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I2ME2 IoT-IBMS:
Un Sistema de Gestión de la Información basado en IoT para Eficiencia Energética en Edificios Inteligentes

I2ME2 IoT-IBMS:
An IoT-based Information Management System for Energy Efficiency in Smart Buildings

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Tesis Doctoral

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Ph.D. Thesis

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A mis padres

Me habéis agregado la fuerza de todos los que viven.
Me enseñasteis a encender la bondad como el fuego.
Me disteis la rectitud que necesita el árbol.
Me enseñasteis a dormir en las camas duras de mis hermanos.
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Capítulo 1

Resumen

1.1. Objetivos y Metodología

Un edificio inteligente es aquel que ofrece a sus ocupantes servicios personalizados gracias a su capacidad de monitorización y gestión del entorno. Siguiendo este enfoque, es posible extraer grandes cantidades de información útil del contexto del edificio, que tras su procesado, permita reconocer patrones de comportamiento de aquellos aspectos involucrados en el consumo energético, y que sirvan para llevar a cabo un control y toma de decisión dirigida al ahorro energético. Sin embargo, y aunque se está prestando mucha atención a las tecnologías desplegadas en edificios, el área de investigación y trabajo que propone explotar la amplia capacidad de sensorización que tecnologías basadas en IoT ofrecen, las cuales permiten integrar información del mundo real en la gestión de las infraestructuras de edificios para eficiencia energética, no ha sido todavía totalmente explotada.

En este sentido, y considerando la urgente necesidad de proponer soluciones que aseguren la eficiencia energética en edificios como factor indispensable para la sostenibilidad de las ciudades modernas y la del planeta, y teniendo en cuenta el gran potencial que ofrece los Sistemas Inteligentes basados en IoT, en esta tesis se analizan cuáles son los principales parámetros que afectan al consumo energético de edificios con el objetivo de proponer acciones que permitan el ahorro energético asociado. Después, se describe una propuesta general de sistema de gestión para edificio inteligente, la cual se basa en la monitorización y análisis de la información recolectada, de forma tal que sea posible proponer acciones específicas para el control de las infraestructuras de edificios con el objetivo de ahorrar consumo energético. La solución propuesta integra información proporcionada por diferentes fuentes de información, y propone acciones concretas para minimizar el consumo del edificio considerando el contexto específico de éste. Para esto se propone una plataforma basada en la integración óptima de diferentes fuentes de información, entre ellas, la información proporcionada por el propio usuario del sistema.

Esta propuesta de sistema de gestión para edificio inteligente aborda los servicios de eficiencia energética, servicios de confort ofrecidos a los usuarios, monitorización ambiental y seguridad, entre otras. El enfoque de nuestra solución está basado en el uso de tecnologías IoT, las cuales nos permiten obtener datos desde una gran cantidad de diferentes fuentes de información, y además, es capaz de gestionar un gran rango de dispositivos automatizados del edificio. De esta forma, nuestro sistema de gestión inteligente analiza toda la información monitorizada, y dependiendo del modo de operación requerido en el edificio y considerando el estado del balance energético en el mismo, tomar decisiones que mejoren la eficiencia energética del edificio, al mismo tiempo que se mantienen niveles aceptables de las condiciones de confort ofrecidas a los ocupantes.

En este sentido, la motivación de esta tesis es la de diseñar un **Sistema de Gestión de la Información basado en IoT para Eficiencia Energética en Edificios Inteligentes**.

Una vez presentada la motivación de la presente tesis doctoral y el tema central de la misma, enumeramos a continuación los objetivos a satisfacer y que sirvieron de guía para el desarrollo de la tesis.

- O1. Análisis e identificación de los requisitos y necesidades de los sistemas de gestión de información para eficiencia energética en edificios inteligentes.
- O2. Identificación de limitaciones y restricciones de las propuestas en literatura relativas a los sistemas de gestión de información para eficiencia energética en edificios.
- O3. Propuesta de una arquitectura general de diseño de sistemas de gestión de edificios inteligentes.
- O4. Propuesta de sistema de gestión de la información para eficiencia energética en edificios inteligentes.
- O5. Validar dicha propuesta de forma que se demuestre la viabilidad de su integración en diferentes escenarios reales.

La presente tesis propone un nuevo enfoque de solución que intenta hacer frente a las cuestiones más relevantes involucradas en el consumo energético en edificios. Este trabajo comienza con el estudio y análisis de cómo la energía es usualmente consumida en edificios. Tras estos análisis, identficamos el conjunto de parámetros que compondrán las entradas de nuestra propuesta de sistema de gestión energética en edificios. Estos parámetros son seleccionados tras la revisión de modelos y estándares sobre el confort y comportamiento energético de edificios. Después, realizamos una extensa revisión de soluciones previas propuestas en literatura que tratan el problema de la gestión de edificios para ahorro energético. Tras esta revisión, identificamos las principales limitaciones y restricciones de las soluciones planteadas hasta la fecha, entre ellas la carencia de incluir al usuario como parte fundamental de la operación del sistema. Con el objetivo de tener información sobre la evolución en tiempo real del valor de las entradas seleccionadas, y la toma de decisión o control asociado que permita asegurar la eficiencia energética y el confort en el edificio, se propone una arquitectura general para nuestro sistema de gestión de edificios inteligentes. Dicha arquitectura se encuentra modelada en tres capas: una primera capa de recolección de datos, una segunda de procesado de la información, y una tercera capa de servicios.

La presente tesis doctoral trabaja sobre esta propuesta de arquitectura genérica instanciada para su aplicación en eficiencia energética de edificios. En este sentido, se propone una estrategia general para el diseño de sistemas de gestión inteligente para el ahorro energético en edificios. Dicha propuesta considera como entradas los parámetros identificados durante la fase previa de análisis como relevantes por su impacto en el consumo energético del edificio. Tras esta propuesta, en este trabajo se analiza cómo la integración de: información de localización de los ocupantes, información sobre las preferencias de estos en términos de confort, y la participación e interacción del usuario con el sistema, afectan al ahorro energético en edificios. Para conseguir dicho ahorro, se proponen medidas de control y gestión de las infraestructuras automatizadas del edificio que aseguren la eficiencia energética del mismo. Siguiendo este enfoque, llevamos a cabo diferentes estudios y experimentos en varios edificios utilizados como referencia. Los resultados de dichos experimentos reflejan que nuestra propuesta de solución consigue ahorrar energía, al mismo tiempo que se mantiene la calidad de los diferentes servicios ofrecidos en el interior del edificio. Tras esta fase de experimentación, demostramos la aplicabilidad de nuestra propuesta.

Teniendo en cuenta la motivación y los objetivos de este trabajo, y tras presentar nuestra propuesta de solución al problema de la gestión de edificios para eficiencia energética, en el siguiente apartado se describen los resultados conseguidos durante el desarrollo de esta tesis.

1.2. Resultados

En el marco de la presente tesis se han realizado numerosas contribuciones recogidas todas ellas en diferentes artículos científicos y capítulos de libro. Algunos de estos trabajos no están descritos en detalle en el presente manuscrito, debido a la normativa para este tipo de presentación de tesis doctoral.

Gran parte del trabajo está basado en estudios y análisis del consumo energético en edificios, así como en la propuesta y experimentación de diferentes estrategias de control para ahorrar energía. Otros trabajos realizados y publicados durante el desarrollo de la presente tesis abordan aspectos más específicos relativos a la gestión de infraestructuras inteligentes, claves para la resolución de los objetivos planteados en esta tesis.

Como ejemplos de estos trabajos más específicos, se participó en la elaboración de dos trabajos que abordan retos relacionados con las ciudades inteligentes [46], [42]. En ellos se propone una plataforma basada en IoT para proporcionar, desde una perspectiva colaborativa y social, servicios inteligentes centrados en el usuario. Adicionalmente, en el trabajo con referencia [59] se abordan los principales retos en materia de seguridad que actualmente plantea el paradigma de IoT, y su impacto sobre la gestión de las ciudades inteligentes.

Abordando el problema central a resolver en el marco de la presente tesis, es decir, la propuesta de un sistema de gestión de la información para eficiencia energética en edificios inteligentes, primero se realizó un análisis para la identificación de los principales parámetros que afectan al consumo energético en edificios [44]. Luego, se llevó a cabo una extensa revisión del estado del arte de las soluciones propuestas hasta la fecha, identificando sus principales limitaciones y restricciones [57], [44].

Tras esta fase inicial de análisis, se propuso una arquitectura general para el diseño de sistemas de gestión de edificios inteligentes [49], [48], [44]. Teniendo en cuenta dicha arquitectura, se diseñó nuestro sistema de gestión de la información para eficiencia energética en edificios inteligentes [44].

Realizada esta propuesta, la resolución de la localización de los ocupantes de edificios fue identificado como un requisito a satisfacer en la propuesta de nuestro sistema. Como solución a este problema, en esta tesis se proponen dos enfoques a la hora de resolver la localización en espacios de interior. Una de las soluciones está basada en un mecanismo híbrido basado en la fusión de información proporcionada por diferentes tipos de sensores, sensores infrarrojos (IR) y un sistema de identificación por radiofrecuencia (RFID). En los trabajos con referencia [53] y [56] (éste último incluido para el compendio de la presente tesis) se describe con detalle dicha solución. La segunda propuesta de solución al problema de la localización en edificios se basa en un mecanismo que utiliza la información proporcionada por los sensores magnéticos integrados en los teléfonos inteligentes. Dicha solución de localización fue integrada en un mecanismo de control de acceso distribuido de objetos inteligentes desplegados en edificios. En los trabajos [45] y [43] se recoge dicha integración, y en el trabajo [58] detallamos el mecanismo de control de acceso en cuestión.

Otro subproblema derivado de la localización, fue el de la monitorización de la trayectoria (tracking) de individuos. Disponer de esta información es útil para inferir el nivel de actividad de cada ocupante, así como para el reconocimiento de patrones de comportamiento en el edificio. Abordando el tema de la fusión de datos multisensoriales y el tracking de individuos, se publicaron los dos siguientes artículos [52], [47]. A pesar de que el contexto de la solución propuesta en estos trabajos no está enmarcado en edificios, es una propuesta válida y extensible a espacios de interior, cuyos principios técnicos fueron posteriormente aplicados para la resolución de la localización [56].

