequently, it is interesting to implement the presented system in a large community so we can see how the consumption distribution changes over time.

To sum up, with the proposed system, we obtained a multiagent recommendation system that is capable of obtaining consumption data with low-cost smart devices; collect information about electricity prices and, with these data, offer recommendations with an incentive to clients and users in order to save energy, save money, and distribute the use of energy in smart cities. Therefore, the established objectives of the work have been accomplished.

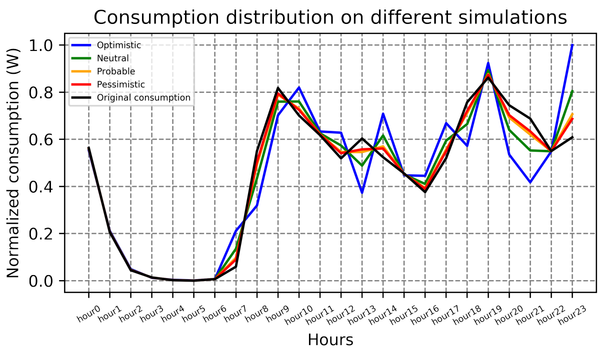

Figure 12. Consumption distribution on the different simulations.

6. Conclusions

This work presents a multiagent recommendation system for smart home electric energy optimization. The system proposed makes use of artificial intelligence in order to resolve a common problem in XXI century cities. The problem is energy optimization and energy saving. Therefore, this system proposes a solution to the problem that the European Union is trying to resolve, which is energy optimization and implementation of new smart systems that can transform actual buildings into smart buildings. This tested solution makes use of a multiagent architecture, data acquisition, data processing, and recommendation techniques. We used modern computer science techniques to resolve a modern problem.

The use of multiagent techniques allow us to make a more flexible system. Thanks to this architecture, we can create independent modules that allow us to do several tasks at the same time while every one of them works in continuous communication to achieve the global goal. This program construction also gives the possibility to add, modify or eliminate the new system's functionalities easily. This action is easy thanks to the agent, fragments of code which can be easily modified. This characteristic is very useful when we want to add new functionalities to the system.

Data acquisition and data processing are important factors for our system because all the recommendations that the system provides are based on information extracted from these data and from data mining. Our system is capable of extracting data from smart devices and also using information stored on the Internet to generate relevant recommendations to the user of the final system. Consequently, these two techniques play an important role in the presented work.

Finally, the use of recommendation techniques is the main contribution of the article. With these recommendations, we outlined a new solution for energy distribution and optimization. The recommendations are based on knowledge and utility. Therefore, the new recommendations are very related to the normal consumption of the user. In addition, we used recommendations with financial incentives. The use of this extra information makes it easier for the user to accept recommendations. Therefore, the recommendations provide the tool to distribute the use of electrical energy during the day. As we showed in Section 5, we achieved distribution of the consumption in the simulations that were carried out.

However, the system has only been tested in a theoretical case study and not in a real environment. This is an aspect that we have considered for future lines based on this system. There are several works of smart cities that have been developed by other authors ([28–31]) that do not include a module for energy optimization. Therefore, including the proposed system in a real smart city is a good chance to test it in different homes and by doing this, we can study the communication between the different multiagent systems so all of them work for the same purpose.

Another aspect for future lines of investigation is generalizing the system. In our case of study, we dealt with the Spanish one. In order to resolve this problem, we obtained data from Spanish electric consumption prices to generate a new dataset. Without a doubt, though, it would be very interesting to try the solution in other countries.

Additionally, the system should not be limited to a single smart plug device. In different countries, there are different popular smart plugs. Therefore, if our objective is to internationalize this system, we should implement a "devices module" for the more popular smart plugs. We must also consider that the recommendation system should also be based on the potential financial impact. With this strategy, the system could reduce the cost more, as well as the consumption peaks during the day.

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3.3.1 Summary in Spanish

Esta subsección muestra un resumen en castellano de los aspectos más relevantes del artículo científico titulado "*Multi-Agent Recommendation System for Electrical Energy Optimization and Cost Saving in Smart Homes*" que en castellano se podría traducir a "Sistema de Recomendación Multiagente para la Optimización de Energía Eléctrica y Ahorro en las Viviendas Inteligentes".

Research objectives

Durante la década de 2010 la Unión Europea ha decidido implementar una serie de medidas para luchar contra el cambio climático y tratar de minimizar las consecuencias que este tendrá para la generación actual y las venideras. Una de esas medidas es la de tratar de optimizar el uso de la energía siendo una de las líneas de investigación que tiene una mayor relevancia. Tanto es así, que la Unión Europea ha diseñado una nueva directiva para regular el rendimiento energético en los edificios. Este plan pretender obtener unos edificios mucho más eficientes enérgicamente y transformar los edificios en edificios inteligentes. Esta trasformación permitirá utilizar sensores y dispositivos que promuevan ese uso eficiente de la energía. Una posible forma de optimizar la energía es hacer un uso más equilibrado a lo largo del día y reduciendo los picos donde se produce un alto consumo energético. En este sentido, los datos que se producen en las viviendas inteligentes son de gran utilidad para extraer los patrones de comportamiento de los usuarios e intentar equilibrar su consumo a lo largo del día. Sin embargo, es fundamental considerar al usuario en esta tarea y promover su participación para lograr el objetivo.

En consecuencia, se propone la creación de un sistema que basándose en los datos de consumo generados por los dispositivos electrónicos de una vivienda sea capaz de ofrecer un beneficio económico a los usuarios y obtener un uso distribuido de la energía eléctrica. Todo el sistema está basado en el uso de los datos a través de los cuales se ofrecerán recomendaciones a los usuarios para promover el cambio del uso de cierto electrodoméstico de una hora a otra junto con un incentivo económico que se obtendrá gracias al diseño de un rastreador o araña web (en inglés *crawler*) que recogerá los datos de los precios de la electricidad. Consecuentemente se diseñará un sistema distribuido multiagente donde cada uno de los agentes trabajen de forma paralela pero coordinada para obtener la distribución del uso energético.

Así pues, los objetivos de investigación de este artículo son los que se describen a continuación:

- Investigación sobre dispositivos de medición de consumo en redes eléctricas.
- Investigación en sistemas de distribución del uso energético y en sistemas de recomendación a través de incentivos con el objetivo de diseñar un sistema de recomendación que distribuya el consumo de energía en las viviendas.
- Investigación y diseño de una araña web para la obtención de los precios diarios de electricidad en España.
- Creación de un sistema multiagente que recopile datos de los dispositivos de medición inteligente y que utilice esa información para realizar recomendaciones de ahorro teniendo en cuenta a su vez los precios de la electricidad.

Methodology

La metodología utilizada para la elaboración de este artículo científico es la ya explicada en la sección 1.2. No obstante, en esta subsección se explicarán cada uno de los pasos o aspectos relevantes tenidos en cuenta durante el proceso de investigación. Para ilustrar este proceso vamos a utilizar algunos de los pasos de la metodología AR.

- **Revisión del estado del arte**: en toda investigación científica es necesario analizar los trabajos previos realizados en el área de investigación de la hipótesis para analizarlas posibles mejoras o lagunas en el área y así poder proponer nuevos avances científicos. En este sentido se estudian las diferentes tipos de sistemas de recomendación haciendo especial hincapié en los sistemas de recomendación orientados a entorno *IoT* o entornos inteligentes. Del mismo modo y de cara a diseñar el mejor sistema inteligente para la vivienda se estudian aquellas características que según la literatura han de tener las viviendas inteligentes.

  Teniendo en cuenta estas características se estudian diversos estudios realizados en el ámbito de las viviendas inteligentes para la optimización del uso de la energía. Se observa que existen diferentes aproximaciones para resolver este tipo de problemas, de forma general todos ellos utilizan la información de consumo de los usuarios para obtener la distribución del uso energético. Sin embargo, existen dos corrientes en cuanto a modo de actuación se refiere, aquellas soluciones que automatizan este proceso y por tanto ofrecen una solución invasiva; y las que dejan en manos de los usuarios la decisión final, ofreciendo de esta forma una solución no invasiva.

- **Análisis y diseño de la propuesta**: analizando los estudios realizados y siguiendo las características y beneficios que han de cumplir los sistemas inteligentes de las viviendas inteligentes se ha propuesto un sistema multiagente que hace uso de dispositivos de medición baratos junto con una araña web para realizar recomendaciones que reducen la factura del usuario así como distribuye el uso energético a lo largo del día. El sistema está compuesto por tres módulos principales, el módulo de dispositivos, el módulo de las arañas web y el módulo de recomendación. Además, existe un módulo de control que controla estos módulos. El módulo de dispositivos se encarga de obtener los datos de consumo de los dispositivos y de guardarlos para la utilización de otros módulos. El módulo de la araña web se encarga de obtener los datos de los precios de la electricidad en las diferentes franjas horarias de forma diaria. Y, por último, el módulo de recomendaciones se encarga del procesamiento de datos, extracción de comportamientos y generar las recomendaciones en base a esos patrones y el algoritmo de recomendación diseñado generando de igual forma el impacto de las recomendaciones en la factura del usuario.

- **Definición del caso de estudio**: para probar la propuesta es necesario diseñar un caso de estudio que la valide. Para este artículo se ha diseñado un caso de estudio español. Primeramente, se ha decido utilizar un enchufe inteligente para la obtención de los datos de consumo de los dispositivos electrónicos. No obstante, y de cara a que otros investigadores puedan repetir y/o mejorar el experimento para validar el sistema se ha utilizado el conjunto de datos "UK-DALE" que contiene datos de consumos de diferentes viviendas y diferentes dispositivos. Para este caso de estudio se utiliza una de las viviendas que tiene un total de 52 dispositivos electrónicos. El siguiente paso es definir aquellos electrodomésticos que pueden sufrir modificaciones en su uso (una nevera no puede sufrir cambios, pero por ejemplo si una aspiradora) y cuanto se puede modificar su uso, en un corto periodo de tiempo o en un largo periodo de tiempo. Por último, en el caso de estudio también se define la información que se recopilará por la araña web para obtener los precios diarios de la electricidad en las diferentes horas del día.

Results

Los resultados de la investigación se dividen en tres partes. Primeramente, el estudio sobre la eficiencia de la recolección de datos; en este sentido el sistema y la arquitectura propuesta no ha mostrado debilidades a la hora de obtener los datos de consumo en una vivienda de tamaño grande. Por lo que le módulo de dispositivos funciona correctamente. Del mismo modo, el módulo de la araña web funciona perfecta obteniendo un conjunto de datos que contiene los datos de los precios de la electricidad de 72 días.

El tercer aspecto para evaluar es las simulaciones llevadas a cabo en el módulo de recomendación. En este sentido se han diseñado diferentes estrategias para simular la respuesta de los usuarios a las recomendaciones realizadas por el sistema de recomendación. Analizando los resultados de las simulaciones con estas estrategias observamos que todas ellas consiguen ofrecer beneficios económicos a los usuarios, así como distribuir el consumo a lo largo del día. Evidentemente las soluciones más optimistas ofrecen un ahorro mayor, pero por el contrario producen nuevos picos en el consumo energético. Sin embargo, esta respuesta no es tan mala como puede parecer en un principio pues si diversos usuarios de una comunidad la aplican la distribución de costes puede ser efectiva consiguiendo una distribución del uso energético a nivel de comunidad. Las estrategias más pesimistas por el contrario consiguen reducir los picos del consumo original y al igual que las optimistas si se aplican a nivel de comunidad pueden lograr el objetivo de la distribución energética.

Conclusions

Tras concluir la investigación de este artículo científico se ha obtenido la creación de un sistema multiagente que trabaja con el objetivo de distribuir el uso de la energía a la largo del día y así reducir los picos que se producen en ciertos momentos del día. Del mismo modo, el sistema proporciona un beneficio económico para los usuarios a través de las recomendaciones sugeridas. Es importante mencionar que el sistema diseñado sigue los beneficios que todo sistema inteligente ha de tener en un entorno IoT y que además se trata de un sistema "no invasivo" en el sentido de que delega la responsabilidad de tomar las decisiones en el usuario de esta forma no se ve limitado si el sistema decide apagar un determinado electrodoméstico o dispositivo.

Por último, como líneas futuras se plantea probar la situación completamente en un entorno real a la vez que tratar de ampliar el sistema para que sea utilizable en otros países, ya sea implementando nuevas arañas web para la obtención de los precios de la electricidad y poder generar el incentivo, así como ampliando la solución a un mayor número de enchufes inteligentes populares.

3.4 Central Heating Cost Optimization for Smart-Homes with Fuzzy Logic and a Multi-Agent Architecture

applied sciences

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Article

Central Heating Cost Optimization for Smart-Homes with Fuzzy Logic and a Multi-Agent Architecture

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Abstract: Recent years have defined the need to reduce gas emissions to fight climate change, and society's move to green energies is important to make responsible use of non-renewable energies. Therefore, it is now important to use technologies to optimize the use of actual energy sources. In this aspect, the Internet of Things (IoT) technology has had a great impact on society. Hence, this research work aims to use IoT technology and multi-agent systems to optimize the use of central heating installation in buildings. It is intended to improve the user's comfort, reduce the consumption of energy and reduce the financial costs. Therefore, a multi-agent system is proposed to collect data from sensors located in a smart-home and obtain the best action to perform in a central heating system. The decisions will be taken by an intelligent agent based on fuzzy logic. This technology will allow for generating the control action with a fuzzy controller. The results obtained show that the proposal improves the actual system in terms of users' comfort and financial and energy savings.

Keywords: central heating; control and automation systems; fuzzy logic; gas emissions reduction; multi-agent system; optimization; smart-home

1. Introduction

In 2019, the debate was climate change, and during that year, several conferences took place in different parts of the world, like COP25 (Conference Of Parties 25), Climate Action Summit 2019, and Youth Climate Summit 2019 [1]. These conferences were able to grab the attention of the greatest media communication platforms and, therefore, the attention of the population. The last statement may make a difference in this debate that has been postponed for decades. People are aware of the risk that future generations will have. Therefore, not only political conferences but also social conferences took place last year [1,2] in which environmental organizations and activists explained the risk and consequences of continuing this type of lifestyle. These people had a great impact on the communications media, which was supported the selection of the Swedish environmental activist Greta Thunberg as "Time Person of the Year" [3], only the second woman to receive this recognition on her own after Angela Merkel in 2015 [4]. The concession of this award to an environmental activist supposes the recognition of the importance of climate change or climate emergency, principally because this award is usually related to important international politicians.

Unfortunately, governments do not have a common agreement to preserve the global environment. Some governments are aware of the critical situation and try to do whatever they can to fight global change. However, these actions are not enough if the most important and polluting countries are against green policies. Therefore, future years and future agreements will determine the future of the Earth. Meanwhile, as mentioned before, some countries have determined that the climate emergency can no longer wait. This is the case with the Spanish government, which recently established a state of climate emergency in order to reduce their gas emissions and obtain a state of zero emissions by 2050 [5]. The location of Spain makes it the ideal country to produce green energy [6]. However, the transition must be progressive, which means that the first steps are to reduce non-green energy and introduce more green energy little by little.