Resuelta la localización e identificada la necesidad de la estimación de las condiciones óptimas de confort a ofrecer a los ocupantes de los edificios, se diseñó un sistema de gestión para eficiencia energética en edificios teniendo en cuenta ambos aspectos [54], [50].

Como extensión de esta primera propuesta de sistema de gestión, se propuso la integración del usuario como parte fundamental de la operación del sistema. Para esto, se analizó el impacto de fomentar la interacción del usuario con el sistema, así como el hecho de proporcionar información del consumo energético del edificio asociado al comportamiento de cada usuario [54], [50], [55],

Para la evaluación y validación de todos las propuestas y mecanismos implementados, los cuales componen el sistema final de gestión desarrollado en esta tesis, diferentes experimentos se llevaron a cabo en varios edificios tomados como referencia. Todas las pruebas realizadas consiguieron validar la viabilidad y eficacia del sistema desarrollado [44].

Con el resultado de la presente tesis, es decir, con nuestra propuesta de sistema de gestión para eficiencia energética en edificios, se participó en los premios nacionales "Contratos y Proyectos Smart Cities 2014", convocada por la Fundación Socinfo y la revista "Sociedad de la Información", de la cual este trabajo resultó merecedor del premio en la categoría "Gestión de Edificios" [1].

Una vez presentados todos los resultados alcanzados tras el periodo de desarrollo de la presente tesis, a continuación se recogen en el Cuadro 1.1 aquellos asociados a la propuesta de un sistema inteligente de gestión de la información para eficiencia energética en edificios inteligentes, indicando además junto a ellos el objetivo al que hace referencia. En el Capítulo 3 se explica con más detalle cómo se consiguieron todos estos resultados, y se presentan las principales características del sistema de gestión propuesto en esta tesis.

Nro.	**Resultado**	**Objetivo**	**Publicación**
1	Análisis de requisitos de los sistemas inteligentes para eficiencia energética en edificios, e identificación de principales parámetros que afectan al consumo energético en edificios	O.1	[44]
2	Identificación de limitaciones y restricciones de las propuestas en literatura relativas a los sistemas de gestión de información para eficiencia energética en edificios.	O.2	[57], [44]
3	Diseño de la arquitectura general de los sistemas de gestión de edificios inteligentes basados en IoT	O.3	[49], [48], [44]
4	Diseño de un sistema de gestión de la información para eficiencia energética en edificios inteligentes	O.4	[54], [50], [55], [44]
5	Implementación y validación de un mecanismo de localización para espacios de interior	O.4	[53], [56]
6	Implementación y validación de un mecanismo de gestión de edificios para eficiencia energética incluyendo información de localización de los ocupantes y sus preferencias en cuanto a las condiciones de confort	O.4	[54], [50]
7	Implementación y validación de un mecanismo de gestión de edificios para eficiencia energética incluyendo al usuario como entrada del sistema	O.4	[55], [48], [51], [44]
8	Validación de la propuesta de sistema de gestión de la información para eficiencia energética en diferentes escenarios reales	O.5	[44]

Cuadro 1.1: Resultados de la tesis doctoral, objetivos asociados y citas a los trabajos donde están descritos.

1.3. Conclusiones

La propuesta de sistemas de gestión para eficiencia energética en edificios ha sido reconocida como una pieza fundamental para asegurar la sostenibilidad energética de las ciudades modernas, así como la del planeta. Las soluciones planteadas hasta ahora al problema del gran consumo energético de edificios presentan numerosas limitaciones, al tiempo que muchas de ellas tienen asociada una gran complejidad.

Los numerosos avances conseguidos en TICs, y sobre todo el paradigma de IoT, presentan un gran potencial en cuanto a la cantidad de información del mundo real que son capaces de proporcionar, al mismo tiempo que permiten interaccionar con el entorno y cambiar su comportamiento para

[1] `http://www.socinfo.es/seminarios/2837-premios-qcontratos-y-proyectos-smart-cities-2014q`

proporcionar servicios más eficientes. En este sentido, los sistemas de gestión de edificios inteligentes centrados en alcanzar su eficiencia energética han cobrado una gran relevancia en los últimos años.

La presente tesis doctoral presenta el diseño de un sistema de gestión de la información basado en IoT para eficiencia energética en edificios inteligentes. La línea de trabajo ha tenido dos vertientes. Por un lado, se ha seguido un enfoque teórico para identificar las necesidades y requerimientos para conseguir eficiencia energética en edificios. A continuación, se analizaron las limitaciones y problemas de las propuestas en literatura que abordan la gestión en edificios para su eficiencia energética.

Tras este estudio teórico, se propuso una modelo de carácter general en el que se establecen las entradas a considerar en la gestión del edificio para conseguir eficiencia energética, así como las posibles salidas del mismo. La idea de este modelo es la de su instanciación específica en edificios enmarcados en un contexto determinado. De esta forma, por cada contexto son analizadas las entradas con un relevante impacto en el consumo energético, así como las salidas a considerar atendiendo a las características funcionales de dicho contexto.

Como parámetros relevantes a considerar durante la gestión del edificio, está la información sobre la localización de los ocupantes. Disponer de esta información permite llevar a cabo una gestión más precisa de las infraestructuras del edificio, al tiempo que se consiguen satisfacer requerimientos más individualizados de los servicios de confort ofrecidos. Por esta razón, en esta tesis se implementó un mecanismo de localización en espacios de interior basado en la fusión de datos provenientes de sensores infrarrojos y un sistema RFID encargado de monitorizar a los ocupantes del edificio. La precisión en los resultados alcanzados tras la evaluación de este mecanismo, cubre de manera satisfactoria las necesidades en cuánto a la precisión requerida en los datos de localización a integrar durante la gestión del edificio, proporcionando una precisión media de 1.5 m de error en localización.

Resuelta la localización, se desarrolló un mecanismo capaz de predecir las condiciones de confort a proporcionar a los ocupantes atendiendo a las preferencias de estos, a las condiciones medioambientales y al nivel de actividad inferido en el edificio. La tasa de éxito media en la estimación de los parámetros óptimos de confort según las condiciones contextuales del problema fue del 91 %.

Una vez implementados los mecanismos encargados de proporcionar información sobre la localización de los usuarios del sistema y las condiciones de confort a establecer según las preferencias de los mismos, se integró dicha información como entradas del sistema de gestión propuesto para eficiencia energética, y se realizaron experimentos en varios edificios inteligentes tomados como referencia. El objetivo de estos experimentos es la de extraer el impacto de incorporar dicha información en términos del ahorro energético alcanzado. Los resultados demostraron que considerando dicha información como entrada del sistema de gestión, y estableciendo las correspondientes medidas de gestión de las infraestructuras del edificio involucradas, es posible alcanzar un ahorro energético medio al mes de operación del sistema de gestión del 20 %, en comparación con el consumo del mes anterior, durante el cual no se consideró ningún tipo de gestión para eficiencia energética en el edificio.

La siguiente extensión del sistema de gestión propuesto consiste en incorporar al propio usuario del sistema en la operación del mismo. El objetivo aquí es el de involucrar al usuario en el ahorro del consumo energético del edificio. Para este objetivo se establecieron diversas estrategias tales como: proporcionar información sobre el consumo energético asociado a la actividad del propio usuario, ofreciendo consejos y recomendaciones a llevar a cabo y dirigidas al ahorro energético, permitiendo al usuario que estableciera su propias reglas de control en el sistema de gestión, etc. Varios experimentos se llevaron a cabo para evaluar el impacto de esta extensión del sistema. Como resultado de dichos experimentos, y tras hacer conscientes a los usuarios del impacto que sus comportamientos tenían en términos de consumo energético, pudo comprobarse cómo los usuarios del sistema cambiaron su comportamiento asociado al uso que realizaban de las infraestructuras del edificio. De esta forma, y tras un mes de experimentación, se consiguió incrementar en un 9 % el ahorro hasta ahora conseguido, alcanzando así hasta un 29 % de ahorro en el consumo energético en un edificio con un alto nivel de sensorización y automatización.

Tras alcanzar todos los objetivos planteados al inicio de la presente tesis doctoral, y en vista de los resultados conseguidos, podemos afirmar que ha sido demostrada y validada la aplicabilidad

y efectividad del sistema propuesto para la gestión de información basado en IoT para eficiencia energética en edificios inteligentes.

Chapter 2

Abstract

2.1. Goals and Methodology

A smart building provides occupants with customized services thanks to their monitoring and management capabilities. Following this approach, it is possible to extract useful information about the context of the building, which, after processing, allows recognition of behaviour patterns of aspects involved in energy consumption to make optimal decisions on saving energy. Nevertheless, although much interest has been put into smart building technologies, the research area of using the great monitoring capacity of IoT technologies, which permits information from the real world to be integrated into the management of building infrastructures to save energy, has not been fully exploited.

In this sense, and considering the urgent need for proposing solutions to the energy efficiency of buildings as indispensable requirement for the sustainability of the planet, and taking into account the powerful possibilities offered by Intelligent Systems based on IoT, this thesis presents an analysis of the main parameters that affect the energy consumed in buildings. We then describe our proposal for smart management systems of buildings, which is based on collecting and analyzing information in an effective way so that specific actions can be proposed for the control of building infrastructures in order to save energy. This solution involves information from a variety of sources, and proposes concrete actions to minimize energy consumption considering the specific context of the target building. For that, we propose a platform based on the optimal integration and use of the gathered information, which is provided by, among others, the users themselves.

This smart management system addresses the problem of energy efficiency of buildings, comfort services for occupants, environmental monitoring and security issues, among others. It focuses on the use of IoT technologies, which allows data to be gathered from a plethora of different sources, and is able to control a wide range of automated appliances in the building. Thus, our smart energy building management system analyzes all monitored data provided and, depending on the required operation mode and considering the energy balance status of the building, takes decisions to improve energy efficiency, while retaining environmental conditions at different user-acceptable comfort levels.

In short, the aim of this thesis is to **design an Information Management System based on the IoT to improve the energy efficiency of smart buildings**. Below, we set out the objectives that must be attained for this aim to be fulfilled, which will serve as a guide to how the thesis is developed.

- O1. Analysis and identification of the needs of Information Management Systems to improve the energy efficiency of smart buildings

- O2. Identification of the limitations and restrictions of previously published proposals concerning Information Management Systems to improve the energy efficiency of smart buildings

- O3. Proposal of a general design of smart building management systems.

- O4. Proposal of an Information Management System to improve the energy efficiency of smart buildings
- O5. Validation of the proposal, confirming the viability of its integration in different real scenarios.

The present thesis proposes a new solution to the most important questions involved in the consumption of energy by buildings. We first analyse how energy is usually consumed in buildings, and then propose a series of parameters that will represent the inputs of our proposal for energy management. These parameters have been selected base on a revision of models and standards on comfort and energy behaviour in buildings. Then, we will make an extensive studio of previous solutions proposed in the literature. We identify the main limitations and restrictions of the solutions proposed to date. With the aim of having information on the real time evolution of the values of the inputs selected and taking decisions to ensure energy efficiency and user comfort in the building concerned, we propose a general architecture for the management of smart buildings. This architecture will be modelled at three levels: data collection; data processing; and lastly, services.

The thesis proposes a generic architecture for application in building management systems. We propose a strategy for designing smart management systems to save energy, using as inputs the parameters identified during the previous phase of the analysis as relevant for their impact on energy consumption. We then analyse how the integration of information on the localization of occupants, their preferences in terms of comfort and the participation and interaction of users affect energy saving. In this way, we carry out studies and experiments in different buildings used as reference. The results of these confirm that our proposal saves energy while maintaining the quality of the comfort services offered in the building.

Bearing in mind the aim of this thesis and after presenting our proposal for an energy saving management system, we describe below the results obtained.

2.2. Results

The body of this thesis is included in several published articles and book chapters. Some of these are not described in detail in the present manuscript due to the norms governing this type of PhD thesis. Much of the work is based on studies and analyses of the energy consumed by buildings and the proposal and experimentation carried out to save such expenditure. Other studies and publications stemming from the thesis tackle specific aspects related with the management of smart infrastructures, key elements for resolving the set objectives.

As an example of such specific works, we took part in two studies related with smart cities [46], [42], in which an IoT-based platform is proposed to supply, from a social and collaborative point of view, user-centred smart services. In [59] we look at the main challenges in terms of security associated with the IoT and the management of smart cities.

As regards the central theme of this thesis, i.e. the proposal of a smart management system of buildings for energy efficiency, we first made an analysis to identify the principal parameters affecting energy consumption in buildings [44], making an extensive revision of the state of the art of the solutions proposed to date, and identifying the main limitations and restrictions of the same [57], [44].

After the initial phase of the analysis we proposed a general architecture for the design of smart building management systems (SBMS) [49], [48], [44]. Bearing in mind this architecture, we designed our information management system to save energy in smart buildings [44].

After this proposal, localization of the occupants of the building was identified as a main problem in the proposed system. To solve this, we propose two solutions to the indoor localization problem. One solution is based on a hybrid mechanism based on the fusion of information provided by different types of sensors – infrared (IR) and radiofrequency identification (RFID). In previous works, [53] and [56] (the latter included in the manuscript of this thesis), this solution is described in detail. The second solution proposed to the localization problem is based on a mechanism that uses information provided by magnetic sensors integrated in smart telephones. This localization solution was integrated in a distributed access control mechanism carried out by smart objects deployed in buildings. In [45] and [43] such an integration is described, and in [58] we retail the access control mechanism in question.

Another problem related with localization is that of user tracking. Such information is useful to infer the level of activity of each occupant, and for establishing user behaviour patterns in the building. Based on the fusion of multisensory data and user tracking, the following two articles were published [52], [47]. Although the context of the solution proposed in these articles was not building-related, the proposal remains valid and extrapolated to interior spaces, and whose technical principles were subsequently applied to solve the localization problem [56]. Having solved the localization problem and identified the need to estimate the optimal comfort conditions of the building occupants, we designed an energy management system bearing both aspects in mind [54], [50].

As an extension of this first proposal of a building management system for energy efficiency, we proposed integrating the user as a fundamental part of the system operation. For this, we analysed the impact of encouraging the interaction of the user with the system and of providing users with information on the energy consumption of the building related with their behaviour [54], [50], [55].

To evaluate and validate all the implemented proposals and mechanisms that compose the final management system of this thesis, several experiments were carried out in different buildings. All the tests confirmed the viability and efficacy of the system [44].

With the results obtained from our management system, we took part in the competition "Contracts and Projects: Smart Cities 2014", organised by the Socinfo Foundation and the Spanish Journal "Sociedad de la Información", and where it was awarded with the first prize in the category "Building Management" [1].

After presenting all the results obtained in this thesis, those associated with the main contribution are presented in Table 2.1, alongside the objective referred to. In Chapter 3 we explain in more retail how these results were obtained, and the principal characteristics of the system proposed in this thesis are presented.

2.3. Conclusions

Energy efficiency in buildings is recognised as a fundamental piece for ensuring energy sustainability in modern cities and even the planet. The solutions put forward to date concerning the great amount of energy consumed by buildings have numerous limitations and many are extremely complicated.

The many advances made in TICs and, especially, IoT represent a great potential as regards the quantity of real world information that can be obtained and, at the same time, permit interaction with the environment and to change behaviour in order to provide more efficient services. In this sense, the information building management systems have taken on more relevance.

This thesis presents an IoT-based design for an information management system to improve energy efficiency in smart buildings. The work plan has followed two perspectives: a theoretical focus to identify the requirements for improving energy efficiency in buildings, followed by an analysis of the limitations and problems of solutions proposed in the literature for this respect.

After this theoretical analysis a general model was proposed in which the inputs and outputs to be considered in the management proposed to improve energy efficiency in buildings were identified. The idea of this model was its instantiation in buildings in a given context. For each context, the inputs representing a relevant energetic impact in buildings are analysed, as the target outputs according to functional characteristics of the building context.

Information on the localization of the occupants is an important factor since it permits a more precise management of the building, while satisfying the individual comfort needs of the occupants. This is why we implement a localization mechanism for enclosed spaces based on fusing the data from infrared sensors and an RFID system. The accuracy obtained after evaluation of the mechanism

[1] `http://www.socinfo.es/seminarios/2837-premios-qcontratos-y-proyectos-smart-cities-2014q`

Nb	Result	Objective	Publication
1	Analysis of the prerequisites for building energy management systems and identification of the principal parameters that affect energy consumption in buildings	O.1	[44]
2	Identification of the limitations and restrictions of previously published proposals concerning Information Management Systems to improve the energy efficiency of smart buildings	O.2	[57], [44]
3	Design of a general architecture for management systems of smart buildings based on IoT	O.3	[49], [48], [44]
4	Design of an information management system for energy efficiency in smart buildings	O.4	[54], [50], [55], [44]
5	Implementation and validation of an indoor localization mechanism	O.4	[53], [56]
6	Implementation and validation of a building management mechanism which integrates user location data and information about comfort preference of occupants for energy efficiency	O.4	[54], [50]
7	Implementation and validation of a building management mechanism which integrates user behaviour and participation for energy efficiency	O.4	[55], [48], [51], [44]
8	Validation of the proposal, confirming the viability of its integration in different real scenarios	O.5	[44]

Table 2.1: Results of the thesis and cites to the associated papers where such results are presented.

amply covered the requirements as regards the data to be integrated in the building management system with a mean accuracy error of 1.5 m.

Having solved the localization problem, we developed a mechanism for predicting the comfort conditions that would be necessary bearing in mind the occupants' preferences, the environmental conditions and the activity level of the building. The mean success rate in estimating the optimal comfort parameters according to contextual conditions was 91%.

The above information concerning user localization and preferred comfort conditions served as input for building management system for energy efficiency, and experiments were carried out in several smart reference buildings. The aim was to assess the effect of the introduced information in terms of energy savings. With these inputs and taking the corresponding infrastructure management measures it was possible to achieve a mean energy saving during operation of 20% compared with the previous month's consumption when no such energy efficiency management system was in operation.

The next move was to incorporate the users themselves into the operation of the system, in the hope of encouraging further energy saving. Several strategies were adopted in this respect, including providing information on the energy consumed as a result of the individual user's activities, offering recommendations for saving energy and permitting the users to establish their own rules for managing the system. Several experiments in this respect confirmed that users will change their behaviour as regards the use they make of the building's infrastructures. A one month experiment led to a 9% saving in the energy consumed, rising to 29% in a building with a high degree of monitoring and actuation.

Having attained all the objectives set out at the beginning of this thesis and in view of the results, the viability and effectiveness of the proposed system for managing IoT-based information to save energy in smart buildings is demonstrated.

Chapter 3

Introduction

Cities are becoming more and more of a focal point for our economies and societies at large, particularly because of on-going urbanisation, and the trend towards increasingly knowledge-intensive economies as well as their growing share of resource consumption and emissions. To meet public policy objectives under these circumstances, cities need to change and develop, but in times of tight budgets this change needs to be achieved in a smart way: our cities need to become "smart cities".

In order to follow the policy of the decarbonisation of Europe's economy in line with the EU 20/20/20 energy and climate goals, today's ICT, energy (use), transport systems and infrastructures have to drastically change. The EU needs to shift to sustainable production and use of energy, to sustainable mobility, and sustainable ICT infrastructures and services. Cities and urban communities play a crucial role in this process. Three quarters of our citizens live in urban areas, consuming 70%[1] of the EU's overall energy consumption and emitting roughly the same share of greenhouse gases. Of that, buildings and transport represent the lion's share.

Within the worldwide perspective of energy efficiency, it is important to highlight that buildings are responsible for 40% of total EU energy consumption and generate 36% of GHG [33]. This indicates the need to achieve energy-efficient buildings to reduce their CO_2 emissions and their energy consumption. Moreover, the building environment affects the quality of life and work of all citizens. Thus, buildings must be capable of not only providing mechanisms to minimize their energy consumption (even integrating their own energy sources to ensure their energy sustainability), but also of improving occupant experience and productivity. In this thesis, we analyse the important role that buildings represent in terms of their energy performance at city level and, even, at world level, where they represent an important factor for the energy sustainability of the planet. In Section 4.3 we describe in more detail the expected reduction in total emissions that can be achieved by smart buildings with energy efficiency goals.