However, during the last decade, not only has climate change had an impact on citizens but also the Internet of Things (IoT). This technology has a great impact on cities, homes, and industries by making it possible to monitor the state of these kinds of infrastructures. IoT allows monitoring the state of living beings, like animals, plants and even human beings. IoT technology consists of placing sensors on a real environment in a distributed way. The sensorization of the environment allows the system to obtain data, and, therefore, information from those entities that the developers of the system want [7]. The information can be processed in the sensor itself (edge computing) [8], or it can be processed in a central system (cloud computing) [9]. In both computing models, data travels from the edge to the cloud; the difference falls on the amount of information/data transferred. Edge computing transfers less data, usually the most relevant, while the cloud computing model usually transfers all the information captured by the sensors. This information is the key to the IoT system. Information is not only useful to monitor the state of the system, but it is also important to act in the system, detect anomalies, and predict the future state of the system between other actions. Hence, the possibilities in this kind of system allow developers to create the perfect system to resolve a real-world problem. It is especially interesting for this article that the information acquired by the sensors or sensor network can provide information on the real context and/or environment in which the sensors are installed. This information can be of great interest for the systems because they can interpret the measured values and associate them with more understandable values for the users of the systems.

Therefore, IoT, smart-cities, and smart-home technologies can be extremely useful to improve the effectiveness of industrial systems. This effectiveness can also lead to sustainability effectiveness. Hence, the use of this technology can reduce pollution and greenhouse emissions. The monitorization of several features in this kind of system or architecture can help the developers and the Artificial Intelligence (AI) models to improve the effectiveness of the systems and consume less energy. IoT and AI work together; IoT can extract the raw data from a real environment, and AI is responsible for extracting all the knowledge and information from the raw data. So, both AI and IoT are, in fact, responsible for effectiveness and pollution reduction [10]. This study makes use of the fuzzy logic that is capable of interpreting the values read by the IoT devices to infer an output that will be a control action that will be triggered on a heating system with the aim of reducing cost and harmful emissions. These technologies can help to implant a progressive plan in order to achieve zero non-green energy emissions. The first step of this plan usually consists of reducing non-green energy emissions while green energy infrastructures are being implemented and introduced in the energy production system. In this way, control systems that are usually responsible for turning the system on/off and/or regulating other aspects of the system like, for example, flow regulation could help to achieve this first step.

As mentioned before, IoT systems are hardware distributed systems in which the different sensors used by the system and even the gateways are distributed in a real environment. This environment can be small or big; this characteristic depends on the problem or real system that the developers want to resolve. However, the crucial thing here is that the system has several components distributed over the area of the system. These hardware components will be controlled by software. Therefore, it is considered that the best software solution for this kind of hardware system is a distributed software system. In particular, a Multi-Agent System (MAS); MAS is a kind of distributed system that is composed of different entities or agents [11,12]. Usually, these agents represent real entities of the world, entities like the sensors of an IoT system. This characteristic is one of the keys that make MASs an ideal solution for IoT infrastructures. However, more advantages of MASs will be explained in future sections.

Hence, with all this information and taking into account that a lot of big and medium cities in Spain still have homes and buildings with central heating installations, it is crucial to develop and research a system that can optimize the use of these old installations while they are replaced with modern ones. This is important given the new policies established in society that aim to reduce energy consumption and gradually introduce green energy; while this transition is developing, proposals like the one presented in this article are important. Therefore, a control system based on MAS architecture and fuzzy logic is presented to optimize the use and reduce the energy consumption of old central heating systems. Data will be collected from sensors that will be integrated into the multi-agent architecture, promoting the correct behavior of the different agents in the system to promote energy savings in the heating system. With the solution presented in this article, it is expected to reduce consumption and, therefore, the emissions of these kinds of systems during the winter months.

The rest of the article will be divided as follows: Section 2 will introduce the most relevant works developed during the last years in this research area, Section 3 will define the proposed system presented in this article, Section 4 will explain the case of study defined in order to prove the effectiveness of the proposed system, Section 5 will show the result obtained from the study and their discussions and finally, Section 6 is where the conclusion of the work and future lines of research will be explained.

2. Background

In this section, the different works developed in the different areas involved in this scientific research during the last years will be analyzed. This section will be divided into different subsections to analyze the different areas of research properly.

2.1. IoT and Smart Environments

The Internet of Things has been defined in different ways since it first appeared. However, almost all the definitions share the same idea. IoT can be defined as an interaction between the physical and digital world, where both of them work together to achieve a common goal. The communication between these two worlds is provided by sensors and actuators. These physical elements have computing and networking capabilities that allow knowing and even changing the state of the element [13–15]. These elements that established the link between the real and digital world are connected between themselves and also with a central system. These communications are enabled thanks to several communication protocols like Wi-Fi, Low Power Wide-Area-Networks (LPWAN), Bluetooth Low Energy (BLE), Near Field Communication (NFC), ZigBee and Z-Wave, among others [14–16]. Therefore, IoT technology can be implanted in every physical environment, creating a smart environment.

Hence, the application of IoT in industry results in the creation of Industry 4.0. This supposes a new revolution in the industry field. The Internet allows for creating smart products, smart production and smart services [17] thanks to the collection and analysis of real-time data to optimize the decision-making process. Industry 4.0 was related to the use of cloud computing [18]; however, in the last years, fog [19] and edge [8] computing has had its impact in the field. This evolution is possible thanks to the increase in computing capacities of small technological devices, like the sensors and actuators themselves.

Several works implement Industry 4.0 principles to obtain sensorized industries that facilitate the employees' tasks or obtain the best products or results. For example, the study developed by Scheuermann et al. [20] shows how a software agile methodology is transferred to an assembly line. This new application of the agile methodology allows for applying a change of the customers during assembly time. On the other hand, Schlechtendahl et al. [21] show how a non-Industry 4.0 factory can be transformed into an Industry 4.0 factory. They describe how to include the sensors and actuators in the existing environment and establish communications with the gateways and the central software system. Ang et al. [22] demonstrate how a computer design of a smart ship allows integrating Industry 4.0 in the ship design process and the ship's through-life. Another important concept in Industry 4.0 is the digital twin that represents a digital image of a real industry [23]. This concept helps, for example, to detect possible failures in industries.

Another important application of IoT is in cities. Smart cities used IoT technology in order to communicate the infrastructures of a city with software. Smart-cities appeared to respond to more economically, environmentally and socially sustainable cities [24]. There are several infrastructures of this time developed in different cities. Latré et al. [25] have developed the "City of Things," a testbed for IoT and smart-cities with distributed nodes in the city of Antwerp. In the Spanish city of Santander, Sánchez et al. [26] have developed another testbed for smart-city experimentation.

Smart-buildings and smart-homes make use of IoT to control or monitor the inside situations of the buildings. The idea is that the building's users can easily monitor and control home devices/appliances or situations. Therefore, several devices, sensors or actuators are going to be connected to the network using the mentioned protocols [27]. Several smart-home implementations have been performed in the last years. In 2015, Ghayvat et al. [28] deployed several sensors over a home to obtain a smart-home environment that could forecast the wellness of an individual and monitor her/his physical activity around their home environment. Mano et al. [29] have developed a Health Smart Home (HSH) that can identify the emotions of patients that are being treated in their homes with the purpose of monitoring patients. This research can support the development of IoT technologies. Datta et al. [30] developed another HSH where researchers can monitor the physical parameters of the patients to provide more personalized healthcare. Apart from HSM, another relevant aspect that is increasing in smart-home design is sustainability. Several works have been published during the last years. Chang et al. [31] have developed a unified energy management framework that can use renewable energy to reduce the impact of non-renewable impacts on the environment and also reduce electricity bills. Other researchers [32] have developed another smart-home that can also reduce the amount of energy used in the home thanks to the AI module that allows appliances to be used more sustainably. Furthermore, Karmakar et al. [33] developed dynamically controlling exterior and interior window coverings to determine their state and apply a control action to heaters, air conditioners, etc.

However, this research usually has a common problem. The lack of interoperability is considered as one of the most important barriers to achieving the integrations of IoT environments in real infrastructures. The different disciplines, vendors and standards make it even an even more complicated task [34]. Therefore, the proposal addressed in this article may help to resolve this problem.

2.2. Control and Automation Systems

Control and Automation Systems (CAS) have been present for more than a century [35]. They are present in our more common automated tasks. CASs can provide a response based on the inputs of the system. Therefore, they are commonly used in big industry systems and automated systems in several kinds of installations, like a heater or freezing system in buildings and homes. There are several types of CASs: proportional controllers, Proportional-Integral controllers (PI), Proportional-Integral-Derivative (PID) controllers and fuzzy controllers. PIDs are very common in industries solutions; however, fuzzy controllers also offer good performance and allow them to control several variables at the time that they produce a unified response.

Fuzzy systems are based on fuzzy logic. This was first proposed by Zadeh [36] in 1965. In this research, Zadeh proposed the basic principles of fuzzy logic, representation and inference, basic rules of inference and the linguistic variables and its applications to fuzzy control. Several works have used fuzzy control systems. Next, some of them are described briefly.

Mier et al. [37] designed a fuzzy adapted method to improve the response of a scalar fuzzy control system for the speed of an induction motor. They demonstrated that the use of an adaptive fuzzy controller shows improvement against the non-adaptive fuzzy controller. However, the fuzzy control systems are not only applied to classic control problems. They are also applied to the smart-environments that surged after IoT technology appeared. Garg and Kaushal [38] designed a traffic light control system using a Wireless Sensor Network (WSN) and fuzzy control. For this specific case, the authors designed four fuzzy controls that work in parallel to obtain a better performance, fault-tolerance and support. Their results support the system that allows the vehicle's waiting times to be reduced. Another example of fuzzy logic applied to a smart-environment, in this case to Industry 4.0, is the study developed by the Chinese and Norwegians researchers Huo et al. [39]. The study shows a fuzzy control system analyzing the real-time data information of an assembly line. The fuzzy system has two different fuzzy systems: the first one controls the re-balancing of the assembly line, and the second one adjusts the production rate of each workstation. Azaza et al. [40] also developed a smart-home fuzzy control system, in this case, for a greenhouse. They tried to promote a comfortable micro-climate for plants while saving energy and water. For this reason, they developed a smart fuzzy logic control system that uses wireless data monitoring to obtain the output of the system.

Several works have used fuzzy logic to control heating systems [41–43]. The studies [41,42] show a fuzzy controller implemented in an 8-bit microcontroller. The fuzzy logic control is based on the definition of an engineering heuristic to determine the boiler temperature. So, the output of the system is based on a heuristic, not real data. The study [43] defines a fuzzy controller in which only the difference between the current temperature and desired temperature is taken into account. This study collects the data from the current temperature inside a building or house; however, this value is usually integrated into the heating systems. However, these works do not make use of all the potential and options offered by the sensor networks, which could obtain data in real-time and apply it to the fuzzy control system. One of the major advantages of sensor networks is to obtain data intelligently from heterogeneous data sources that can extend the capabilities of the system and improve its performance. In this sense, the work presented must obtain information of the context where the system is located using different types of sensors and make it available to the fuzzy control system. Moreover, with these technologies, it is possible to establish a balance between user comfort and energy saving.

2.3. Multi-Agent Systems

The sensorization of cities, homes and factories, among other infrastructures, allows the deployment of distributed systems. A computer system is needed to manage these complex systems. Due to the nature of these systems, the natural choice is to develop a distributed computer system capable of administering the system. Therefore, MAS offers a valid solution for this new trend.

A distributed system is the main characteristic of a MAS. Every agent is independent of the others, making their own decisions and performing their goals. However, this is not the only characteristic of a MAS; other features are listed below [44]:

- Flexibility allows the system to change against agents' and the environment's modifications.
- Adaptability enables it to change the behavior or actions of the agents easily.
- Scalability is the ability of MASs to add new devices to their structure.
- Leanness is the feature that establishes a difference between agents but without incrementing the categories of agents.
- Resilience allows obtaining the community goal, even if an agent fails or is corrupted.

Thanks to these characteristics, the MAS has become an excellent solution to control and manage IoT infrastructures.

Other researchers have taken this into account; hence, they have developed multi-agent architectures in the IoT field. Recently, Spanish researchers Francisco et al. [45] have created a distributed model predictive control based on a multi-agent system. They see MAS properties as the perfect solution for the distributed model predictive control that uses fuzzy logic to resolve their case of study. However, this multi-agent architecture is not useful in other IoT infrastructures since its implementation is mainly focused on the case study addressed in the paper. Therefore, this MAS cannot be applied without changes in their structure to another case study or IoT environment. The same problem occurs in a framework designed by Maleš et al. [46]. This solution proposes a multi-agent system with deep learning techniques to allow face tracking. The solution is focused on resolving the IoT problem, but the proposed MAS does not record the video sequence by itself, another subsystem is responsible for that task.

Hedjazi et al. [47] propose a solution for maintenance scheduling in industry 4.0 using a MAS. The MAS enables decision-making and promotes competition between the different agents to obtain the global good. The MAS implements a different kind of agent; however, none of them are connected to a smart device or sensor in the industry. On the other hand, Wang et al. [48] have also developed a MAS for Industry 4.0. This solution provides a full solution for this kind of IoT area. The proposed framework is divided into four layers, every one of them with different kinds of agents. Nonetheless, the framework does not include a layer or module to obtain data from the Internet. Researchers from the United Kingdom and the United States of America, Salvador Palau et al. [44], have developed another MAS for Industry 4.0. Same as above, the MAS is well-designed for the Industry infrastructure, but it does not provide a global alternative.

Similarly, Modoni et al. [49] have carried out a study in the context of a MAS carried out in JADE (Java Agent Development framework) to obtain information from a network of sensors inside a smart home and to monitor the home and its users.

Another area in which the agent's theory has a lot of influence is in smart-grids and micro-grids. Proof of this is the study elaborated by Karavas et al. [50], who developed a MAS for the design and control of autonomous poly-generation microgrids. According to the authors, a decentralized system is a right solution for this kind of system. Hence, the agents help to perform a perfect distributed system, although the presented MAS has a simple architecture with only five agents and it does not have modules to distinguish between different kinds of agents. Modules help to make a difference between agents of the same type, so it is easier to scale the system.

Recent work from the University of Málaga's (Spain) researchers, Ayala et al. [51], has established a global solution for a multi-agent architecture in the field of IoT. To test their proposal, they created the "GreenManager system," a MAS oriented for smart-homes and power consumption management. They have created several agents that oversee the electronic devices of the house and a "Green Manager Agent" that acts as a supervisor agent. This agent is the one that controls the whole system. It knows when to send a request to a device agent according to the information that it receives. Therefore, the authors apply the MAS to reduce the electric consumption of houses during the peak hours where the electricity is more expensive.

Therefore, in this article, a fuzzy control system based on a multi-agent platform is proposed to control the effectiveness of home and building central heating systems. The main contributions of the paper are listed below: (I) the proposal of a self-designed MAS for IoT and smart-environments, (II) the communication behavior between the MAS's agents, (III) the collection of sensor data recollected by intelligent agents and (IV) the design of an intelligent control system based on fuzzy logic principles. In the next section, the proposal will be explained in more depth. Table 1 shows a comparison between the proposal and other similar studies. Some of these research studies have been explained before. The study [52] defines a non-linear mathematical model that takes into account information from several sensors inside and outside the home that can produce control of the heating system in small buildings and homes.

Table 1. Studies comparison.