Analysis of the energy efficiency of the built environment has received growing attention in the last decade [2], [34], [23]. Various approaches have addressed energy efficiency of buildings using predictive modelling of energy consumption based on usage profiles, climate data and building characteristics. On the other hand, studies have demonstrated the impact of displaying public information to occupants and its effect in modifying individual behaviour in order to obtain energy savings [11], [14]. Nevertheless, most of the approaches proposed to date only provide partial solutions to the overall problem of energy efficiency in buildings, where different factors are involved in a holistic way, but which, until now, have been addressed separately or even neglected by previous proposals. This division is frequently due to the uncertainty and lack of data and inputs included in the management processes, so that analysis of how energy in buildings is consumed is incomplete. In other words, a more integral vision is required to provide accurate models of the energy consumed in buildings [38].

The need for the robust characterization of energy use in buildings has gained attention in light of the growing number of projects and developments addressing this topic. Although much interest has

[1] `Source:EuropeanCommission2013`

been put into smart building technologies, the research area of using real-time information has not been fully exploited. In order to obtain an accurate simulation model, a detailed representation of the building structure and its subsystems is required, although it is the integration of all these pieces that requires the most significant effort.

The integration and development of systems based on ICT and, more specifically, the IoT [32], are important enablers of a broad range of applications, both for industries and the general population, helping make smart buildings a reality. IoT permits the interaction between smart things and the effective integration of real world information and knowledge in the digital world. Smart (mobile) things endowed with sensing and interaction capabilities or identification technologies (such as RFID) provide the means to capture information about the real world in much more detail than ever before. Nevertheless, challenges related with: (1) the management of the huge amount of data provided in real-time by a large number of IoT devices deployed, (2) the interoperability among different ICT, and (3) the integration of many proprietary protocols and communication standards that coexist in the ICT market applicable to buildings (such as heating, cooling and air conditioning machines), need to be faced before flexible and scalable solutions based on the IoT paradigm can be offered.

The structure of the present chapter is as follows: Section 3.1 describes the key issues involved in energy efficiency in buildings. Among these issues, relevant parameters affecting energy consumed in buildings are described and proposed to be included as input data of building management for energy efficiency. Then, Section 3.2 reviews the main related work which propose partial solutions to the problem addressed in this thesis. Section 3.3 presents a general architecture proposal for management systems of smart buildings, which is modelled in three layers with different functionalities. Section 3.4 describes our proposal for an energy efficiency building management system. This proposal tackles three different subproblems, each one of these is introduced here. Finally, Section 3.5 summarizes the experiments carried out to evaluate and validate the different proposals and mechanisms developed in this thesis.

3.1. Addressing Energy Efficiency in Smart Buildings

Optimizing energy efficiency in buildings is an integrated task that comprises the whole lifecycle of the building. For buildings to have an impact at city level in terms of energy efficiency, different challenges have been identified[2] in the building value chain (from design to end-of-life of buildings), which can be summarized as follows:

1. *Design.* The design of buildings should be integrated, holistic and multi-target.
2. *Structure.* The structure of buildings should provide features such as safety, sustainability, adaptability and affordability.
3. *Building envelope.* This should ensure efficient energy and environmental performance. Prefabrication is a crucial step to guarantee energy performance. Multifunctional and adaptive components, surfaces and finishes to create added energy functionality, and durability should all be built in.
4. *Energy equipment and systems.* Advanced heating/cooling and domestic hot water solutions, including renewable energy sources, should focus on sustainable generation as well as on heat recovery. Among these systems, thermal storage (both heat and cold) is recognized as a major breakthrough in building design. Distributed/decentralised energy generation should address the key requirement of finding smart solutions for grid-system interactions on a large scale. ICT smart networks will form a key component in such solutions. In [25], for instance, the authors study the communication requirements for smart grids and describe the most suitable communication protocols, wired and wireless, with special attention to the latest proposals in this field.

[2] `http://www.ectp.org/`

5. *Construction processes.* These should consider ICT-aided construction, improving the energy performance delivered, and automated construction tools.

6. *Performance monitoring and management.* This should ensure interoperability among the different subsystems of the building, including smart energy management systems that provide flexible actions to reduce the gap between predicted and actual energy building performance, occupancy modelling, the fast and reproducible assessment of designed or actual performance, and continuous monitoring and control during service life. Finally, knowledge sharing must be considered by means of open data standards that allow collaboration among stakeholders and interoperability among systems.

7. *End of life.* This should include decision-support concerning possible renovation or the construction of a new building and associated systems.

During these phases it is necessary to continuously re-engineer the indexes that measure energy efficiency to adapt the energy management system to the building's conditions. Hereinafter, we refer only to electrical energy consumption since other kinds of energy such as fuel, gas or water are beyond the scope of this work.

Taking as reference the energy performance model for buildings proposed by the *CEN Standard EN15251* [1], it proposes criteria for dimensioning the energy management of buildings, while indoor environmental requirements are maintained. According to this standard, there are static and dynamic conditions that affect the energy consumption of buildings. Given that each building has a different static model according to its design, we try to provide a solution for energy efficiency focusing on analysing how dynamic conditions affect the energy consumed in buildings. Thus, we propose an initiative for the challenges involved in the living stage buildings: *Performance monitoring and management* mentioned in the above list. In this stage, we need to identify the main drivers of energy use in buildings. After monitoring these parameters and analysing the associated energy consumed, we can model their impact on energy consumption, and then, propose control strategies to save energy. The main idea of this approach is to provide anticipated responses to ensure energy efficiency in buildings.

Bearing in mind all these concerns, we enumerate below the stages [21] that must be carried out to achieve efficiency building energy management:

1. **Monitoring.** During the monitoring phase, information from heterogeneous sources is collected and analysed before concrete actions are proposed to minimize energy consumption, bearing in mind the specific context of a given building. Since buildings with different functionalities have different energy use profiles, it is necessary to carry out an initial characterization of the main contributors to their energy use. For instance, in residential buildings the energy consumed is mainly due to the indoor services provided to their occupants (associated to comfort), whereas in industrial buildings energy consumption is associated mostly with the operation of industrial machinery and infrastructures dedicated to production processes. Considering this, and taking into account the models for predicting the comfort response of buildings occupants given by the *ASHRAE* [4], we describe below the main parameters that must be monitored and analysed before implementing optimum building energy management systems. In this way, from this set of parameters affecting energy consumption in buildings, we can extract the input data to be included in the proposal.

    a) Electrical devices always connected to the electrical network. In buildings, it is necessary to characterize the minimum value of energy consumption due to electrical devices that are always connected to the electrical network, since they represent a constant contribution to the total energy consumption of the building. For this, it is necessary to monitor over a period of time the energy consumed in the building when there is no other contributor to the total energy being consumed. This value will be included as an input to the final system responsible for estimating the daily electrical consumption of the building.

b) Electrical devices occasionally connected. Depending on the kind of building under analysis, different electrical devices may be used with different purposes. For instance, for productive aims in a company, for providing comfort in a home, etc. On the other hand, the operation of such devices could be independent of the participation and behaviour of the occupants; for example, in the context of a factory or an office where there are timetables and rules. Whatever the case, recognition of the operation pattern of devices must be included in the final system responsible for estimating the daily electrical consumption of the building. To obtain these patterns it is necessary to monitor previously the associated energy consumption of every device or appliance. To monitor each component separately in the total power consumption in a household or an industrial site over time, cost effective and readily available solutions include Non-Intrusive Load Monitoring (NILM) techniques [41].

c) Occupants' behaviour. Energy consumption of buildings due to the behaviour of their occupants is one of the most critical points in every building energy management system. This is mainly because occupant behaviour is difficult to characterize and control due to its uncertain dynamic. First of all, it is necessary to have solved the occupants' localization before behaviour models associated to them can be provided. Depending on the building context, the impact of occupant's behaviour on total energy consumption is different. For example, in residential buildings the impact of the behaviour in the energy consumed is one of the biggest, followed by environmental conditions. However, in buildings with productive goals, the electricity consumed by the appliances and devices working for such goals is usually the main contributor to the total energy consumed in the building. Therefore, it is necessary to monitor and analyse this issue to be able to provide behaviour patterns that will be included in the final estimation of the daily energy consumption of the building. Occupants' behaviour can be characterized for features such as:

- Occupants localization data
- Activity level of occupants
- Comfort preferences of occupants

d) Environmental conditions. Parameters like temperature, humidity, pressure, natural lighting, etc. have a direct impact on the energy consumption of buildings. Nevertheless, depending on the specific context of the building and its requirements, this impact will differ and be greatest in the case of indoor comfort services (like thermal and visual comfort). Therefore, forecasts of the environmental condition should also be considered as input for the final estimation of energy consumption of the building.

e) Information about the energy generated in the building. Sometimes, alternative energy sources can be used to balance the energy consumption of the building. Information about the amount of daily energy generated and its associated contextual features can be used to estimate the total energy generated in the future. This information allows us to design optimal energy distribution or/and strategies of consumption to ensure the energy-efficient performance of the building.

f) Information about total energy consumption. Knowing the real value of the energy consumed hourly or even daily permits the performance and accuracy of the building energy management program to be evaluated, and make it possible to identify and adjust the system in case of any deviation between the consumption predicted and the real value. In addition, providing occupants with this information is crucial to make them aware of the energy that they are using at any time, and encourage them to make their behaviour more responsible.

In this work we focus on residential buildings, where both comfort and energy efficiency is required. As regards the comfort provided in buildings, we focus on thermal and visual comfort.

2. **Information Management.** An intelligent management system must provide proper adaptation countermeasures for both automated devices and users with the aim of providing the most important services in buildings (comfort) and satisfying energy efficiency requirements. Therefore, energy savings needs to be addressed by establishing a trade-off between the quality of services provided in buildings and the energy resources required for the same, as well as the associated cost.

3. **Automation.** Automation systems in buildings take inputs from the sensors installed in corridors and rooms (light, temperature, humidity, etc.), and use these data to control certain subsystems such as HVAC, lighting or security. These and more extended services can be offered intelligently to save energy, taking into account environmental parameters and the location of occupants. Therefore, automation systems are essential to answer the needs for monitoring and controlling energy efficiency requirements [12]. At this respect, the *1888-2011 IEEE Standard for Ubiquitous Green Community Control Network Protocol* [29] describes remote control architecture of digital community, intelligent building groups, and digital metropolitan networks; specifies interactive data format between devices and systems; and gives a standardized generalization of equipment, data communication interface, and interactive message in this digital community network.

4. **Feedback and user involvement.** Feedback on consumption is necessary for energy savings and should be used as a learning tool. Analysis of smart metering, which provides real-time feedback on domestic energy consumption, shows that energy monitoring technologies can help reduce energy consumption by 5% to 15% [11]. As can be deduced, a set of subsystems should be able to provide consumption information in an effective way. These subsystems are:

   - Electric lighting.
   - Boilers.
   - Heating/cooling systems.
   - Electrical panels.

   On the other hand, to date, information in real-time about building energy consumption has been largely invisible to millions of users, who had to settle with traditional energy bills. In this, there is a huge opportunity to improve the offer of cost-effective, user-friendly, healthy and safe products for smart buildings, which increase the awareness of users (mainly concerning the energy they consume), and permit them to be an input of the underlying processes of the system. Therefore, an essential part of any intelligent management system is user involvement through their interactions and their associated data (identity, location and activity), so that customized services can be provided.

Taking into account all aspects identified as relevant for their impact in energy consumption of buildings, we review how related works from the literature tackle them. In this way, we can extract the main limitations and constraints of these works, and suggest proposals to address them.

3.2. Related Work

A complete review of previous solutions from the literature was carried out during the development period of the present thesis. We tried to find ways that would enable us to propose holistic solutions to building energy management problems, which should address the relevant aspects mentioned previously, i.e. a complete monitoring phase, the efficient management of information, using automation systems and involving occupants during the system operation. Nevertheless, different proposals were found for different goals, but none was integrated all the aspects. This was the first constraint identified among previous solutions. Consequently, we decided to review the main related work tackling each one of these aspects separately.

As regards the monitoring aspect, initial solutions to energy efficiency in buildings were mainly focused on non-deterministic models based on simulations. A number of simulation tools are available with varying capabilities. In [3] and [9] a comprehensive comparison of existing simulation tools is provided. Among these tools are ESP-r [8] and Energy Plus [10]. However, this type of approach relies on very complex predictive models based on static perceptions of the environment. For example, a multi-criteria decision model to evaluate the whole lifecycle of a building is presented in [7]. The authors tackle the problem from a multi-objective optimization viewpoint, and conclude that finding an optimal solution is unreal, and that only an approximation feasible.

With the incessant progress made in the field of ICT and sensor networks, new applications to improving energy efficiency are constantly emerging. For instance, in office spaces, timers and motion sensors provide a useful tool to detect and respond to occupants, while providing them with feedback information to encourage behavioural changes. The solutions based on these approaches are aimed at providing models based on real sensor data and contextual information. Intelligent monitoring systems, such as automated lighting systems, have limitations such as those identified in [17], in which the time delay between the response of these automated systems and the actions performed can reduce any energy saving, whilst an excessively fast response can produce inefficient actions. These monitoring systems, while contributing towards energy efficiency, require significant investment in an intelligent infrastructure that combines sensors and actuators to control and modify the overall energy consumption. The cost and difficulty involved in deploying such networks often constrain their viability. Clearly, an infrastructureless system that uses existing technologies would provide a cheaper alternative to building energy management systems. On the other hand, building energy management must bare with the inaccuracy of sensors, the lack of adequate models for many processes and the non-deterministic aspects of human behaviour.

In this sense, there is an important research area that proposes techniques of artificial intelligence as a way of providing intelligent building management systems. Rather than solving the above drawbacks. This approach involves models based on a combination of real data and predictive patterns that represent the evolution of the parameters affecting the energy consumption of buildings. An example of such an approach is [18], in which the authors propose an intelligent system able to manage the main comfort services provided in the context of a smart building, i.e. HVAC and lighting, while user preferences concerning comfort conditions are established according to the occupants' locations. Nevertheless, the authors only propose the inputs of temperature and lighting in order to make decisions, while many more factors are really involved in energy consumption and should be included to provide an optimal and more complete solution to the problem of energy efficiency in buildings. Furthermore, no automation platform is proposed as part of the solution.

Regarding building automation systems, many works extend the domotics field which was originally used only for residential buildings. A relevant example is the proposal given in [19], where the authors describe an automation system for smart homes based on a sensor network. However, the system proposed lacks automation flexibility, since each node of the network offers limited I/O capabilities through digital lines, i.e. there is no friendly local interface for users, and most importantly, integration with energy efficiency capabilities is weak. The work presented in [30] is based on a sensor network to cope with the building automation problem for control and monitoring purposes. It provides the means for open standard manufacturer-independent communication between different sensors and actuators, and appliances can interact with each other with defined messages and functions. Nevertheless, the authors do not propose a control application to improve energy efficiency, security or living conditions in buildings.

The number of works concerning energy efficiency management in buildings using automation platforms is more limited. In [31], for instance, a reference implementation of an energy consumption framework is provided, but it only analyses the efficiency of ventilation system. In [13] the deployment of a common client/server architecture focused on monitoring energy consumption is described, but without performing any control action. A similar proposal is given in [37], with the main difference that it is less focused on efficiency indexes, and more on cheap practical devices to cope with a broad pilot deployment to collect the feedback from users and address future improvements for the system.

Regarding commercial solutions for the efficient management of building infrastructures, there are proposals such as those given by the manufacturer *Johnson Controls*[3], a company that provides products, services and solutions that help increase energy efficiency and reduce the operation costs of its clients' buildings. Another well-known manufacturer is *Siemens*[4], who offer a technical infrastructure for building automation and energy efficiency in the form of market-specific solutions in buildings and public places. The main differences between these commercial solutions and our proposal for automation and energy efficiency management in smart buildings are those related with the open and transparent character of our proposal, as well as its capability to gather data from a large number of heterogeneous sources.

As regards user involvement in building energy management, there are studios that maintain that energy usage feedback is the most successful approach, whereby users are involved in saving energy in buildings [14] [11]. However, few works have been addressed this aspect. It is important to note that energy usage feedback in building energy management systems needs to be provided to users frequently and over a long time, offering an appliance-specific breakdown, while presented in a clear and appealing way using computerized and interactive tools.

Concerning the fact that users have little awareness of the energy wastage associated with their energy consumption behaviours is due partly to the fact that most people do not know what the optimum comfort conditions are according to environmental features and their needs. It is clear that, while each person has his/her own comfort preferences and these preferences are strongly conditioned by subjective concerns, there are a minimal and a maximum set of comfort conditions recognized as common to everyone to ensure the quality of life [20]. Therefore, the confidence and respect that users give to the intelligent services that are offered to them in terms of comfort and energy efficiency concerns in smart buildings, are crucial constraints in this type of system.

Nevertheless, thanks to pervasive computing practices, the integration and development of systems based on IoT support and encourage the cooperation between humans and devices in terms of:

- Facilitating communication between things and people, and between things, by means of a collective network intelligence context.
- People's ability to exploit the benefits of this communication through their increasing familiarity with ICT.
- A vision where, in certain respects, people and things are homogeneous agents endowed with fixed computational tools.

Smart buildings should prevent users from having to perform routine and tedious tasks to achieve comfort, security, and effective energy management. Sensors and actuators distributed in buildings can make user life more comfortable; for example: i) room heating can be adapted to user preferences and to the weather; ii) room lighting can change according to the daylight; iii) domestic incidents can be avoided with appropriate monitoring and alarm systems; and, iv) energy can be saved by automatically switching off electrical equipment when not needed, or regulating their operating power according to user needs, thus avoiding any energy overuse. In this sense, IoT is a key enabler of smart services to satisfy the needs of individual users, who apart from being users of the system, can also be seen as sensors in the same way as temperature, thermal, humidity and presence sensors deployed in the building.

As can be noted, most of the approaches proposed to date only provide partial solutions to the overall problem of energy efficiency in buildings, where, although different factors are involved holistically, until now they have been addressed separately or even neglected by previous proposals. This division is frequently due to the uncertainty and lack of data and inputs in the management processes, so that analysis of how energy in buildings is consumed is incomplete. In other words, a more integral

[3] `http://www.johnsoncontrols.co.uk/content/gb/en/products/building_efficiency.html`

[4] `http://www.buildingtechnologies.siemens.com/bt/global/en/energy-efficiency/Pages/Energy-efficiency.aspx`

vision is required to provide accurate models of the energy consumed in buildings [38]. In this sense, no solutions have been proposed tackling the full integration of information related with all relevant aspects directly involved in the energy consumption of buildings (which are described in Section 3.1). For example, there are not previous solutions that fully integrate information about the occupants of buildings, despite of the fact that human behaviour has been recognized as one of the most important aspect affecting energy consumption in buildings. Information about the identities of occupants, their locations and activities, their comfort preferences, their levels of awareness with the problem of the high energy consumption of buildings, their participation to get energy saving, etc. must be included, jointly to other relevant information, in any building energy management system. In this thesis, we present our own smart system proposal, which is a holistic and flexible solution based on collecting and analysing information of both the building context and its occupants, and propose concrete actions which could be applied in the management of any controllable infrastructure of buildings to ensure their energy efficient performance. Our proposal of solution considers occupants as a key piece of our management system, and we demonstrate the benefits of following this approach in term of the energy saving achieved in various buildings used as reference.

3.3. A Proposal of General Architecture for Management Systems of Smart Buildings

The architecture of our proposal for smart building is modelled in layers which are generic enough to cover the requirements of different smart environments of cities, such as intelligent transport systems, security, health assistance or, as is the case analysed in this thesis, smart buildings. This architecture promotes high-level interoperability at the communication, information and services layers. The layers of such architecture are depicted in Figure 3.1, and are detailed below.

Data Collection Layer

Looking at the lower part of Figure 3.1, input data are acquired from a plethora of sensor and network technologies such as the Web, local and remote databases, wireless sensor networks, etc., all of them forming an IoT ecosystem. Sensors and actuators can be self-configured and controlled remotely through the Internet, enabling a variety of monitoring and control applications. In this sense, and considering the instance of this architecture for the building management system proposed in this thesis, it gathers information from sensors and actuators deployed in the building.

Given the heterogeneity of data sources and the necessity of seamless integration of devices and networks, a common language structure to represent data is needed to deal with this issue. Therefore, the transformation of the collected data from the different data sources into a common language representation is performed in this stage.