Study	Has MAS	Collects Sensors Data	Uses Fuzzy Logic
[41]	✖	✖	✔
[42]	✖	✖	✔
[43]	✖	✖	✔
[52]	✖	✔	✖
This study	✔	✔	✔

3. Proposed System

As discussed in the previous section, the main contribution of this research article is the multi-agent system for central heating cost optimization in smart-homes. Multi-agent technology provides a

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distributed architecture. The distributed architecture is composed of different agents. Every agent performs their task. However, the agents work together to accomplish the final goal of the system. Therefore, one of the most important features of MAS is that every agent works in a coordinated way. MASs have other advantages that, together with the features mentioned in the background section, make MASs an ideal solution. These advantages are mobility, the dynamic behavior, and the high level of communications through the transparent management of the message queues. The system is developed in the Python programming language. To construct the MAS, SPADE Python's library [53] was used. Smart Python Agent Development Environment (SPADE) is a Python library developed by Gregori et al. [54,55] that allows for creating a multi-agent platform based on instant messaging (XMPP). Other alternatives were evaluated, such as JADE [56], PANGEA (Platform for Automatic coNstruction of orGanizations of intElligent Agents) [57,58], AIOMAS [59] and osBrain [60]. However, SPADE was selected because its focus on the Python programming language allowed it to be easily integrated with the simulation model that will be explained later. On the other hand, Python is one of the most relevant languages today and is especially focused on data processing. This means that the system can be improved in the future by other researchers. Hence, when a SPADE's MAS is deployed, its agents run their tasks in an XMPP server to establish the communications between them. This characteristic is outstanding for the SPADE platform. So, with the use of this software, it can develop a MAS that is going to be deployed in a central system. Consequently, some of the agents of the designed platform may be connected with physical objects through the specific communication protocol.

The architecture designed for this article is shown in Figure 1. Proposed multi-agent system. One of the main characteristics of the proposed architecture is that the agents are divided into different modules which establish a difference between the agents. It is assumed that the agents that belong to the same group could be similar or work together in order to obtain a sub-goal of the system. With these modules, it is easier to include, delete or modify agents. Furthermore, the different modules, agents and communication between agents will be explained in the following subsections.

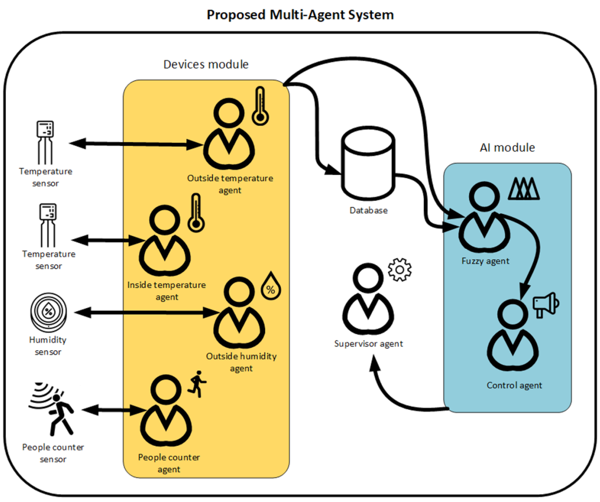

Figure 1. Proposed multi-agent system.

3.1. Supervisor Agent

The supervisor agent is the agent that controls and supervises the rest of the agents. It is in charge of initiating the rest of the agents. It controls and verifies that all the agents do their tasks. Agents have an associated behavior that defines how they are going to perform their tasks. Different kinds of behaviors exist, like one-shot behavior, cyclic behaviors and periodic behaviors between other more complex behaviors [61]. The supervisor agent has different types of behavior: (I) a one-shot behavior to initialize the agents at the beginning of the MAS initialization, (II) a periodic behavior to check that the rest of the agents are still active, and (III) a cyclical behavior to receive messages from the AI module agents. After performing the simulation, which is its main task, the agent ends its behavior and, therefore, its activity, ending the execution of the program and the MAS.

3.2. Devices Module

The devices module is one of the two modules in which this proposed architecture is formed. This module contains the sensors' agents. Every module inside this architecture will be connected to a specific sensor through the specific protocol. The number of devices agents will depend on the number of circumstances that the central system wants to control or measure. In the current proposal, the system will have four different device sensors. These four sensors are listed below.

- Outside temperature agent: the proposed system will include a temperature sensor located outside the home or building to obtain the temperature in the closest possible environment to the building. The use of a crawler agent and a crawler module were considered in obtaining the outside temperature. This module would connect itself to the Internet to obtain the temperature. However, usually the sensors that different webpages use are located outside the cities. Hence, temperature values could not be as reliable as expected.
- Inside temperature agent: the system will also include a temperature sensor inside the house to know if the control system achieves the comfort temperature. There could be as many temperature sensors as the user wanted (for example, one per room). However, in this case, the mean temperature of all rooms will be considered. It is important to obtain the inside temperature since the control system will determine its action taking into account this value as we will see.
- Outside humidity agent: another aspect that is important to consider when a control system wants to maximize the user's comfort is the humidity. Since the user is going to be inside the building, the proposed system will only consider the outside humidity; inside humidity will depend on the aimed temperature.
- People counter agent: the control system will also be informed if there are people or not inside the building, so no energy is wasted at all. The control system will consider this information and will only turn on the system when there are people inside the building. Different kinds of sensors can be used for this purpose, from simple ones like PIR (Passive InfraRed sensor) sensors or presence sensors to more sophisticated sensors like thermal sensors or optical sensors. Furthermore, we can collect the total number of people inside the house or just if there is someone inside the building. The definition of this sensor could change, depending on the circumstances evaluated in the study case. However, the result will be the same, to know if there are people or not inside a building.

All these agents work in very similar ways. As it is logical, each one of them will be connected to a different sensor, but its operation is practically identical. All of them have a cyclic behavior in which they obtain the current data that the sensor is measuring. Depending on this value, the agent will act in an intelligent way and will determine the most convenient action, even changing its behavior. All the agents share a common characteristic; they have a small temporary memory that stores the last n values measured by the sensor and collected by the agent. The value of the variable n is totally configurable; for this proposal, we have selected a value of $n = 50$. This temporary memory will be used with two purposes: (I) to check that the current measured value is not an extreme value (Equation (1) is used for this purpose) and (II) to check that the current measured value is not equal to the last $n/25$ values available in the temporary memory. If the purpose (I) is fulfilled, the value is automatically discarded, and it is not saved in the system database, the agent temporary memory, nor sent to the fuzzy agent. Once checked (I), if it is also fulfilled (II) the agent intelligently increases the waiting time to take the next value, understanding that the values are stable, and it is not necessarily a constant consultation to the sensor. In this way its activity and energy reduces consumption. The more times this situation occurs in a row, the longer the waiting time will be. In addition, the value will be stored in the temporary memory but will not be stored in the system memory or sent to the fuzzy agent. When the agent detects again a change in the measured values, it will return to its normal activity, send data to the fuzzy agent and store them in the global system database.

$$extreme\ value \Leftrightarrow x > mean(X) + std(X) \cdot threshold \quad (1)$$

where x is the current measured value, X is the set of values stored in the sensor agent's temporary memory, $mean(X)$ is the average of the values of the set X, $std(X)$ is the standard deviation of the values of X and *threshold* is a defined value; in this case, the value 3 has been used.

3.3. Artificial Intelilligence Module

This module will be the brain of the system. It is going to use the information collected by the previous module and transmitted by the supervisor agent to evaluate all the variables and obtain the appropriate output for the present situation. So, the agents present in this module will be described as follows:

- Fuzzy agent: this agent will be the key to the control system. It includes a fuzzy control system that can use the information collected by the sensor agents and generate a control action that will be sent to the system. Inside it, the rules and membership functions of the different variables will be defined, so the appropriate control action can be resolved. It receives the data from the agents in the sensor module to carry out the control action. This implies that it is listening to this group of agents. However, if any of them are not sending measurements because the values do not change or because the agent has fallen, the agent will pick up the last record stored by that agent from the database. When this circumstance takes place, a message will be sent to the agent supervisor to check that the agent is still active. This agent has a periodical behavior since it will not be constantly generating an output to be applied in the heating system.
- Control agent: the last agent is the control agent, which is responsible for setting the control action defined by the fuzzy agent and informing the supervisor agent that an action has been set in the physical system. The behavior of this agent is very simple, but its importance is crucial since it is in charge of changing the state of the system. As the agent has to be listening to the message sent from the fuzzy agent, its behavior will be cyclic and will perform its task every time it is required.

3.4. Communications between Agents

In these subsections, the behavior of the system will be explained. How agents communicate with each other will be explained in detail.

The proposed architecture is based on different modules, and every one of them is specialized to a different task or goal. However, the proposal is also based on the communication between the different modules, so they can share the results of their objectives to solve the common problem together. The communication between agents and modules is also a basic behavior of MAS.

Once the system is deployed, the first agent that starts working is the supervisor agent. Once the supervisor agent is started, its first task is to start the rest of the agents of the system. These agents include sensor agents and AI agents. Once the rest of the agents are initiated, they will begin to work as defined by their behavior. Meanwhile, the agent supervisor will periodically check that the rest of the agents are alive. If some of them have failed and have stopped being active, the agent supervisor will be in charge of activating that agent/s again. On the other hand, the sensor agents will work in the way defined in the previous section, recovering the measured values and evaluating this value to determine their action or if they should change their behavior. When the action is to send the measured values, these will be sent to the fuzzy agent.

Here, the fuzzy agent will be listening to the messages that can come from the sensor agents to obtain the values that will determine the control action to be done. If not all the values are obtained after a considerable time, the last values stored in the database will be used and the supervisor agent will be warned that something may have happened with some sensor agent. When all the values are received, the blurred control system will be initialized. The rules and membership functions will depend on the study case. Therefore, in Section 4, rules and membership functions will be explained and analyzed. Consequently, once the output is defined, the fuzzy agent will send another message to the control agent. This agent will apply the output to the physical system and once it is done, it will inform the supervisor agent through a message.

This process will be repeated as many times as desired. The most interesting approach is to run this process every, for example, five minutes to check if the environmental circumstances have changed since the last control action was performed and therefore, the control action has also changed. With this approach, the computational cost, as well as the impact on a real distributed sensor network, will be minimized since sensors will not be constantly sending data. This strategy will also reduce energy consumption since agents can sleep while this window of time is closed, decreasing the consumption of said agents as well as sensors. A lower interval is possible; however, the energy consumption of the system and sensors will increase. A higher interval is also possible, although the measured values may change during that time as it might affect the users' comfort. Consequently, it is considered that the appropriate interval should be set to five minutes. The whole process is illustrated in Figure 2 for a better understanding.

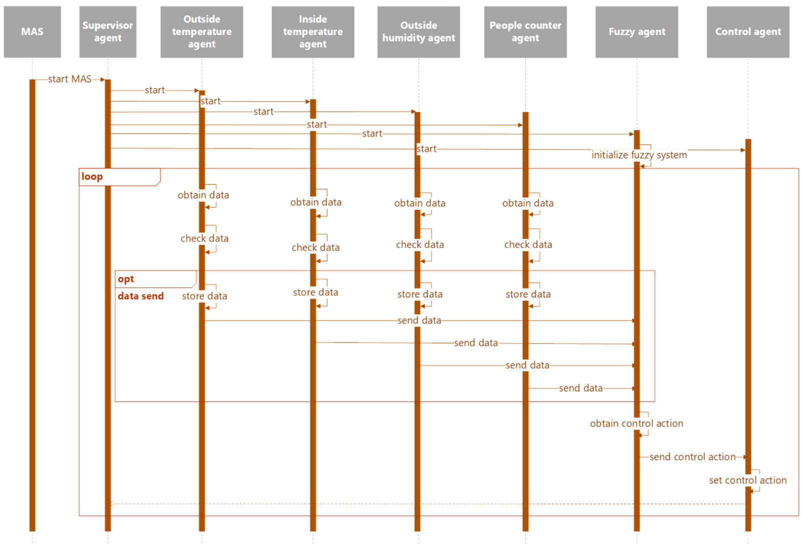

Figure 2. Communication behavior.

This communication between agents also leads us to evaluate the computational cost that the proposed system has. In general terms, the computational cost can be defined as follows in Equation (2):

$$O = (\sum_{i=0}^{n} s_i + m_i) + f + m_c + m_s \quad (2)$$

where O is the cost, i is the number of the sensor, s_i is the time consumed in obtaining the data from the sensor (this value will change according to the specific sensor and communication protocol), m_i is the time consumed in the message form one agent to another, f is the time consumed by the fuzzy system in obtaining the appropriate exit to the system, m_c is the consumed time in the request to control agent and m_s is the time consumed in the message from control agent to supervisor agent.

The cost associated to the operation of the test is the minimum possible, because, in order to carry out the system function, only those agents that are essential are used and with the lowest number of messages between agents possible. It is crucial that each agent works independently from the other in order to minimize the cost. In this way, the sensors' agents will be collecting the data and sending it when they consider it necessary so that the fuzzy agent determines the action to be carried out and this is applied to the heater. At the end of the process it is necessary to send a message to the supervisor agent so that it is aware that the function of the system has been carried out correctly and that it is functioning normally.

4. Case Study

A case study is necessary to test and verify that the architecture presented in Section 3 can achieve the goal of the paper. Therefore, this section will explain in detail the case study followed in this research. All the considerations, assumptions, and system specifications and definitions will be mentioned in the current section.

4.1. Baseline

In order to compare the results obtained with the proposed method it is essential to equate it with a common solution of the problem. Consequently, a baseline is required. Additionally, to test and validate the proposal and possible changes in the system, the simulations will be run in a virtual environment rather than in a real one. MATLAB's Simulink toolbox [62] has been used for this purpose.

There is a Simulink model that simulates the behavior of the house heating system [63]. The model mimics the behavior of a simple house heating system. It has a heater, a basic controller typically used in this kind of installations, and a house with four rooms and one radiator in every one of them. Each path inside the heating system is simulated as a combination of thermal convection, thermal conduction, and the thermal mass.

The controller implemented in the baseline is a proportional control that evaluates the actual temperature of the house regarding the aimed temperature, with an error of ± 2 °C, a 4 °C hysteresis. Hence if the actual temperature is higher than the aim one plus 2 °C, the controller does not open the gas valve; otherwise, if the actual temperature is lower than the aimed one minus 2 °C, it opens the valve. Equation (3) describes the controller behavior. As can be seen, the control seems to be very simple, but it is effective. Many heating controllers use this kind of controllers to satisfy the requirements of a house or building:

$$V_g(t) = \begin{cases} 1, & T_c < T_a - 2 \\ 0, & T_c > T_a + 2 \end{cases} \quad (3)$$

where $V_g(x)$ is the state of the valve at moment t, T_c is the current temperature, and T_a is the aimed temperature.

The heater of the system receives the fuel that the valve, regulated by the aforementioned control, supplies, and the water inside the thermal system and returns the same water but hotter thanks to the boiler effect. The boiler acts under constant circumstances of humidity and air. It can transfer the heat generated by the combustion to the water thanks to a heat exchanger [64]. So, the water that leaves the heater is much hotter than the one that enters it.

As mentioned before, the model of the house has four rooms, with one radiator in each one of them. These rooms receive the influence of the outside temperature that changes over time. In this approach, the external temperature is simulated using Equation (4):

$$T(t) = A \cdot \sin(F \cdot t + P) + b \tag{4}$$

where T is the temperature obtained at a specific time t, A is the amplitude of the sin function, F is the frequency (rad/s), P the phase (rad), and b the bias applied to the function.

To obtain the temperature values, the amplitude was defined to 6, the frequency to $\frac{2 \cdot \pi}{12 \cdot 3600}$, the phase to 0, and the bias to 5.