Data Processing Layer

The data processing layer is responsible for processing the information collected and making decisions according to the final application context. A set of information processing techniques is applied to extract, contextualize, fuse and represent information for the transformation of massive input data into useful knowledge, which can be distributed later towards the services layer.

Different algorithms can be applied for the intelligent data processing and decision making processes, depending on the final desired operation of the system (i.e. the services addressed). Considering the target application of smart buildings, data processing techniques for covering, among others, security, tele-assistance, energy efficiency, comfort and remote control services should be implemented in this layer. And following a user-centric perspective for services provided, intelligent decisions are made through behaviour-based techniques to determine appropriate control actions, such as appliances and lights, power energy management, air conditioning adjustment, etc.

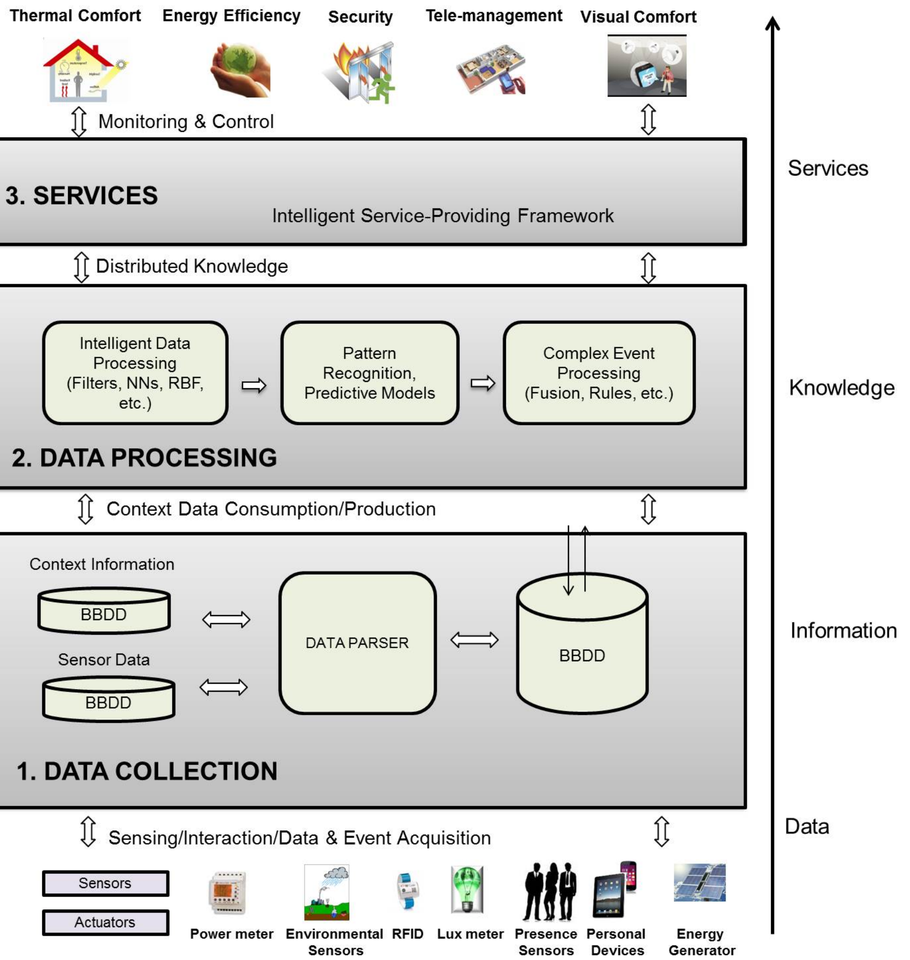

Figure 3.1: Layers of the base architecture for smart buildings

Services Layer

Finally, the specific features for providing services, which are abstracted from the final service implementation, can be found in the upper layer of the proposed architecture (see Figure 3.1). Our approach offers a framework with transparent access to the underlying functionalities to facilitate the development of different types of final application.

This generic proposal of architecture for smart buildings has been instantiated in the system known as *City explorer*. City explorer, which was developed at the University of Murcia, integrates an automation platform which is divided into an indoor part, and all the connections with external elements for remote access, technical tele-assistance, security and energy efficiency/comfort providing services in buildings.

Figure 3.2 shows a schema of City explorer offering ubiquitous services in the smart buildings field. The main components of City explorer were presented in details in [40] [57].

The work developed in this thesis is based on using City explorer as platform of experimentation and validation of our proposal of building management to achieve energy efficiency. For this, we have instantiated each generic layer of the architecture shown in Figure 3.1, with the goal of offering a solution to energy efficiency in smart buildings.

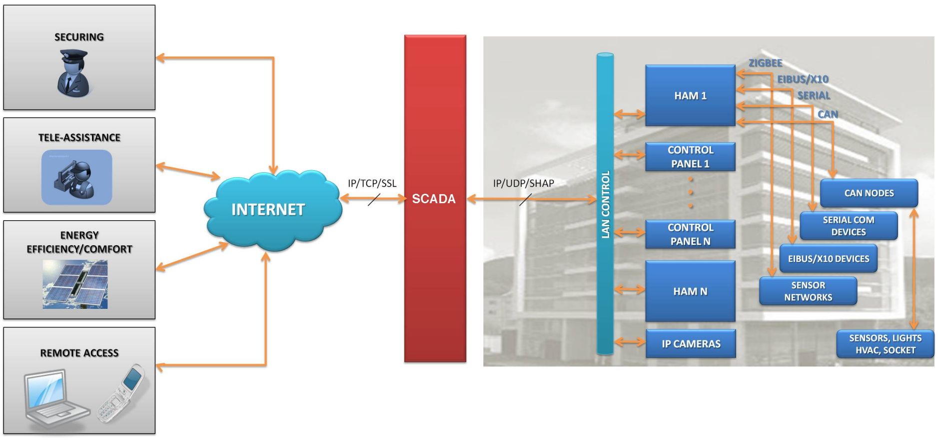

Figure 3.2: City explorer applied to smart buildings

3.4. I2ME2 IoT-IBMS: IoT-based Information Management System for Energy Efficiency in Smart Buildings

As mentioned before, our proposal of I2ME2 IoT-IBMS uses the City explorer platform applied to achieve energy efficiency in buildings. Our proposed system has the capability, among others, to adapt the behaviour of automated devices deployed in the building in order to meet energy consumption restrictions, while maintaining comfort conditions at the occupants' desired levels. More specifically, the goals of our intelligent management system are the following:

- High comfort level: learn the comfort zone from users' preferences, guarantee a high comfort level (thermal, air quality and illumination) and a good dynamic performance.
- Energy savings: combine the control of comfort conditions with an energy saving strategy.
- Air quality control: provide CO_2-based demand-controlled ventilation systems.

Satisfying the above control requirements implies controlling the following actuators:

- Shading systems to control incoming solar radiation and natural light as well as to reduce glare.
- Window opening for natural ventilation or mechanical ventilation systems to regulate natural airflow and indoor air changes, thus affecting thermal comfort and indoor air quality.
- Electric lighting systems.
- Heating/cooling (HVAC) systems.

As a starting point, we focus only on the management of lights and HVAC subsystems, since they represent the highest energy consumption at building level.

User interactions have a direct effect on the whole system performance, because the occupants can take control of their own environment at any time. Thus, the combined control of the system requires optimal operation of every subsystem (lighting, HVAC, etc.), on the assumption that each operates normally in order to avoid conflicts arising between users' preferences and the simultaneous operations of such subsystems.

Figure 3.3 shows a schema of the different subsystems comprising the intelligent management system integrated in City explorer, where the outputs of the system are forwarded to the actuators deployed in the building.

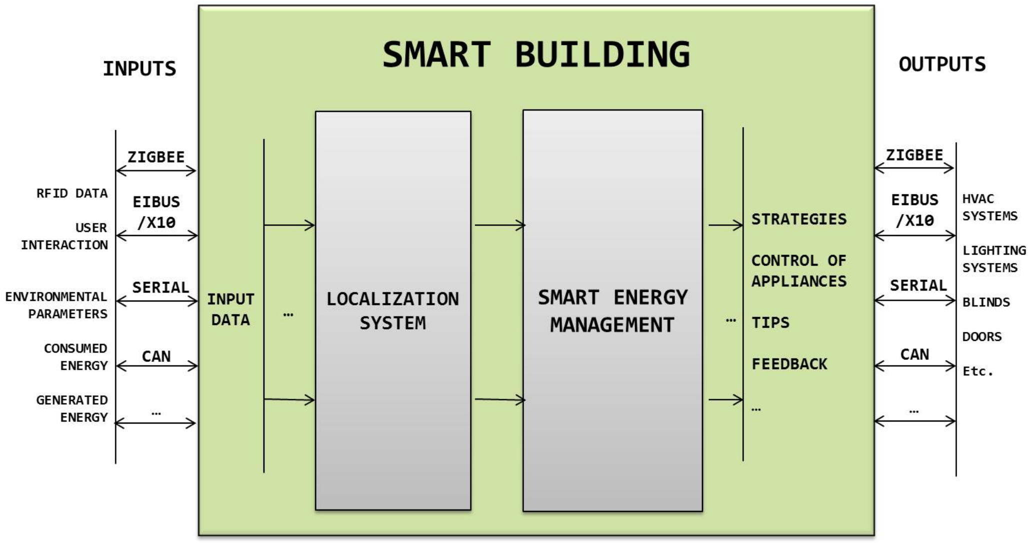

Figure 3.3: Schema of the modules composing the management system in charge of the building comfort and energy efficiency

As can be seen in Figure 3.3, the first task to solve is related with user identification and localization, and the second problem is related with the issues of comfort and energy efficiency in the management of the building. In the following subsections we describe the different issues involved and which were solved during this work, and represent our proposal of building energy management system for energy efficiency.

3.4.1. Indoor localization problem

In a smart building, embedded sensors measure and record user activities, making it possible to predict their future behaviour, prepare everything one step ahead according to the individual user's preferences or needs, and provide the most convenient energy efficient services. These services need to operate by acquiring contextual information both from users and the environment. Therefore, to make buildings smart and to be able to offer users customized services, it is indispensable to previously solve the implicit indoor localization problem. Furthermore, user identities need to be taken into account so that the intelligent system can learn and manage devices according to their behaviour and/or preferences.

We obviously need to solve **user identification** in smart buildings to provide customized comfort services committed to energy efficiency, but while **user privacy** must also be respected because occupants care about their private and social activities, and want full control of how their personal location information and history are used. Hence, there is a need to rely on **non-intrusive, ubiquitous** and **cheap** sensors to minimise infrastructure deployment and prevent user dissatisfaction. Indeed, some sensors cannot be installed in buildings; for instance, in Spain video cameras cannot be legally used in offices. Problems like this make some localization systems unsuitable for use in smart buildings.

In the scenario addressed in this work, the whole area of a smart building is divided into locations (rooms, open areas, corridors, etc.) with different comfort conditions in each one; for instance, optimum lighting conditions in a corridor are different from those required in an office; or the optimum level of air conditioning in an individual bedroom is different from that required in a very crowded dining room. Furthermore, in each of these areas (an individual bedroom, a dining room, an office, etc.), it is necessary to carry out a further division depending on the service area of each comfort appliance deployed. Therefore, our indoor localization system must be able to **locate a user in**

terms of regions, which correspond to the service areas of the appliances or devices involved in her/his comfort condition.

Recent years have seen great progress in indoor localization systems, but there are still some weaknesses in terms of the accuracy of location data, the time required for calibration processes, poor robustness, or high installation and equipment costs [24]. Furthermore, when user identification is needed, most of the systems proposed present difficulties concerning complexity, computational load and inaccurate results. Since the indoor localization problem does not have obvious solutions, we review relevant solutions from the literature and identify the technological options most suitable in light of our problem.

Accuracy is usually the most important requirement for positioning systems. In the location problem involved in energy efficiency of buildings, we conclude that the accuracy required for our localization system depends on the service areas of the appliances and devices involved in the comfort and energy balance of the building.

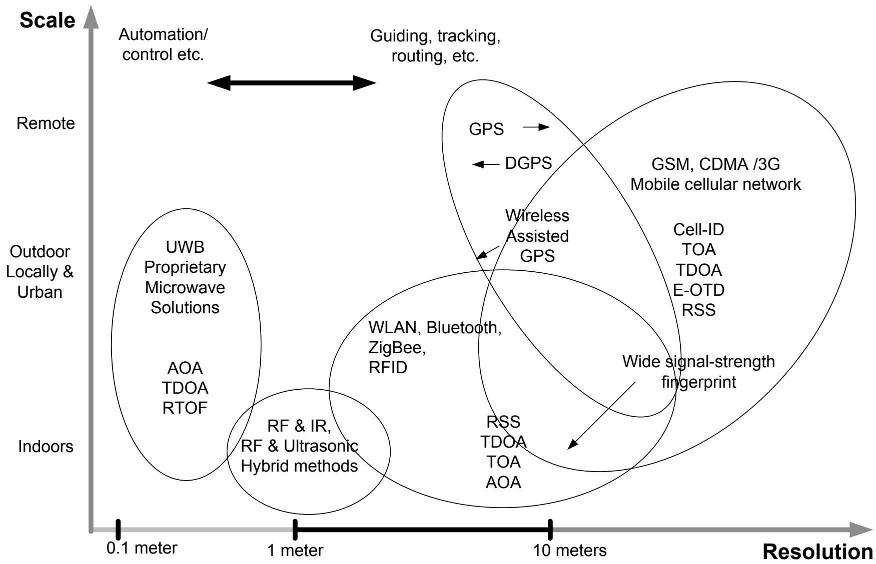

Figure 3.4: Outline of some positioning systems [24]

In Table 3.1 we cite some examples of location works using different technological solutions, together with whether or not they fulfil the different location requirements of our problem. Besides, in Figure 3.4 a rough outline of some positioning systems is presented, with their accuracy ranges achieved until now according to the literature.

Since each localization technology has its particular advantages and disadvantages, we suggest that by combining several complementary technologies and applying data fusion techniques, it is possible to improve the overall system performance and provide a more reliable indoor localization system, since more specific inferences can be achieved than when using a single kind of data sensor. Therefore, after analysing Figure 3.4, we choose a hybrid solution based on RF and non-RF technologies.

Considering the context of our problem, i.e. smart buildings, we survey the technological systems commonly found in these environments for providing typical indoor services. The aim is to find possible technological systems which can be used for solving indoor localization problems, with a consequent cost saving (i.e. savings in the acquisition, installation, etc. of the required devices). Following this approach, using the RFID/NFC (Near Field Communication) system typically used for access control in buildings, and the infrared (IR) commonly used for automatic control of alarm system, to solve

Table 3.1: Requirement analysis

Technology	**Example work**	**Ubiquity**	**Non-intrusive**	**Low cost**	**User ID**
Load sensors	[39]	-	√	√	-
Pressure sensors	[27]	-	√	√	-
Cameras	[22]	√	-	-	-
UWB	[36]	√	√	-	√
Microwave	[35]	√	√	-	-
Ultrasonic	[5]	√	√	-	-
Hybrid RF and non-RF	[26]	√	√	√	√
WLAN	[16]	√	√	√	√
RFID	[28]	√	√	√	√

localization problems represents a cost savings in those buildings where access control and/or alarm systems are also provided as pervasive services. Hence, our technological solution is based on a single active RFID system and several IR transmitters. Indeed, the integration of these two technologies in a final and commercial system is already available. Thus, all the RFID tags used are IR-enabled tags whose IR sensor is powered by an IR transmitter. These tags communicate with a nearby RFID reader. Each RFID tag indicates to the reader its identifier ID_{tag}, as well as the identifier of its associated IR transmitter ID_{ir}.

Since our RFID location method is tag-based, we use the RSSI values corresponding to the reference RFID tags (whose locations are known) - which are computed and gathered by the RFID reader - to estimate the location of the monitored RFID tags. Therefore, our solution does not require a huge training phase, because new RSSI data belonging to the RFID reference tags are provided and used to estimate target position in each new iteration of the mechanism. This represents an important advantage for systems that work in real-time (the case of indoor services offered in smart buildings), since it is not necessary to process great amounts of data for each localization estimation. Moreover, no great measuring effort in the environment is necessary, and imprecise results due to inappropriate granularity levels caused by long training processes are avoided. The mechanism implements a Radial Basis Function Network to estimate the positions of the occupants, and a Particle Filter to track their next positions. Figure 3.5 introduces a schema of the stages that compose our localization mechanism. For more details about this mechanism, in Section 4.2 we present the data processing techniques implemented as well as the evaluation processes carried out. This system has been tested in real scenarios with satisfactory results, achieving the accuracy required for the most common indoor services offered in buildings, while using a single RFID to solve the indoor localization problem to provide a smart energy control system with location information about occupants.

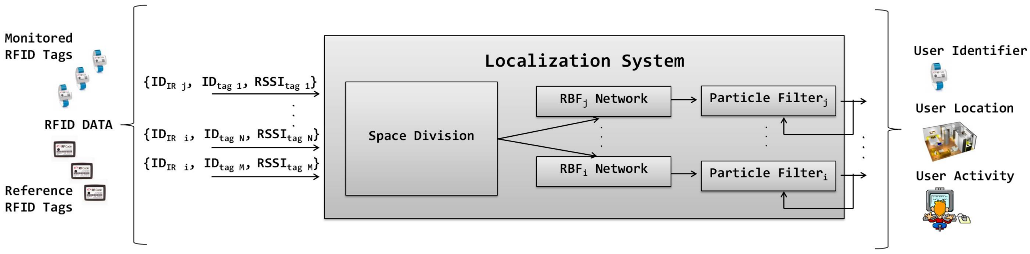

Figure 3.5: Schema of the data processing for position calculation

3.4.2. Integration of location data and comfort preferences of occupants in the system operation

According to Figure 3.3, the second problem to solve is related with the integration of localization data and comfort preferences of occupants in our building energy management proposal. Here, the main goal is to ensure that the electrical equipment in charge of comfort provides the occupants with the optimum comfort conditions according to their preferences, while bearing in mind energy consumption aspects of the building.

Our management system is gradually provided with innovative strategies and improvements based on the feedback received from users, who are active actors in the operation of the system, rather than passive receivers. In this sense, and as starting point of the system operation, maximum and minimum comfort parameters are established as control points for ensuring the minimal comfort conditions for occupants, while energy efficiency aspects are also considered. For this purpose, we take into account the comfort models proposed in [4], which predicts the comfort response of building occupants, considering features such as location type, user activity and date.

In addition, our system is able to manage the presence of several occupants sharing the same comfort appliances. When this occurs, the system provides them with optimum comfort conditions considering the individual preference of each one of them. This optimization is based on the priorities assigned to occupants according their predefined roles given a specific context. Moreover, the system tries to satisfy the preferences of the highest number of occupants. This problem can be stated as a multiobjective optimization problem (MOP) with two subobjectives. In MOPS solutions are not the optimal for all objectives. Algorithms for MOPs try to find a solution in which the objectives are satisfied in an acceptable factor. This solution can not be improved for any objective without affecting another. Our attempt to solve this problem used Genetic Algorithms (GAs) [6], which are usually suitable resolving MOPs because they maintain a population of solutions, enabling solutions to be found in parallel [15]. This mechanism improved the results accomplished by the handcrafted process.

Therefore, after the identification and localization of occupants inside the building (which is performed by our localization system integrated in City explorer and presented previously), different comfort profiles for each user are generated with default settings according to their preferences. In this way, considering accurate user positioning information (including user identification) as well as user comfort preferences for the management process of the appliances involved, energy wastage derived from overestimated or inappropriate settings is avoided.

Nevertheless, occupants are free to change the default values for their own preferences when they do not feel comfortable. For this, users can communicate their preferences to the system through the control panel of the automation module of City explorer associated to their location, or through the SCADA-web access of City explorer. Our management system is able to update the corresponding user profiles as long as these values are within the comfort intervals defined according to a minimal level of comfort in light of the features of the building context (according to the models proposed in [4]). Furthermore, our system can detect inappropriate settings indicated by users according to both their comfort requirements and associated energy consumption. On the other hand, when occupants are distributed in such way that the same appliance is providing comfort services to more than one occupant, our intelligent system is able to provide them with comfort conditions that satisfy the greatest number of them (always considering minimal levels of comfort).