The radiators of the rooms transfer the heat in the water to the air. The model's rate of heat transfer is proportional to the temperature difference between the air and the fluid, the heat transfer coefficient (100 W/m^2 k), and the surface area in contact with the liquid (5 m^2). Every radiator in the system shares these properties. The convective heat transfer is defined in Equation (5). Furthermore, each room exchanges heat with its environment through its exterior walls, roof, and windows. In this model, it is assumed that rooms do not exchange heat between each other. The rooms have six different types of heat transfer: roof-atmosphere convection, roof-atmosphere leakage, air-roof convection, wall-atmosphere convection, wall-atmosphere leakage, wall-roof convection, window-atmosphere convection, window-atmosphere leakage, and window-roof convection. The heat transfer is additionally defined by Equation (5) However, in this case, some considerations must be taken into account. These concerns are described in Table 2:

$$Q = k \cdot A \cdot (T_A - T_B) \tag{5}$$

where Q is the heat flow, k is the convection heat transfer coefficient, A the surface area, and T_A and T_B the temperatures of the two bodies.

Table 2. Heat transfer convection coefficients.

Heat Transfer	Convection Heat Transfer Coefficient (W/(m^2 k))	Surface Area (m^2)
Roof-atmosphere convection	38	75.188
Roof-atmosphere leakage	38	75.188 · 0.1
Air-roof convection	38	75.188
Wall-atmosphere convection	34	Room's wall area
Wall-atmosphere leakage	34	Room's wall area · 0.15
Wall-roof convection	34	Room's wall area
Window-atmosphere convection	32	Room's window area
Window-atmosphere leakage	32	Room's window area · 0.2
Window-roof convection	32	Room's window area

Rooms, wall and window areas are defined in Table 3.

Table 3. Rooms, wall and window areas.

Room Number	Wall Area (m^2)	Window Area (m^2)
#1	95.6667	3
#2	83.3333	2
#3	72.6667	2
#4	59.3333	2

Consequently, these tables conclude the summary and explanation of the baseline used to compare the proposal presented in this article. Additionally, these tables include the Building Information Modeling (BIM) used for this study. This BIM is defined in MATLAB's model and our proposal will use the same one to compare both prototypes under the same circumstances. Given that the proposal presented is practically a software project that collects data from sensors distributed throughout the house and that these have their own power supply system or are connected to the house's electrical network, the system will not influence the house's construction standards. It will be implemented in already-built houses that have a central heating system. The only aspect to be considered is how to send the on/off signal to the boiler, but since each brand can use its own standard and this study focuses on the theoretical study of the proposed method, this will not be done.

4.2. Evaluated Proposal

Once the baseline has been explained, it is time to clarify how we evaluate the proposal described in Section 3. In the case study, the evaluated proposal does not differ a lot from the baseline. The model is very similar. The only thing that changes is the control. The control will be replaced by a fuzzy controller. Moreover, the MAS proposed will be included to evaluate the proposed method. However, Simulink does not provide a multi-agent platform. Therefore, it is necessary to implement a MAS outside the Simulink software. Fortunately, MATLAB (R2019a, The MathWorks Inc., Natick, MA, USA, 2019) includes a Python API that allows the use of MATLAB's features inside a Python program. Among these features is the ability to interact with a Simulink model prom Python code. So, the evaluated proposal, the MAS, and the fuzzy control will be built in Python and will interact with a modified version of the baseline. The following subsections will explain how the system was built for this case study.

4.2.1. MAS' Design

As mentioned before, the MAS is designed with SPADE. All the agents described before will be included in this case study. However, there are two groups of agents that need a deeper explanation in this research.

The first group is the devices module. In Section 3, it was mentioned that the agents will be connected to a sensor via the specific protocol. Unfortunately, the simulation does not have real sensors. Therefore, the sensor agents will establish a connection with a Simulink component that simulates a real sensor. These components will measure different processes over time and the sensor agents will be able to collect these values whenever they desire. So, for this case study, sensors will be replaced by Simulink components and the sensor agents will be able to obtain the values of this component thanks to the Python MATLAB's API. The MATLAB's API provides access to variables stored in the workspace. Therefore, these Simulink components update the value of the workspace variables so that in this way and using the MATLAB's API, the agents can access the current values of the simulation.

These components will simulate the values. The values will be replicated following the logic behavior of these components in the real world. The gap temperature shows the difference between the actual temperature inside the house and the desired temperature. This desired temperature is defined as a constant value, 23 °C. On the other hand, the outside temperature has to change over time. In this approach, the external temperature is simulated using Equation (4) as well.

To obtain the temperature values, the amplitude was defined to 6, the frequency to $\frac{2\cdot\pi}{12\cdot3600}$, the phase to 0, and the bias to 5. Another measured value is the humidity, this variable is also simulated with Equation (4). In this case, the amplitude was defined to 6, frequency to $\frac{2\cdot\pi}{12\cdot3600}$, the phase to 0, and the bias to 75; furthermore, the phase is set to π to simulate the logic behavior between outside temperature and outside humidity. The last measured value is the amount of people, in this case, the simulation is provided by random numbers in the interval [0, 10] that changes every 30 min.

The second group of agents is the ones included in the AI module. However, these agents will be explained better in the next subsection.

4.2.2. Control's Design

It is important to describe how the control has been designed. The fuzzy control and the communication of the output to the Simulink's model will be defined in this subsection.

The fuzzy agent will incorporate a fuzzy controller developed with the Scikit Fuzzy Python API [65]. The fuzzy model developed for this case study has four input variables and one output variable. The four inputs are related to the measured values of the sensors and the output value is the control action determined by the fuzzy logic. The fuzzy logic controller is based on Takagi-Sugeno architecture [66]. The main characteristic of this kind of fuzzy controllers is that the output of the control can be defined by the designer of the system. This kind of fuzzy system is considered to be the appropriate one for the current work since the output of the system should be "on" or "off" (one or zero). Therefore, the output of this fuzzy controller will not experience any fuzzification or defuzzification processes. On the contrary, other systems such as Mamdani assume that the output must be defuzzified, so that the relevant fuzzy sets would have to be defined and the output would be defined by one of these fuzzy sets and its value of belonging to the one that is active. This type of output is not the desired one in the proposed system, but we only want to obtain two values 0 to 1, off or on, respectively. This type of output is provided by the Takagi-Sugeno system that has been designed.

Therefore, in the designed Takagi-Sugeno system, the output does not need to be configured. However, the four inputs of the system have to be adjusted or defined to infer the fuzzy logic principles over them. So, the membership functions for each one of these inputs has to be defined. Table 4 collects all the information needed to delimit the inputs' membership functions. But first, the four inputs have to be described. The first input is "temperature gap," it is the difference of the aimed temperature and the current temperature value collected by the sensor agent. The second is "outside temperature," it is the current temperature value from outside of the building. "Humidity" is the humidity outside the building, and "people" indicates the number of individuals inside the house.

Table 4. Input membership functions definition.

Input	Input Universe	Input Intervals		Membership Functions' Type
Temperature gap	[−10, 10]	Negative	[−10, −8, −2, −0.5]	Trapezoidal
		Zero	[−1, 0, 1]	Triangular
		Positive	[0.5, 2, 8, 10]	Trapezoidal
Outside temperature	[−46.25, 74]	Very cold	[−46.25, −15, 5]	Triangular
		Cold	[3, 9, 14]	Triangular
		Warm	[14, 17, 20]	Triangular
		Hot	[19, 23, 27]	Triangular
		Very hot	[26, 50, 74]	Triangular
Humidity	[−41.67, 140]	Low	[−41.67, 0, 30]	Triangular
		Medium	[20, 40, 60, 80]	Trapezoidal
		High	[70, 100, 140]	Triangular
People	[0, 15]	Zero	[0, 0, 1]	Triangular
		Few	[0, 3, 6]	Triangular
		Medium	[4, 5, 7, 8]	Trapezoidal
		Lot	[7, 10, 13]	Triangular

Input universe refers to the space where the values of this input are going to be, although, if a value gets out of this universe, the fuzzy system can deal with it without any problems. On the other hand, input intervals refer to the different groups or fuzzy values that the input can have. The types of membership functions are defined as triangular and trapezoidal; trapezoidal functions are used in larger intervals with the aim of achieving greater membership during the whole interval, while triangular functions are selected for shorter intervals. To illustrate this information better, Figure 3 shows the definition of the membership functions:

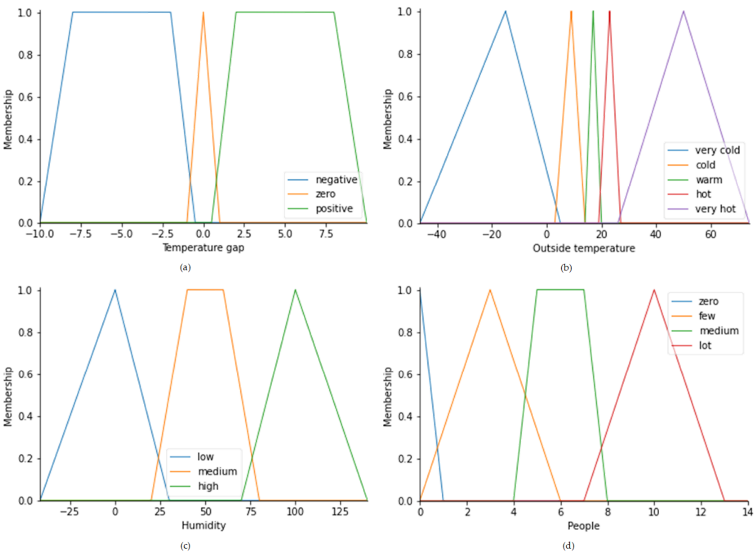

Figure 3. Membership functions. (**a**) Temperature gap's membership functions, (**b**) outside temperature's membership functions, (**c**) humidity's membership functions, (**d**) people's membership functions.

As shown in the previous figure, these fuzzy groups represent the membership functions of the system and they define when a value is of one type or another. These fuzzy groups, combined with a series of rules, will define the behavior of the fuzzy system. Rules will evaluate the values of the measured variables and their belonging to any of the membership functions so they can obtain the output of the system. The rules defined for the current case study are defined below. They try to summarize a logic behavior based on the user's experience and knowledge:

1. IF "temperature gap" IS "negative" OR "temperature gap" IS "zero" THEN 0
2. IF "temperature gap" IS "positive" AND "people" IS "zero" THEN 0
3. IF "temperature gap" IS "positive" AND "outside temperature" IS "very cold" THEN 1
4. IF "temperature gap" IS "positive" AND "outside temperature" IS "cold" THEN 1
5. IF "temperature gap" IS "positive" AND "people" IS "few" AND "outside temperature" IS "warm" THEN 1
6. IF "temperature gap" IS "positive" AND "people" IS "medium" AND "outside temperature" IS "warm" THEN 1
7. IF "temperature gap" IS "positive" AND "people" IS "lot" AND "outside temperature" IS "warm" THEN 0
8. IF "temperature gap" IS "positive" AND "outside temperature" IS "warm" AND "humidity" IS "high" THEN 1
9. IF "temperature gap" IS "positive" AND "outside temperature" IS "warm" AND "humidity" IS "medium" THEN 1

10. IF "temperature gap" IS "positive" AND "outside temperature" IS "warm" AND "humidity" IS "low" THEN 1
11. IF "temperature gap" IS "positive" AND "outside temperature" IS "hot" THEN 0
12. IF "temperature gap" IS "positive" AND "outside temperature" IS "very hot" THEN 0

In the previous list, 0 and 1 represent the output of the control system that is going to be applied to the physical system, off and on, respectively. With these rules, the control system infers the normal actions that users could take in their homes and buildings to promote sustainable use of central heating systems. In fuzzy control systems, the rules are usually implemented by experts; in this case study, the experts are the users of the system.

After the fuzzy agent obtains the appropriate control action, the communication will send this action to the Simulink's component to continue the simulation. Once the actions are sent and processed by the virtual system, the sensor's agents will measure the variables and the process continues until the simulation ends.

4.3. Simulations

After the baseline and the approach followed in this study are explained, it is time to run the simulations. However, it is also important to define the circumstances of these replications. In these subsections, these circumstances will be explained.

To test the proposed system, a deep simulation has been performed to assess the proposal during a long period. Hence, it will simulate the contaminated running of central heating for 50 h. With this approach, we will simulate the behavior and response of the proposal in almost all the possible conditions. Furthermore, it will be possible to better observe if the proposal allows for a reduction in the consumption of fuel and therefore a reduction of gas emissions to the atmosphere.

5. Results and Discussion

According to the experiments mentioned in the previous section, this segment will show the results of those experiments and the discussion of the results. The results will be divided into different subsections.

5.1. Multi-Agent System

One of the main contributions of this scientific work is the use of a MAS to coordinate different entities to achieve a common goal. The architecture proposed has shown to offer good performance in terms of communication between agents and the performance of every individual agent. The communication behavior between agents allows for the establishment of a good execution of the whole system. Thanks to the messages, the supervisor agent can control the whole system and it knows exactly when to act or send other messages. Furthermore, the MAS has shown that even if an agent fails, it can continue working with the rest of the agents without any problems. This is one of the main characteristics of MASs and the proposed system incorporates it.

Additionally, the communications between agents are done quickly and no delays have been detected during the simulation. Hence, after observing the behavior of the agents, it can be noted that the proposed multi-agent architecture seems to work perfectly in these kinds of systems and that the idea mentioned in the proposal section is confirmed now, MASs are ideal for a distributed system that aims to achieve a common goal.

To test the effectiveness of the proposed MAS, a small sensor network has been deployed, which interacts with the MAS. The sensor network has two Xiaomi NUN4019TY (humidity and temperature sensor, Xiaomi Inc., Beijing, China) and two Garza Power 430041 (presence sensor, Garza, Fuenlabrada, Spain). We established the appropriate connections with them and ran the fuzzy algorithm with the measured values of the sensors. To obtain the number of persons inside the house/building, an algorithm was deployed to interpret the presence's sensors data. The MAS and the strategy defined

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to obtain the data from the sensors have demonstrated that it works perfectly in a small sensor network's environment; this type of environment is the normal setting in homes and flats.

5.2. Fuzzy Control System

The other great contribution of this work is the proposed fuzzy system in charge of controlling the behavior of the system. The aim was to design a new controller that could be able to reduce the use of fuel and therefore to reduce the cost for the citizens. So, the results shown by the fuzzy control system will be explained in this subsection.

Firstly, once the simulation is done, it will be interesting to compare how the fuzzy controller works related to the original controller. Both controllers want to control the temperature inside the building, so it could be interesting to observe that variable. Hence, Figure 4 shows how this variable is controlled by both controllers:

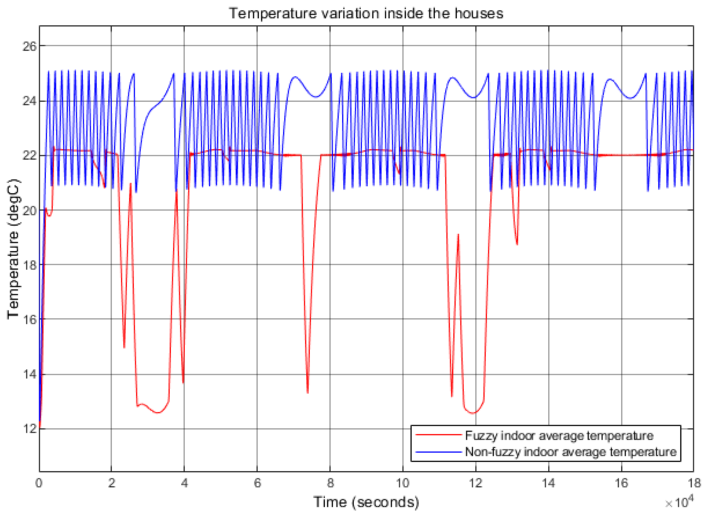

Figure 4. Temperature variation with the different controllers.

The previous figure shows the temperature variation. The original controller (non-fuzzy) shows a more changeable behavior. This type of behavior may have bad consequences for the system's users' health due to the quick changes in temperature. On the other hand, the proposed system does not vary at all when there are people inside the house. This characteristic facilitates the users' comfort. In Figure 4 we can also observe that the fuzzy controller also has a temperature loss during some specific moments. This behavior can be linked to a bad performance of the controller, however, in Figures 5 and 6 it can be seen that this temperature loss is due to the case in which there are no people inside the building/house.

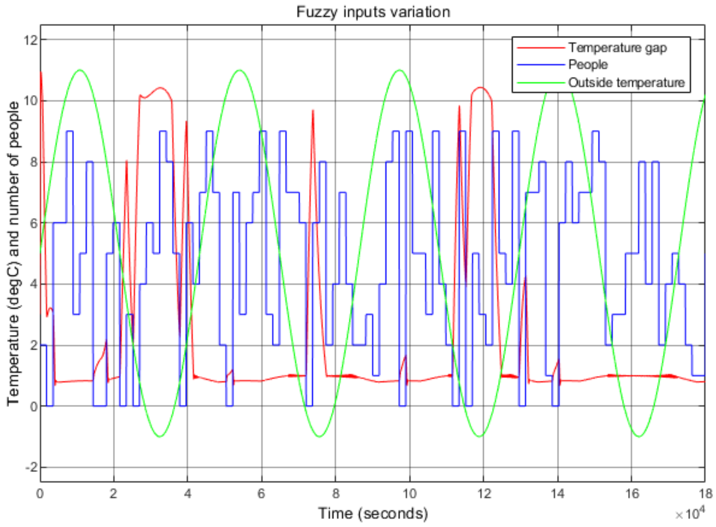

Figure 5. Fuzzy inputs variation.

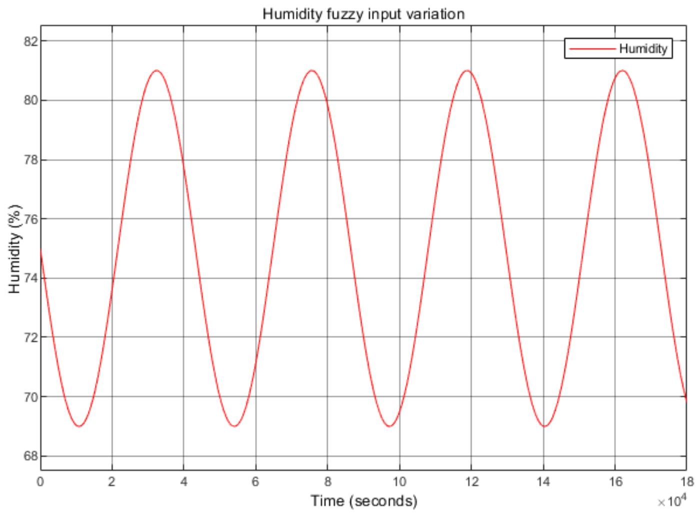

Figure 6. Humidity fuzzy input variation.

Figure 5 also shows that the fuzzy controller does not achieve the desired temperature, however, the error is stable, and the difference does not have a significant impact on users' comfort. Therefore, we can conclude that the fuzzy controller works stably and that it does not compromise the comfort of the users.

Another important characteristic when applying a new proposal is to reduce the cost or decrease the emissions of the system. In the evaluated system, these two concepts are linked since the fuel necessary to heat the system's water is the one responsible for gas emissions, while at the same time it is also the one responsible for the cost waste. So, it is important to evaluate the impact on the cost that the system has. This cost is obtained with the amount of fuel consumed and the price established in the baseline. To answer this question, Figure 7 is presented. In it, we can see that in just 50 h of continuous performance of the system, the proposal reduces significantly the cost of this type of system. Hence, the ROI (Return on Investment) is guaranteed.

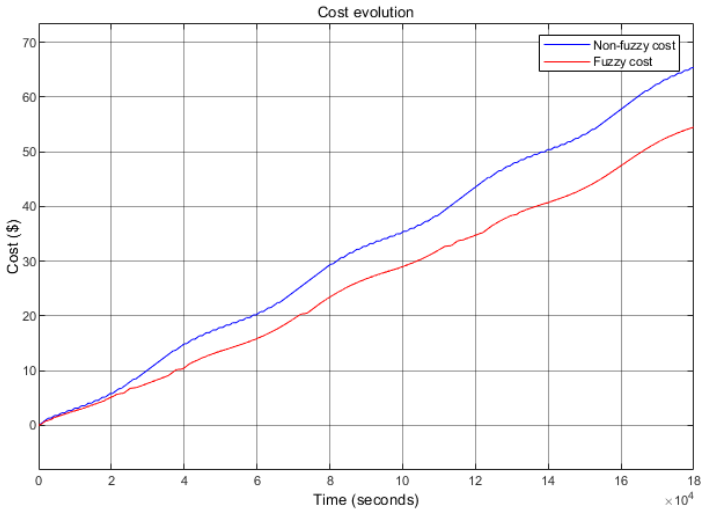

Figure 7. Cost evolution.

In addition, to better illustrate the total cost of both simulations, Table 5 is included. It shows the total cost of each simulation and the average temperature over the simulation. As can be seen, the proposed system decreases the cost by $10.84. The total cost is obtained by multiplying the fuel consumption by a fixed price (0.3002 $/l) defined again by the MATLAB Simulink model. However, the mean temperature is a bit lower because of the behavior explained before where the temperature decreases when there are no people in the building. That temperature is the average temperature during the entire simulation. In the proposal, the average temperature decreases when there are no people in the house, the heating system is turned off. During those moments, the temperature inside declines. Therefore, it is normal that these moments are reflected in the calculation of the average temperature. However, during the rest of the situations in which the heating is on, the temperature remains stable.

Table 5. Simulations comparation.

Simulation	Variable	Value
Non-fuzzy	Mean temperature	23.20 °C
	Cost	65.35 $
Fuzzy	Mean temperature	20.76 °C
	Cost	54.51 $

Since the fuzzy simulation did not achieve the aimed temperature, it was decided that a second simulation of both systems should be run. This time the fuzzy proposal will have an aimed temperature of 24 °C instead of 23 °C. The non-fuzzy proposal will have an aimed temperature of 23 °C. The results of the simulation are shown in Figures 8–11.

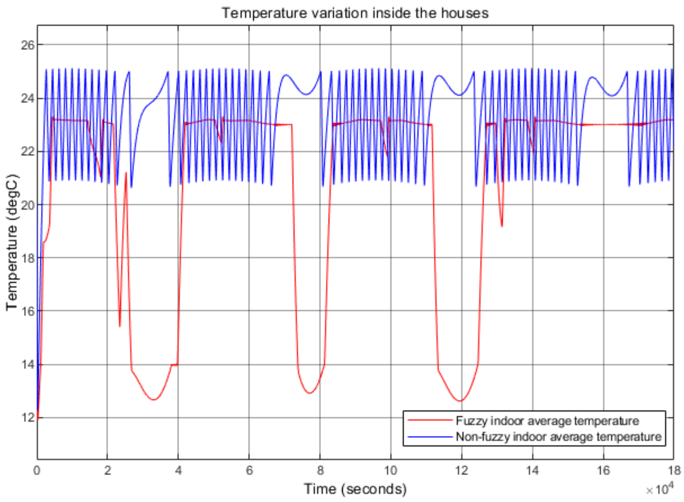

Figure 8. Temperature variation with the different controllers in the second simulation.

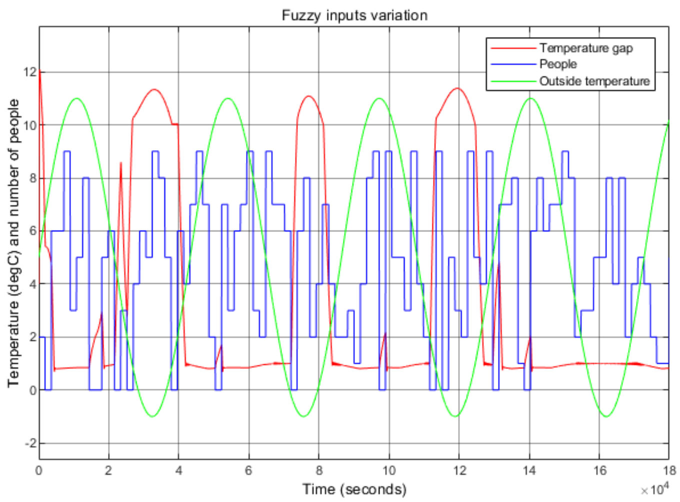

Figure 9. Fuzzy inputs variation in the second simulation.

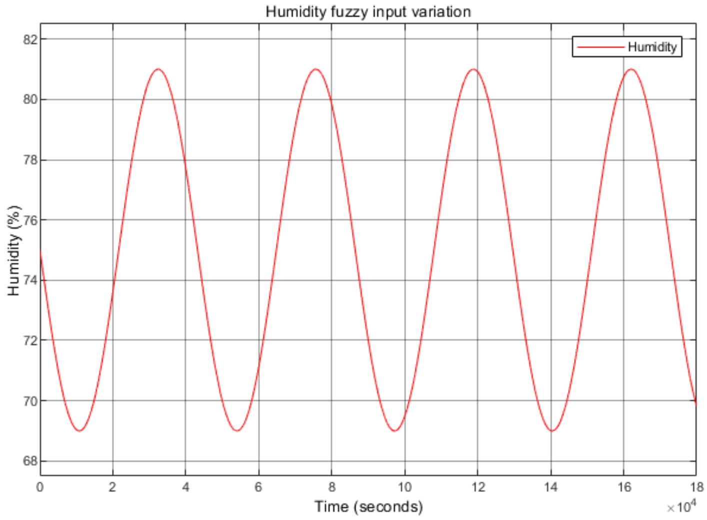

Figure 10. Fuzzy inputs variation in the second simulation.

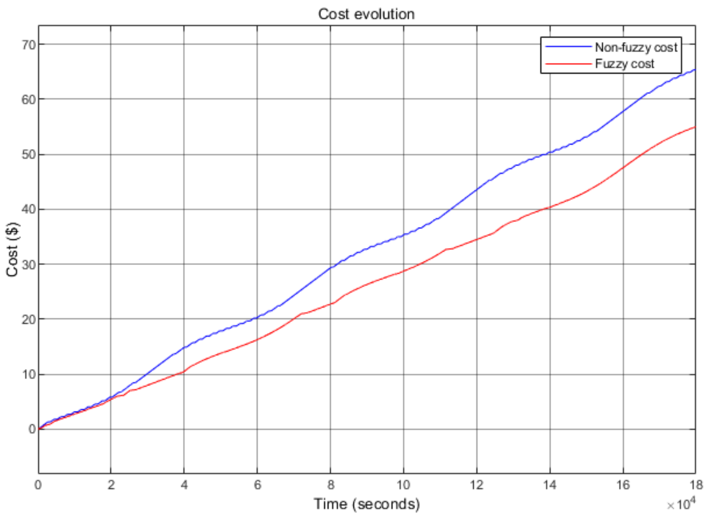

Figure 11. Cost evolution in the second simulation.

The fuzzy proposal retains a slight error in regards to the target temperature. However, now both systems achieve the same temperature (23 °C). The fuzzy proposal still has temperature losses due to the fuzzy rules defined when there are no individuals in the building. Additionally, Figure 11 shows the effectiveness of the proposed system related to cost and energy used reduction. This output can also be seen in Table 6. Therefore, the proposed system achieves one of its main goals: cost reduction, energy use reduction, and, consequently, the reduction in gas emissions.

Table 6. Two simulations comparation.

Simulation	Variable	Value
Non-fuzzy	Mean temperature Cost	23.20 °C 65.35 $
Fuzzy	Mean temperature Cost	20.89 °C 55.00 $

The results show that the fuzzy proposed system works much better than the baseline reducing cost for the users and therefore the amount of fuel needed to feed the heating system while increasing the comfort of the users. It is true that on average the temperature is lower in the proposed system. However, this fact is due to the behavior of the proposed fuzzy system. As shown in the rules defined, several circumstances (that there are no people inside the house, the temperature outside is too high, there are too many people inside the house, etc.) force the central heating to turn off, reducing the inside temperature on some occasions. These circumstances are controlled thanks to the fact that the fuzzy logic allows us to reduce the cost and obtain one of the goals of the research.

5.3. ROI Analysis

Once the simulations are evaluated, it is also important to include a deep analysis of the ROI. Considering the costs of non-fuzzy and fuzzy simulations and the number and prices of sensors needed to implement this new solution in a real environment, we have included the ROI analysis. Table 7 shows this analysis. Both simulations achieve quick benefits. In around ten days, the users of the systems will be saving money.

Table 7. Return on investment (ROI) analysis.

Simulation	Sensors	Price	Number of Sensors	Total Cost	ROI (Days)
Fuzzy #1	Xiaomi NUN4019TY Garza Power 430041	14.05 $ 11.84 $	2 2	28.01 $ 23.68 $	9.93
Fuzzy #2	Xiaomi NUN4019TY Garza Power 430041	14.05 $ 11.84 $	2 2	28.01 $ 23.68 $	10.40

6. Conclusions

In this article, a MAS for a fuzzy logic controller has been presented. Regarding the results mentioned, it was demonstrated that the proposed system can achieve the expected results and that this kind of architecture can be applied to a distributed system in the field of IoT and smart-environments. Another important assumption is that this technology can reduce gas emissions in this kind of system. Additionally, if this solution is deployed at a great scale, the gas emissions to the atmosphere in big cities will be reduced significantly. The simulation presented in the study supports this idea.

However, there are several lines of research that this article does not cover. Therefore, these will be defined as future lines of research. The most important one is to perform a MAS that can deploy several fuzzy agents instead of just one. The idea behind this is that the system will be able to control radiators in community buildings to reduce consumption and make sustainable use of the central heating in those buildings. Furthermore, it is expected that families will be able to reduce their taxes. This future line of research is important since it will automatically control the new installations of central heating in Spain.

Another action that must be considered as a future line of research is to deploy the proposal of this article in a real environment to prove if the same results can be achieved in a real situation. Furthermore, once we have deployed the system, we can collect data from other types of sensors, like windows sensors or door sensors, and add them to the fuzzy controller. By doing this, the system will be more complex.

Finally, to prove the efficiency of the MAS, it is important to test it in another kind of real environment so we can observe the behavior of the system in a different situation and validate it as a solution for a distributed system in the field of IoT. Probably a smart-city environment would fit well with the system, due to the fact that the number of the sensor will increase significantly and therefore the communications between agents will rise accordingly. This situation will determine the robustness of the proposed MAS.

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3.4.1 Summary in Spanish

Esta subsección muestra un resumen en castellano de los aspectos más relevantes del artículo científico titulado "*Central Heating Cost Optimization for Smart-Homes with Fuzzy Logic and a Multi-Agent Architecture*" que en castellano se podría traducir a "Optimización del coste de la calefacción central para viviendas inteligentes con lógica difusa y una arquitectura multiagente".

Research objectives

El año 2019 ha sido un año importante de cara a la lucha contra el cambio climático. Diferentes conferencias se han realizado al rededor del mundo y el mensaje ha calado entre la sociedad que cada vez es más consciente del problema que supone esta situación. Sin embargo, la clase política aún no ha llegado a acuerdos relevantes para poner solución a este problema global. No obstante, el gobierno español es consciente de la situación y ha declarado un estado de emergencia climática en el que pretenden conseguir un estado con cero emisiones para el año 2050. En este sentido la transición ha de ser progresiva reduciendo poco a poco el consumo de fuentes de energías no renovables. En este sentido y teniendo en cuenta también los avances realizados en los últimos años en el campo del internet de las cosas, el uso de esta tecnología puede ayudar a obtener sistemas más eficientes en cuanto a consumo de energía y reducir el efecto invernadero y la contaminación. Los sistemas del internet de las cosas en colaboración con los algoritmos y técnicas de inteligencia artificial pueden ayudar a reducir el consumo de fuentes de energía no renovables.

Teniendo en cuanta lo expuesto, se propone la investigación y creación de un sistema que basándose en datos recogidos por sensores pueda interpretarlos mediante un sistema de control borroso y determinar la salida más adecuado para un sistema de calefacción central con el objetivo de reducir el impacto energético del mismo en el medio ambiente sin que el confort del usuario se vea afectado. El sistema está basado en los datos recogidos por los sensores y que determinan el estado final del sistema. Sin embargo y con el objetivo de que el sistema sea aún más inteligente se pretende incorporar un sistema multiagente en el que los diferentes agentes del mismo colaboran entre sí para la consecución del objetivo. Estos agentes además constan de cierta inteligencia pudiendo cambiar su comportamiento en función de la información que reciben del entorno.

De esta forma, los objetivos de investigación del presente artículo son los siguientes:

- Investigación sobre dispositivos de medición de variables ambientales.
- Investigación en sistemas de control borroso y más concretamente en aquellos diseñados para controlar el funcionamiento de sistemas de calefacción.
- Creación de un sistema multiagente que recopile datos de los dispositivos de medición inteligente y que utilice esa información para determinar la salida de un sistema de control borroso que optimice el uso de energía no renovable y reduzca por tanto las emisiones contaminantes y la factura del cliente.

Methodology

La metodología utilizada para la elaboración de este artículo científico es la ya explicada en la sección 1.2. No obstante, en esta subsección se explicarán cada uno de los pasos o aspectos relevantes tenidos en cuenta durante el proceso de investigación. Para ilustrar este proceso vamos a utilizar algunos de los pasos de la metodología AR.

- **Revisión del estado del arte**: es necesario realizar una investigación en relación a los trabajos previos realizados por otros investigadores en el área de conocimiento de la investigación realizada en este artículo. El objetivo de esta investigación previa es analizar en detalle los trabajos actuales y poder ampliarlos, mejorarlos o reutilizarlos para que el conocimiento científico plasmado en este artículo fuese de calidad para otros investigadores. Es por ello, que se realiza un estudio de los trabajos realizados en el ámbito de los sistemas de control borroso, los entornos de IoT y de los sistemas multiagentes.

  Teniendo en cuenta estas características se estudian diversos artículos realizados en el ámbito de las viviendas inteligentes. Sin embargo, muchos de ellos son estudios bastantes antiguos que no hacen uso de las tecnologías y algoritmos actuales para resolver el problema o caso de estudio que presentan. De forma general, casi todos ellos utilizan los principios de la lógica borrosa para resolver el problema, sin embargo, muchos no controlan diferentes variables ambientales que son de extremada necesidad para resolver el problema eficientemente. Del mismo modo, ninguno de ellos hace uso de una arquitectura multiagente para conectar los diferentes componentes del sistema y que estos interactúen entre ellos.

- **Análisis y diseño de la propuesta**: analizando todo lo aprendido durante la revisión del estado del arte, se propone un sistema multiagente que hace uso de un modelo de simulación de una vivienda y su sistema de calefacción desde donde se obtienen las variables ambientales y a donde se comunica la salida del sistema borroso incluido en el sistema multiagente que trabaja en colaboración con otros agentes. Concretamente existen dos módulos de agentes, el de dispositivos encargados de obtener los datos de los sensores y trasmitirlos mediante un comportamiento inteligente a la base de tatos y al módulo de inteligencia artificial encargado de gestionar el sistema de control borroso y de comunicar al modelo la salida proporcionada por el mismo. Por último, pero no menos importante, tenemos el agente supervisor que se encarga de gestionar que todos los agentes de los diferentes módulos se encuentren activos y en funcionamiento.

- **Definición del caso de estudio**: la propuesta ha de ser validada por un caso de estudio. En este sentido se ha utilizado un sistema de MATLAB Simulink para simular una vivienda. Este sistema está conectado a un sistema multiagente desarrollado en Python. Además, para establecer una comparativa con el sistema propuesto se ha incluido el modelo que proporciona MATLAB y de esta forma ver como la propuesta mejora el sistema existente. Ambos modelos son lo más realistas posibles simulando perdidas o ganancias de calor en la vivienda. Como se ha mencionado antes el sistema multiagente incluye el sistema de control borroso que tiene en cuenta cuatro variables diferentes, la diferencia de temperatura entre la temperatura objetivo y la actual, la temperatura exterior, la humedad interior y la cantidad de gente en la vivienda. Estas variables definirán las reglas del sistema borroso. Por último, se establece un tiempo de simulación de 50 horas.

Results

Los resultados de la investigación se dividen en dos partes. Primeramente, el estudio sobre la arquitectura multiagente empleada en el artículo; ha demostrados ser eficiente y en las diversas simulaciones realizadas ha demostrado no fallar y establecer la correcta comunicación entre los agentes de la misma.

El segundo aspecto a evaluar es la eficacia del sistema de control borroso implementado. Se han realizado varias simulaciones y en todas ellas se observa que el objetivo propuesto se alcanza, se mejora el funcionamiento del sistema elegido como base y se obtiene una disminución en combustible empleado y por lo tanto se genera un beneficio económico sustancial para los clientes. En las diferentes simulaciones se observa que en la solución planteada se producen perdidas de calor en determinadas ocasiones, pero esto es debido a las características y las reglas definidas en el sistema borroso. Aun así, el sistema borroso recupera de forma más o menos rápida la temperatura objetivo siempre y cuando las circunstancias ambientales exijan recuperar esa temperatura.

Además, para terminar el análisis de resultados se ha llevado a cabo una estimación del retorno de la inversión si este modelo se implantase en una vivienda real con dispositivos reales. En este análisis se observa que en las simulaciones realizadas se comienza a obtener beneficios económicos aproximadamente a los 10 días.

Conclusions

En este articulo científico se ha obtenido un sistema multiagente que es capaz de obtener datos de sensores y computarlos en un sistema de lógica borrosa para determinar la acción a realizar sobre un sistema de calefacción central y de esta forma reducir el impacto que este tipo de sistemas tienen en el medio ambiente. A la vez y gracias a reducir el consumo energético, el sistema también proporciona un beneficio económico a los usuarios del mismo. Del mismo modo, la arquitectura utilizada puede ser de utilidad en otros entornos IoT.

Para finalizar, se plantean posibles líneas de investigación futuras que resultan interesantes. como la posibilidad de que el sistema multiagente sea capaz de gestionar diferentes modelos borrosos con el objetivo de no actuar sobre la caldera del sistema de calefacción sino sobre los radiadores de la instalación. Igualmente resultaría interesante el probar esta arquitectura multiagente en un entorno real aumentando el número y tipo de sensores. Al mismo tiempo, la arquitectura puede ser probada en otros entornos de IoT para probar que esta solución y propuesta se puede aplicar a diferentes ambientes sin problemas.

Chapter 4

Conclusion

This final chapter of the Ph.D. thesis resumes the conclusions extracted from the research developed during the last years and showed in the previous chapters. The chapter resumes as best as possible the outcomes and contributions of the research as well as describes the future lines of research for next years regarding the subject of the thesis.

4.1 Contributions

This subsection describes the main contributions and outcomes of the developed work.

Several reviews about the state of the art have been developed in this research. First, a review of the different applications and protocols in IoT environments was developed. This review allows us to understand and identify the strengths and problems of IoT as well as understand the communications protocols and technologies. The in deep research about the different protocols allowed to select the best ones in the cases of study developed in the research articles.

Second, several intelligent algorithms have been analyzed to select the best technique for every one of the developed articles and cases of study. These intelligent algorithms make use of the data extracted from an IoT environment to extract the knowledge hidden between the data. ML algorithms, recommendation algorithms, and control systems have been studied to develop the proper system for every situation.

Also, a review of the MASs has been developed. This review outcomes the main characteristics of a MAS which makes us understand and identifies the features that the designed MAS had to have. Also, this review shows the importance that MASs are having in IoT and ML solutions nowadays.

Taking into account the reviews mentioned in this work a system with the following features have been developed: (I) the system use sensor networks to collect data that it sent to a central system, (II) the data is stored and analyzed using intelligent algorithms to maximize the efficiency of the system, (III) the system is based in a multi-agent architecture to solve the problem and achieve the goals of the different agents, and (IV) the system tries to minimize the impact that homes' energy consumption has on the environment.

In consequence, and to prove the mentioned system several cases study has been designed. These are explained in detail in the scientific articles of this Ph.D. thesis. Three different studies have been carried out. The first one proposes a multi-agent system that can collect data from the electric network using sensors and compute that data to identify the electronic devices connected in a home. The method used to identify the devices combines NILM techniques and ML algorithms, which offers a new perspective to resolve this kind of problem. Furthermore, the proposed system reduces the impact that electrical energy has on the environment since it includes a policy to turn off some of the devices that are not important or are not being used.

The second study also uses a multi-agent system to obtain data from sensors and a web crawler to offer recommendations to users that want to change their pattern behavior to reduce the impact that the electrical energy consumption has on the environment. This new contribution to the area of research has demonstrated to work perfectly and the recommendations are adapted to the user pattern behavior to not provoke a huge change in the user lifestyle. Also, the different simulations of the system show that if this solution is applied to several homes or neighbors the impact on electricity consumption can be important and therefore the pollution can be reduced.

The third case study shows how a MAS can be applied to a central heating system to reduce fuel consumption and to reduce pollution. The system proposed uses sensors to obtain the environment data and use it to determine the appropriate state of the heating system. In this case, a control system determinates the best output. The proposed innovative solution has demonstrated that it offers a reduction in energy consumption, in the bill, and reduces pollution. Therefore the proposed solution seems to achieve its proposal. Furthermore, the results illustrate that the hardware cost of this solution can be extremely cheap having a ROI of around ten days.

Last, during the Ph.D. academic years apart form the scientific contributions showed in this book, other scientific articles have been published in relevant scientific journals or international conferences and congress. Furthermore, following the criteria of the Ph.D. academic commission, several courses and conferences have been attended to increase the background knowledge and several international stays have been done.

4.2 Future work

This section resumes all the future lines of research that the research and the studies developed has.

Firstly, all the studies have demonstrated to work perfectly. However, it would be really interesting to prove the proposed system in a more professional environment and extended it to a bigger environment, like a city or a neighborhood.

More particularly, the first study can be improved easily by increasing the number of devices detected by the proposed system. Besides, use a more complex technique to identify the patterns in the data can increase the results of the system and therefore the users' experience.

The second study can be amplified by extending the study to other countries by collecting electricity prizes data. Also, the solution cannot be limited to a single model of a smart plug. If the system wants to be implemented in other countries, other smart plugs brands and models have to be studied. Additionally, if the recommendation system is based on the potential financial impact the cost and the consumption peaks can be reduced.

Finally, the third study can be studied in a completely different way. Instead of control the central heating with a single control, the radiators of the different rooms can be controlled by several controls, this solution can increase the comfort of the users since they can define different temperatures in different areas of the home. Moreover, this study is based on a software simulation, it would be very interesting to test it in a real environment as mentioned before.

Appendix A

Journals' impact factor

A.1 Complexity information

- **Journal name**: Complexity
- **URL**: https://www.hindawi.com/journals/complexity/
- **Editorial**: Hindawi
- **ISSN**: 1076-2787
- **Languages**: English
- **Categories**: "Multidisciplinary sciences", "Mathematics, interdisciplinary applications"
- **2018 JCR impact factor**: 2.591
- **2018 Quartile**:
  - **"Multidisciplinary sciences"**: Q2
  - **"Mathematics, interdisciplinary applications"**: Q1
- **2018 Ranking**:
  - **"Multidisciplinary sciences"**: 25/69
  - **"Mathematics, interdisciplinary applications"**: 21/105

A.2 Energies information

- **Journal name**: Energies
- **URL**: https://www.mdpi.com/journal/energies
- **Editorial**: MDPI
- **ISSN**: 1996-1073
- **Languages**: English
- **Categories**: "Energy & Fuels"
- **2019 JCR impact factor**: 2.702
- **2019 Quartile**:

  - **"Energy & Fuels"**: Q3

- **2019 Ranking**:

  - **"Energy & Fuels"**: 63/112

A.3 Applied Sciences-Basel information

- **Journal name**: Applied Sciences-Basel
- **URL**: https://www.mdpi.com/journal/applsci
- **Editorial**: MDPI
- **ISSN**: 2076-3417
- **Languages**: English
- **Categories**: "Chemistry, multidisciplinary", "Physics, applied", "Materials science, multidisciplinary", "Engineering, multidisciplinary"
- **2019 JCR impact factor**: 2.474
- **2019 Quartile**:
  - **"Chemistry, multidisciplinary"**: Q2
  - **"Physics, applied"**: Q2
  - **"Materials science, multidisciplinary"**: Q3
  - **"Engineering, multidisciplinary"**: Q2
- **2019 Ranking**:
  - **"Chemistry, multidisciplinary"**: 88/177
  - **"Physics, applied"**: 62/154
  - **"Materials science, multidisciplinary"**: 161/314
  - **"Engineering, multidisciplinary"**: 32/91

Appendix B

Resumen en castellano

Este anexo tiene como objetivo ofrecer un resumen de toda la información contenida en los capítulos 1, 2 y 4 en lengua castellana. El capítulo 3 no se ha resumido ya que se encuentra escrito prácticamente al completo en castellano. En el resumen de los citados capítulos la información no será tratada con tanta precisión y profundidad de contenido como se ha realizado en los capítulos, sino, que se explicaran brevemente tanto la información como conceptos claves necesarios para entender la tesis doctoral.

B.1 Capítulo 1 - Introducción

En la actualidad la población se está concentrando en medianas y grandes ciudades en lugar de en pequeñas ciudades o pueblos. La era de la industrialización y las oportunidades existentes promovió la movilización hacia las medianas y grandes ciudades. Esto hizo que las ciudades cada vez fuesen más grandes y que el poder económico aumentase considerablemente tanto en empresas o industrias privadas como en ciertos sectores de la población. Este avance económico y tecnológico promovió el uso de nuevos y modernos dispositivos electrónicos, como el teléfono inteligente; que según estudios recientes lo ostenta el 45,04% de la población mundial.

La población no solo utiliza el teléfono inteligente en su día a día; son los jóvenes los que especialmente utilizan más dispositivos electrónicos con los que son capaces de acceder a cantidades ingentes de información a través de internet. Esta es la característica principal de muchos dispositivos, conectarse a internet. Todos los dispositivos que comparten esta característica conforman el internet de las cosas (IoT, del inglés *Internet of Things*). Se trata de un campo en auge ya que se estima que en 2027 existirán 41 mil millones de dispositivos conectados a internet. Es por ello que las empresas actuales y del futuro estarán basadas en la tecnología IoT.

No obstante, IoT no solo está formado por dispositivos físicos, sino, también por los datos generados, transmitidos o medidos por estos dispositivos. En internet se generan cantidades inmensas de información, prueba de ello es que el motor de búsqueda de Google genera 3.877.140 búsquedas por minuto cada día, Amazon entrega 1.111 paquetes, Netflix reproduce 97.222 horas de vídeo entre otros ejemplos. Es por ello que los campos de IoT y el del *big data* son y serán importantes para afrontar todos los desafíos que los dispositivos y su información producen.

Las grandes cantidades de datos supone uno de los mayores desafíos actualmente. Grandes empresas, gobiernos y corporaciones tratan de extraer de esos datos la información relevante. Para ello es necesario definir una buena estrategia que permita obtener, transmitir, almacenar y analizar los datos de una forma eficiente y reduciendo costes. Las cantidades ingentes de datos también permiten a los investigadores estudiar nuevas técnicas y algoritmos que automaticen este proceso y permitan ahorrar tiempo y esfuerzo a los humanos ofreciendo incluso mejores resultados.

De esta forma, el objetivo de una plataforma IoT es obtener resultados significativos de los datos; para ello el sistema ha de trabajar como una única entidad. Esta tarea muchas veces se complica debido a que estas plataformas están compuestas por diferentes elementos físicos distribuidos alrededor de un entorno y con funciones específicas. Por ello, es necesario la correcta definición y construcción de un sistema IoT.

Por otro lado, en la actualidad existe otro gran problema que ha de ser solucionado lo antes posible, el cambio climático. A lo largo del año 2019 se han llevado a cabo diferentes conferencias que han calado en la sociedad. Prueba de ello es le nombramiento de Greta Thunberg como persona del año por la revista Time. De esta forma, el debate sobre el cambio climático ha llegado para quedarse y los gobiernos deberán tomar acciones para solventarlo.

En este sentido, el mayor productor de CO_2 es la industria de generación eléctrica. La electricidad se produce bajo demanda de edificios residenciales e industrias. La solución ideal para este gran problema es el uso de energías verdes o renovables. Sin embargo, muchos países no están preparados para este gran cambio aún. Por ello, es de extremada importancia promover una solución que promueva la transición de energías no renovables a renovables mediante la reducción de emisiones de CO_2. Esta solución permitirá mientras tanto que los países se adapten a las energías renovables.

Teniendo en cuenta esto, queda bastante claro que las tecnologías IoT puede ayudar a diseñar un sistema capaz de utilizar los datos y reducir el impacto que los humanos tienen a la hora de consumir diferentes tipos de energía. Así pues, esta tesis doctoral pretende investigar una arquitectura IoT que permita obtener un sistema distribuido que trabaje en conjunto para reducir las emisiones de gases contaminantes y promover el uso eficiente de la energía en los humanos.

B.1.1 Hipótesis y objetivos

En la actualidad existen un gran número de arquitecturas y sistemas en torno al campo del IoT. Sin embargo, el aumento del uso de dispositivos inteligentes en viviendas supone un nuevo desafío para investigadores del campo debido a los datos generados por estos dispositivos y la información que esconden tras ellos, así como posibles acciones de control. De esta forma, es necesario una arquitectura bien diseñada y distribuida para alcanzar los objetivos y tener un impacto en la experiencia del usuario y la sociedad.

De esta forma, la siguiente hipótesis ha sido seleccionada como base para esta tesis doctoral:

Hipótesis

Diseño de un modelo arquitectónico para aplicaciones IoT que incluya elementos físicos distribuidos y modelos de inteligencia artificial para la obtención de conocimiento que pueda facilitar la experiencia de los usuarios y contribuir a la lucha contra el cambio climático.

Para validar esta hipótesis varios objetivos han de ser alcanzados. Estos objetivos son los siguientes:

- Investigar en la recolección de datos de redes de sensores inalámbricas en entornos de corta distancia. Al mismo tiempo, investigar en sensores que faciliten la obtención de los datos apropiados de forma eficiente y reduciendo el consumo eléctrico.
- Investigar diferentes modelos y técnicas de inteligencia artificial que permitan estudiar los datos y extraer de estos conocimiento y patrones de comportamiento de los usuarios. Al mismo tiempo, el preprocesamiento y tratado de los datos mediante las técnicas más apropiadas será estudiado.
- Investigar en diferentes tipos de arquitecturas IoT para la recolección de datos y análisis de los mismos. Estará enfocada en sistemas que permitan integrar diferentes entidades que trabajen como una única entidad para lograr sus objetivos.
- Establecer diferentes casos de estudios para ayudar en la lucha contra el cambio climático gracias a su contribución con la reducción del consumo de energías no renovables mientras se ayuda a los usuarios a reducir costes y/o mejorar su calidad de vida.

B.1.2 Metodología de investigación

La metodología *Action Research* (AR) se ha utilizado durante el desarrollo de esta tesis doctoral. Esta investigación es ampliamente utilizada en trabajos y proyectos similares.

AR se basa en resolución de un problema existente basándose en una hipótesis. Si las conclusiones no apoyan la hipótesis, la metodología AR permite repetir el proceso hasta que la hipótesis es aceptada o refutada. En consecuencia, se trata de una metodología cíclica que se caracteriza por las siguientes fases o pasos:

- **Definición del problema**: identificación de los problemas y de sus variables para obtener la hipótesis de investigación y sus objetivos.
- **Revisión del estado del arte**: estudio de investigaciones previas y estudio de los conceptos y técnicas básicas y fundamentales relacionadas con la hipótesis de investigación.
- **Análisis y diseño de una propuesta**: análisis en profundidad del estado dela arte para definir una propuesta que pruebe la hipótesis.
- **Definición de casos de estudio**: definición de uno o varios casos de estudio que tengan como objetivo probar el diseño propuesto.
- **Pruebas y extracción de resultados**: ejecución de los casos de estudio y extracción de resultados para su posterior análisis.
- **Análisis de resultados y discusión**: los resultados obtenidos son evaluados y explicados en detalle para analizar la razón o el porqué de los mismos.

- **Definición de las conclusiones**: se evalúan las conclusiones para aceptar o refutar la propuesta y/o hipótesis. Después de este paso el ciclo puede ser reiniciado.

El uso de esta metodología de investigación permite a los investigadores probar sus estudios con casos de estudio reales de modo que los estudios puedan ser transferidos más fácilmente a la sociedad. Además, también se focaliza en la transmisión de los resultados obtenidos a través de publicaciones en revistas científicas o conferencias. Esta última frase es bastante importante ya que el objetivo de toda investigación es trasferir el conocimiento obtenido al resto de la comunidad científica.

B.1.3 Estructura de la tesis

Una vez definidas la hipótesis, esta debe ser investigada. Esta investigación se define en el resto de los capítulos cuya estructura se resume a continuación.

- **Capítulo 2. Estado del arte**: el capítulo contiene el estudio del arte relacionado con la hipótesis. Contiene un estudio profundo de las diferentes entornos y tecnologías relacionadas con el IoT. Estudia las diferentes técnicas, modelos y modelos de inteligencia artificial. Algo esencial para poder extraer el conocimiento de los datos y poder aplicar decisiones útiles y acciones sobre el sistema. Además, el estudio sobre las arquitecturas distribuidas existentes para el campo IoT son estudiadas.

- **Capítulo 3. Lista de artículos científicos**: el tercer capítulo de la tesis doctoral contiene los artículos usados para esta tesis en la modalidad de compendio de artículos. Primero, una subsección que explica la relación entre los artículos. A continuación, se muestra los artículos originales junto con un resumen en castellano. Este resumen contiene los objetivos de investigación, la metodología empleada, los resultados y las conclusiones extraídas de los artículos.

- **Capítulo 4. Conclusiones**: finalmente el último capítulo incluye las conclusiones extraídas tras el desarrollo del trabajo de investigación de esta tesis doctoral.

B.2 Capítulo 2 - Estado del arte

B.2.1 Entornos IoT

Los sensores han sido ampliamente utilizados especialmente en los entornos industriales, sin embargo, en los últimos años su uso se ha masificado. Esto es debido especialmente a la reducción de los precios de los sensores causada por:

- Las empresas dedicadas a este sector.
- La constante actualización y mejora de los sensores en cuanto a capacidades y rendimiento.
- La facilidad de instalación de los sensores.

De esta forma, el IoT ha emergido entre la sociedad. No obstante, sigue siendo un concepto bastante abstracto y es necesaria una definición. El IoT define una interacción entre el mundo físico y digital para alcanzar mediante la colaboración. La comunicación entre los mundos es proporcionada por sensores y actuadores debido a sus capacidades de computación y conectividad.

No obstante, es importante mencionar las limitaciones con las que los desarrolladores sen encuentran a la hora de crear una infraestructura IoT:

- **Sensores limitados**: a pesar de los grandes avances realizados aun cuentan con algunas limitaciones, batería, ancho de banda, capacidades *hardware*.
- **Problemas con el tiempo**: los sensores pueden estar repartidos en diferentes localizaciones por eso es importa tener en cuenta que mediada de tiempo están utilizando cuando realizan los registros. Por otro lado, los sensores pueden tener errores de sincronización en su reloj interno.
- **Problemas de localización**: la ubicación de los sensores puede ser un problema debido a la temperatura y altitud. Del mismo modo las zonas más remotas pueden tener problemas de comunicación. Incluso dependiendo del país hay que tener en cuenta ciertos aspectos legales debido a razones políticas y de privacidad.
- **Volumen de datos**: las grandes cantidades de datos generados por este tipo de infraestructuras provoca que muchas veces, en los primeros años de vida de la infraestructura, surjan problemas para manejar y extraer el conocimiento de los datos en crudo.

Aplicaciones IoT

Existen diferentes aplicaciones de la IoT presentas en el día a día.

- **Viviendas y edificios inteligentes**: esta aplicación, también conocido como automatización de edificios y viviendas, ha sufrido un gran desarrollo durante los últimos años. Las aplicaciones de esta área ofrecen servicios y ayudas a los usuarios para mejorar su vida diaria.
- **Ciudades inteligentes**: con sensores distribuidos alrededor de la cuidad esta aplicación pretende aumentar la calidad y el confort de los ciudadanos. Pueden ofrecer servicios sanitarios, de seguridad, de optimización energética entre otros.
- **Red eléctrica inteligente**: esta aplicación dispone de diferentes elementos como contadores inteligentes, dispositivos inteligentes, fuentes de energía renovables y recursos de energía eficiente. Las redes eléctricas inteligentes son posibles gracias a las *Power Line Communications* (PLC) que permiten transportar datos a través de la red eléctrica permitiendo ofrecer una gran cantidad de soluciones y servicios.
- **IoT industrial**: supone el uso de la tecnología IoT en sectores industriales como el transporte, logística, fabricación, minería, aviación, etc. Pretende obtener datos de maquinaria o de procesos industriales para ofrecer un servicio o facilitar las tareas en las industrias. No obstante, en muchas de estas industrias se

requiere de una gran precisión. Es un área que aún se encuentra en desarrollo y que está recibiendo una gran inversión.

- **Agricultura y ganadería inteligente**: supone una aplicación con gran número de soluciones y servicios. La ganadería y agricultura se ha reinventado con el uso de la tecnología IoT. De esta forma se pueden crear aplicaciones como predicción del tiempo, riego, fertilización y fumigación de precisión, monitorización del ganado y de flotas entre otras. En esta área la calidad de las comunicaciones es un factor fundamental.
- **Salud inteligente**: esta aplicación pretende mejorar los sistemas de salud mediante el IoT. Promueve la monitorización de pacientes, detección de caídas, los sistemas de ayuda a la decisión, detección de enfermedades, etc. No obstante, estos servicios aún están por ser altamente efectivos, debido, en muchos casos, a la falta de colaboración de los servicios sanitarios y a las políticas de privacidad.

Protocolos IoT

Las telecomunicaciones funcionan siguiendo el modelo OSI (*Open Systems Interconnection*) que dispone de cinco capas, la capa física, la capa de enlace, la capa de red, la capa de transporte y la capa de aplicación. Existen diferentes protocolos relacionados con cada una de las capas. Estos protocolos han de ser seleccionados teniendo en cuenta los requisitos y peculiaridades del sistema.

Un componente importante cuando se habla de protocolos IoT son las llamadas puertas de acceso que conectan dos redes diferentes que se comunican entre si mediante protocolos diferentes.

A continuación, se nombran algunos de los protocolos más utilizados:

- ***Bluettoth Low Energy***: especialmente diseñado para dispositivos de bajo consumo que requieren poco intercambio de datos. En la red pueden existir muchos dispositivos que trabajen con este protocolo desempeñando las acciones de emisor o de receptor.
- **6LoWPAN**: diseñado para redes de bajas capacidades, pero con escasa confianza en el aspecto de la seguridad; siempre es conveniente aplicar algún tipo de encriptación a los mensajes. Los dispositivos dentro de la red pueden tener dos roles, *router*, que envía datos a otros dispositivos, o huéspedes, que recogen y comparten datos.
- **ZigBee**: se trata de un protocolo con un gran sistema de seguridad. Transfiere la información haciendo uso de muy poca energía por lo que su alcance es corto, no obstante, el mensaje puede recorrer distancias largas rebotando en otros dispositivos ZigBee. Posee un bajo consumo de batería. Una red ZigBee posee una puerta de acceso que comunica los mensajes a internet.
- **NFC**: se trata de un protocolo que comunica dispositivos NFC (*Near Field Communication*) en distancias extremadamente cortas. Los dispositivos NFC son muy baratos y existen dos tipos, los dispositivos NFC que son capaces de intercambiar información y las tarjetas NFC que son elementos únicamente de lectura.

- **Sigfox**: se trata de un protocolo de bajo consumo que es capaz de enviar mensajes con un rango bastante amplio. Del mismo modo, los dispositivos son bastante baratos dados sus bajos, pero potentes requisitos.
- **LoRaWAN**: protocolo diseñado para comunicaciones de amplio rango, bajo ancho de banda y baja frecuencia. Es necesario el uso de una puerta de acceso para realizar las comunicaciones y los dispositivos pueden ser de diferentes tipos y tener diferentes comportamientos en función de las necesidades. Se trata de un protocolo de código abierto.
- **Wi-Fi**: se trata de un protocolo de comunicación que usa los estándares de Ethernet por lo que cuando se envía un mensaje la recepción del mismo no está garantizada. El principal problema es que consume una gran cantidad de energía por lo que no suele ser recomendado en dispositivos con cargas pequeñas o sin acceso fácil a la corriente eléctrica.
- **Móvil**: la tecnología móvil se comunica a través de ondas de radio. Utilizan tecnología IP con una gran tasa de datos. La principal ventaja de esta tecnología es que funciona perfectamente cuando un dispositivo cambia de una red a otra. Sin embargo, su uso de energía es considerablemente alto.
- **MQTT**: del inglés *Message Queue Telemetry Trasport* y operando sobre los protocolos IP y TCP se trata de uno de los protocolos más utilizados y conocidos en el campo del IoT. Es un protocolo de bajo consumo y que utiliza un ancho de banda pequeño. Las redes MQTT se componen de mensajeros, intermediarios y subscriptores utilizando para ello la arquitectura mensajero/subscriptor.
- **HTTP**: opera sobre los protocolos IP y TCP. Es muy útil en muchos sistemas IoT debido a su fiabilidad a la hora de enviar mensajes y su fácil disponibilidad e implementación. Sin embargo, no es el más apropiado dado el tamaño de los mensajes, su consumo y complejidad para dispositivos IoT.
- **CoAP**: del inglés *Constrained Application Protocol*; opera sobre los protocolos UDP e IP y está diseñado para dispositivos de bajo recursos. Transmite los mensajes siguiendo la arquitectura cliente/servidor.
- **DDS**: su abreviatura proviene de los términos ingleses *Data Distribution Service*. Es un protocolo que utiliza los estándares de comunicación *peer-to-peer* y la arquitectura mensajero/subscriptor.

B.2.2 Algoritmos inteligentes

Para una correcta implementación de un sistema IoT es necesario extraer todo el conocimiento e información almacenado en los datos recogidos por los sensores físicos. Con ese objetivo se pueden utilizar algoritmos inteligentes que se describen en las siguientes subsecciones.

Algoritmos de aprendizaje automático

El aprendizaje automático se defino como un área de las ciencias de la computación en el que algoritmos tratan de imitar el comportamiento del cerebro humano para aprender y tomar decisiones en base a experiencias previas y los datos. El uso de las técnicas de aprendizaje automático con respecto a las más tradicionales supone que se pueda extraer el conocimiento escondido en los datos con mucha mayor rapidez, de una forma más fácil de mantener y de forma general con mejores resultados. Esta área de las ciencias de la computación es especialmente útil cuando existe grandes cantidades de datos. El aprendizaje automático se clasifica en cuatro tipos:

- **Aprendizaje supervisado**: se utilizan datos etiquetados para que el algoritmo obtenga el conocimiento.
- **Aprendizaje no supervisado**: se utilizan datos sin etiquetar para obtener un conocimiento.
- **Aprendizaje semisupervisado**: utilizan la gran cantidad de datos sin etiquetar y una pequeña cantidad de datos etiquetados, suelen combinar técnicas de los dos tipos anteriores.
- **Aprendizaje reforzado**: en este tipo de aprendizaje se aprende teniendo en cuenta la acción realizada y la respuesta del entorno a esa acción. De esta forma, el algoritmo recibe una recompensa que determina si la acción es positiva o negativa.

Sin embargo, estos tipos de aprendizaje tienen algunos problemas y limitaciones comunes que dificultan el aprendizaje por parte de los algoritmos. Estos problemas son la cantidad de datos, datos poco representativos, datos de poca calidad, características irrelevantes para resolver el problema y sobreajustar o subajustar el modelo.

Del mismo modo, y para evitar algunos de estos problemas es muy importante configurar la estrategia de entrenamiento con los diferentes subconjuntos de datos que se van a utilizar en el proceso. De forma general se distinguen tres tipos de subconjuntos, el de entrenamiento, el de validación y el de prueba. La configuración correcta de este procesa determinará en parte el éxito del algoritmo entrenado.

A continuación, se describen brevemente algunos algoritmos de aprendizaje automático.

- **RIPPER**: se trata de un algoritmo basado en reglas que se crean y después se podan mediante un proceso con el que se asegura que no se pierde precisión en el algoritmo.
- **PART**: es un algoritmo basado en reglas que combina los algoritmos C4.5 y el RIPPER para obtener el conjunto de reglas. Las reglas se obtienen de árboles de decisión parciales, una regla por cada árbol generado.
- **C4.5**: se trata de un algoritmo de árboles de decisión. Los árboles se construyen teniendo en cuenta la ganancia de información y el ratio de ganancia.
- **Random Forest**: nuevamente es un algoritmo de árboles de decisión en el que los árboles se construye de forma totalmente aleatoria pero reduciendo la varianza para mejorar los resultados.
- **Random Tree**: de la misma forma que en el caso anterior, este algoritmo construye árboles aleatorios. No obstante, en este caso solamente un árbol es construido.

- **REPTree**: este algoritmo también construye un árbol de decisión, pero en este caso un árbol "rápido". Para ello utiliza las variables numéricas en los primeros nodos y la ganancia de información. Se produce un proceso de poda para disminuir la dimensión del árbol una vez éste está construido.

- ***k*-Nearest Neighbors**: se trata de un algoritmo que basa su conocimiento en las instancias del conjunto de datos. Las utiliza como vectores n dimensionales y compara esos k vectores más cercanos para determinar la clase de las nuevas instancias.

- ***k*Star**: es otro algoritmo basado en aprendizaje por instancias, pero en este caso no utiliza la distancia entre instancias si no la probabilidad de que una instancia se transforme en otra.

- **Redes bayesianas**: se basa en el principio de Bayes y pretende clasificar instancias mediante el cálculo de probabilidades.

- **Redes neuronales**: en la actualidad existen diferentes tipos de redes neuronales, muchas de ellas especializadas en tareas concretas dentro del área del aprendizaje automático. La red neuronal utilizada es el perceptrón multicapa donde diferentes capas de neuronas conectadas entre sí determinan la salida del algoritmo teniendo en cuenta sus pesos y el *bias* de cada capa. Tanto el *bias* como los pesos son modificados en cada una de las fases del entrenamiento con el objetivo de poco a poco ir mejorando los resultados ofrecidos por el algoritmo.

Algoritmos de sistemas de recomendación

Los sistemas de recomendación se pueden definir como algoritmos de toma de decisiones para usuarios en plataformas con gran cantidad de información. Resultan de gran utilidad cuando un usuario es nuevo en un sistema.

No obstante, los sistemas de recomendación también cuentan con una serie de problemas o limitaciones que es importante evitar o solventar. Estos problemas son el problema del arrancado en frío, la escasez de datos, el llamado problema de la oveja negra, la similitud entre objetos a recomendar o las valoraciones compradas por las marcas.

A continuación, se mencionan los diferentes tipos de sistemas de recomendación existentes:

- **Filtrado colaborativo**: en este tipo de técnica se utiliza una matriz usuario-objeto donde se guardan las preferencias de los usuarios por esos objetos. Esta matriz sirve para calcular la similitud entre los usuarios y poder hacer recomendaciones de productos o usuarios similares. Existen dos aproximaciones, las basadas en memoria (utilizan únicamente la matriz para establecer las recomendaciones) y las basadas en un modelo (utilizan un modelo de aprendizaje automático o minería de datos para establecer las recomendaciones).

- **Filtrado basado en el contenido**: se basa en las características de los productos u objetos para buscar otros similares mediante aprendizaje automático u otras técnicas y así realizar las recomendaciones.

- **Filtrado híbrido**: como su nombre puede indicar es una técnica que hace uso de varias, en este caso del filtrado colaborativo y del basado en el contenido. Combinando ambas técnicas se pueden obtener mejores resultados y evitar los fallos de ambas técnicas.
- **Otros técnicas**: existen otras aproximaciones a los sistemas de recomendación propuestos por otros autores para el caso específico de sistemas IoT. Estas técnicas son: la basado en conocimiento en donde se intentan satisfacer los requisitos predefinidos por los usuarios y la basada en utilidad que recomienda acciones para satisfacer la utilidad definida por el usuario.

Sistemas de control

Los sistemas de control han demostrado ser la solución perfecta para muchos sistemas IoT. Son capaces de regular el comportamiento de complejos sistemas o dispositivos mediante ciclos de control. En esos ciclos se utiliza la respuesta del sistema para comparar la salida del control con la deseada y aplicar la diferencia para determinar el nuevo estado del sistema. No obstante, existen diferentes modelos de control y no todos utilizan la respuesta del sistema. A continuación, se detallan los más importantes.

- **Control lógico**: responde a cambios en sensores e interruptores y ejecutan la acción deseada. Son muy utilizados en industria.
- **Control de encendido y apagado**: estos controles utilizan la respuesta que recibe el sistema para determinar si han de cambiar el estado del sistema pasando de encendido a apagado o viceversa.
- **Control lineal**: estos controles utilizan una respuesta negativa para obtener el valor deseado en la salida del sistema. Existen diferentes tipos, (I) control proporcional, (II) control proporcional integrado y (III) control proporcional integrado derivativo. Cada uno de ellos es una evolución del anterior para de esta forma solventar los posibles problemas que puedan tener.
- **Control borroso**: está basado en los conceptos de la lógica donde se definen conjuntos para determinar la permanencia de un valor a dicho conjunto. Estos conjuntos borrosos pueden ser definidos de diferentes formas en función de las características del problema a resolver. De forma general, durante el proceso del control borroso existen dos pasos fundamentales, la "fuzzificación" y la "desfuzzificación". El primero transforma una variable no borrosa en una borrosa y el segundo hace la acción inversa. Por otro lado, existen diferentes tipos de controles borrosos, sin embargo, los más comunes son, (I) Mamdani y (II) Takagi-Sugeno. De forma general, son bastante parecidos entre sí ya que ambos utilizan una serie de reglas y el proceso de "fuzzificación". No obstante, (I) utiliza el proceso de "desfuzzificación") y (II) utiliza una función predefinida en función del problema que determina la salida.

B.2.3 Sistemas multiagentes

Un agente se define como una entidad física o de software que puede interactuar con su entorno y que tiene un comportamiento propio. Los sistemas de agentes ya han sido aplicados a entornos de IoT. De hecho, es lógico pensar que los agentes se puedan utilizar en este tipo de sistemas ya que son sistemas que cuentan con un gran número de sensores y actuadores que pueden ser controlados de forma inteligente.

Los agentes comparten una serie de características que los definen bastante bien: adaptabilidad, autonomía, comportamiento colaborativo, racionalidad, proactividad, iniciativa, movilidad, benevolencia, presencia, carácter y personalidad. Por otro lado, los agentes se pueden clasificar en cuatro tipos distintos: (I) agentes de reflejo, simplemente actúan frente a una acción desarrollada en el entorno; (II) agentes de reflejo interno, que también hacen uso de información interna para determinar la salida; (III) agentes basados en objetivos, tratan de alcanzar sus objetivos en base a sus posibles acciones; y (IV) agentes basados en utilidad, determinan la acción a desarrollar estudiando cual de todas las posibles es la que ofrece una mayor utilidad.

Cuando existen varios agentes en un mismo entorno y no solo interactúan con este sino también entre ellos se forma un sistema multiagente. Estos sistemas permiten a los agentes desarrollar habilidades sociales, establecer comunicaciones, compartir información y trabajar conjuntamente para lograr el objetivo global del sistema. Las características principales de los sistemas multiagentes son: flexibilidad, adaptabilidad escalabilidad, diferenciación y resistencia.

B.3 Capítulo 4 - Conclusiones

B.3.1 Contribuciones

Se han desarrollado varias revisiones del estado del arte durante esta investigación. Primero, una investigación sobre las diferentes aplicaciones y protocolos en entornos IoT. Esta revisión ayudo a comprender e identificar las fortalezas y debilidades de la tecnología IoT, así como estudiar los protocolos y tecnologías de comunicación. Este estudio permitió seleccionar los protocolos más adecuados para los casos de estudio mostrados en los artículos de investigación.

La segunda revisión nos permitió analizar diferentes algoritmos de inteligencia artificial y seleccionar el mejor para cada uno de los casos de estudio. Estos algoritmos hacen uso de los datos de un entorno IoT para obtener el conocimiento escondido en los datos. Los algoritmos de aprendizaje automático, algoritmos de recomendación y sistemas de control han sido estudiados para desarrollar el sistema más apropiado a cada situación.

Además, también se ha desarrollado una revisión sobre los sistemas multiagentes. Esta revisión permitió identificar las principales características de los sistemas multiagentes y así entender e identificar las características que han de tener. Por otro lado, esta revisión acentuó la importancia que los sistemas multiagentes tienen actualmente en el campo del IoT y del aprendizaje automático.

Teniendo en cuenta las revisiones mencionadas, en este trabajo se ha desarrollado un sistema con las siguientes características: (I) el sistema usa redes de sensores para recoger datos y enviarlos a un sistema central, (II) los datos son almacenados y analizados usando algoritmos inteligentes para maximizar la eficacia del sistema, (III) el sistema está basado en una arquitectura multiagente para resolver problemas y alcanzar los objetivos de los diferentes agentes y (IV) el sistema trata de minimizar el impacto que tiene el consumo de energía de las viviendas en el medio ambiente.

En consecuencia y para probar el mencionado sistema, se han diseñado diferentes casos de estudio. Los casos de estudio son explicados en detalle en los artículos científicos de esta tesis doctoral. Se han llevado a cabo tres estudios. El primero de ellos propone un sistema multiagente que pueda recoger datos de la red eléctrica mediante el uso de sensores y la computación de esos datos para identificar los dispositivos electrónicos conectados en una vivienda. El método usado para identificar los electrodomésticos combina técnicas NILM y algoritmos de aprendizaje automático, lo cual, ofrece una nueva perspectiva para resolver este tipo de problemas. Es más, el sistema propuesto reduce el impacto que la energía eléctrica tiene en el medio ambiente debido a una política de apagado para algunos electrodomésticos que no son importantes o no están siendo usados.

El segundo estudio también hace uso de un sistema multiagente para obtener los datos de los sensores y un robot web para ofrecer recomendaciones a los usuarios que desean cambiar su patrón de comportamiento para reducir el impacto que el consumo de energía eléctrica tiene en el medio ambiente. El sistema desarrollado ha demostrado funcionar perfectamente y las recomendaciones se adaptan a los patrones de consumo para no provocar grandes y repentinos cambios en el estilo de vida de los usuarios. Además, las diferentes simulaciones del sistema muestran que si esta solución es aplicada a varias viviendas o vecindarios el impacto causado en el consumo eléctrico puede ser importante y de esta forma que la contaminación ambiental se reduzca.

El tercer estudio muestra como un sistema multiagente puede ser utilizado en un sistema de calefacción central para reducir el consumo de combustible y la polución. El sistema propuesto usa sensores para obtener del entorno datos y usarlos para determinar la salida más apropiada para el sistema de calefacción. La solución propuesta ha demostrado que ofrece una reducción en consumo de energía, en la factura y reduce la contaminación. Es por ello que la solución parece que alcanza su objetivo. Es más, los resultados ilustran que el coste del *hardware* es extremadamente barato teniendo un retorno de la inversión de alrededor de 10 días.

Por último, durante los años académicos de este doctorado, además de las contribuciones científicas mostradas en este libro, otros artículos científicos han sido publicados en relevantes revistas científicas o congresos y conferencias internacionales. También, y siguiendo los criterios de la comisión académica del programa de doctorado, se han realizado varios cursos y se han asistido a conferencias para aumentar el conocimiento base; además se han realizado varías estancias internacionales en varias instituciones.

B.3.2 Trabajo futuro

Esta sección resume las líneas futuras de investigación de este trabajo.

En primer lugar, todos los estudios han demostrado funcionar perfectamente. Sin embargo, sería realmente interesante probar el sistema propuesto en un entorno más profesional y extender el sistema a un entorno más grande, como una ciudad o un vecindario.

Particularmente, el primer estudio puede ser mejorado fácilmente aumentando el número de dispositivos detectados por el sistema propuesto. Además, el uso de una técnica más compleja para identificar los patrones en los datos puede mejorar los resultados y de esta forma la experiencia de los usuarios.

El segundo estudio puede ser ampliado extendiendo el estudio a otros países colectando para ellos los precios de la electricidad. Además, la solución no puede estar limitada a un único modelo de enchufe inteligente; si el sistema quiere ser implantado en otros países otras marcas de enchufes inteligentes han de incluirse en el estudio. De forma adicional, si el sistema de recomendación esta basado principalmente en reducir impacto financiero, los costes y los picos de consumo pueden verse reducidos.

Finalmente, el tercer estudio se podría plantear de una forma totalmente diferente. En lugar de controlar la calefacción central con un único control, los radiadores de las diferentes habitaciones pueden ser controlados por diferentes controladores. Esta solución puede aumentar el bienestar de los usuarios dado que pueden definir diferentes temperaturas en las diferentes áreas de la casa. Es más, el estudio está basado en una simulación software, pero sería muy interesante probarlo en un entorno real como ya se ha mencionado anteriormente.

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