As regards user interactions with the system to communicate their comfort preferences and energy control strategies, City explorer lets users explore monitored data by navigating through the different automated areas or rooms of the building, while its intuitive graphic editor also allows users to easily design any monitoring/control tasks and/or actions over the actuators (appliances) deployed in the building. The setting of the system can also be carried out by users using City explorer without the need to program any controller by code. In this way, it is possible to set up the whole system by simply adding maps and pictures over which users can place the different elements of the system (sensors, HAM units, etc.), and design monitoring and control actions through arrows in a similar way to that in which a flowchart is built. Therefore, our system gives users integral control of any aspect involved in the management of the building. An example of the graphic editor of City explorer, where some rules were defined by users, is shown in Figure 3.6.

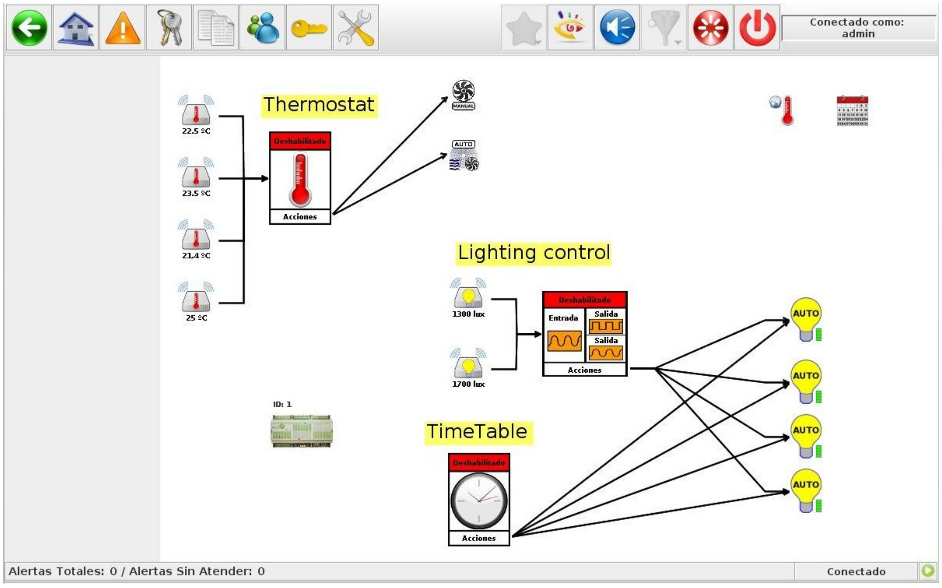

Figure 3.6: Example of rules defined through the City explorer's editor

Thus, and finally, we apply logic rules over the whole body of the available knowledge to take decisions related with the control of the key automated appliances involved during the considered operation time of the system, to optimize their energy consumption. Such target knowledge makes up the final inputs of the management system shown in Figure 3.3, which deals with appliance management of the building, considering both comfort and energy efficiency goals. Apart from the control of appliances, outputs like providing occupants with information about strategies to save energy, tips or feedback about their consumption are also available in our system. In Figure 3.7 is shown a schema of the smart energy management described here, in which we can see the inputs and outputs mentioned. In Section 4.3 we provide a more complete description of the developments and analysis carried out addressing these issues and included in our proposal of management system.

3.4.3. User involvement in the system operation

Following this approach to provide human-centric services in the context of smart buildings, users can be seen as both the final deciders of actions, and system co-designers in terms of feedback that conditions future rules and contributions to the software issuing these rules. In this sense, in our energy building management system we consider the data provided directly by users through their interactions when they change the comfort conditions provided automatically by the system and, consequently, the system learns and auto-adjusts according to such changes and to the control comfort/energy strategies defined by users using the graphic editor of City explorer.

Furthermore, with the aim of offering users information about any unsuitable design or setting of the system, as well as to help them easily understand the link between their everyday actions and environmental impact, City explorer is able to notify them about such matters (i.e. acting as a learning tool). On the other hand, when the system detects disconnections and/or failures in the system, it sends alerts by email/messages to notify users to check these issues. All these features, which are included in our management system, contribute to user behaviour changes and increase their awareness as time passes, or detect unnecessary stand-by consumption of the controllable subsystems

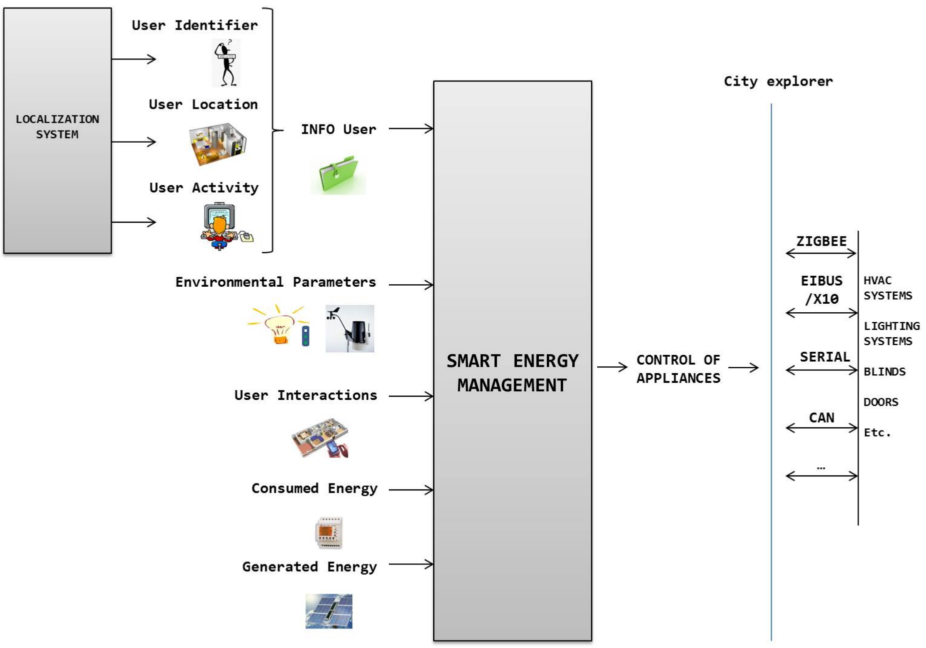

Figure 3.7: Schema of the module of building energy management including information about occupants localization and comfort preferences

of the building.

Finally, to understand the background of energy behaviour of users involved in our experiments and to be able to form an initial context pattern for the usability of the system under different constraints, we carried out a follow-up study based on questionnaires that were given to participants. Our goal was to get user feedback about their experience with our system during the two months of tests. Another reason to carry out this study was the identified lack of research in the building energy management area, where large-scale deployment needs to be accompanied by a body of study on user behaviour, motivation and preferences. The same was pointed out by [14]. In Figure 3.8 is shown the schema of our final building energy management solution. All details about the user-centric perspective implemented in our intelligent building system are presented in Section 4.4.

3.5. Evaluations and System Validation

In this section we present three examples of smart buildings in which City explorer has been deployed and our proposal of intelligent building management for energy efficiency has been evaluated. The target services to provide in the context of these buildings are comfort and energy efficiency.

As mentioned in Section 3.1, the parameters identified as those with the highest impact on energy consumption involved in providing comfort services in buildings are the environmental conditions and the occupants' behaviour. To analyse the impact of each one of these parameters and design smart rules and strategies to save energy, experiments were carried out in different smart scenarios. These cases provide a general overview of different buildings in which energy efficiency could be addressed, and where the factors involved in energy consumption are clearly identified. Finally, different levels of building management are proposed according to the dimension and features of each problem. The different experiments carried out were as follows:

- 1st Experiment. A representative building was selected where people usually spend long periods of time and the behaviour of the occupants clearly differs. We chose a large building of the

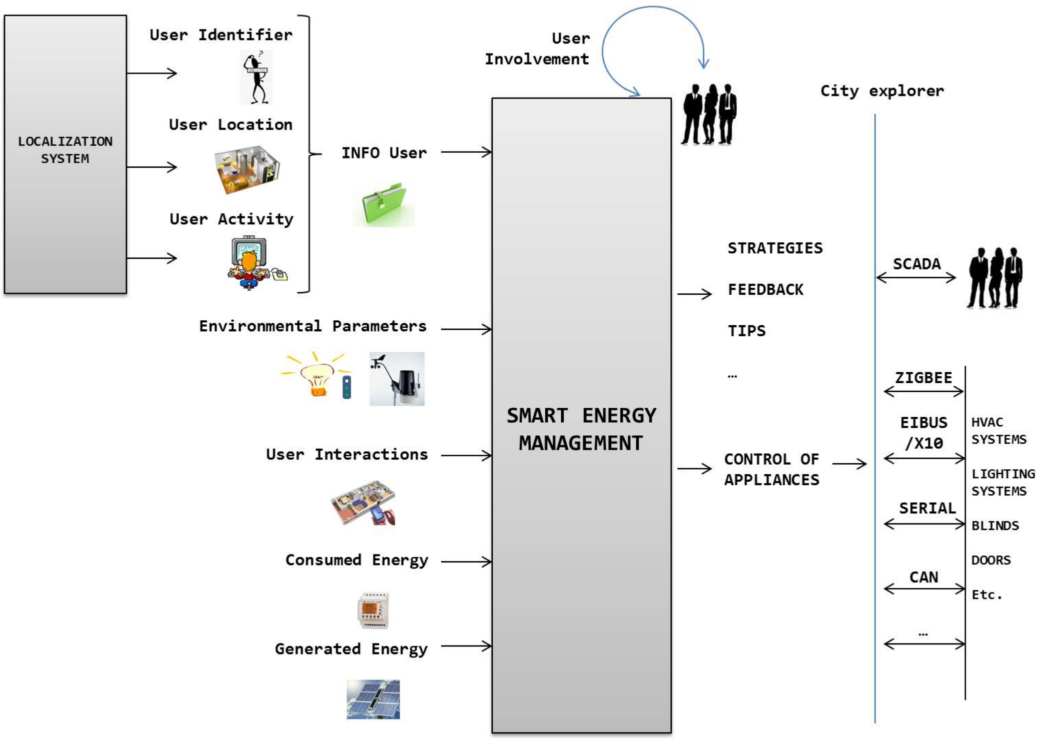

Figure 3.8: Schema of the definitive module of our building energy management system

University of Murcia, which we consider an example of a scenario where energy efficiency is a requirement given the large amount of energy consumed. After demonstrating and analysing the impact of such inputs on the energy consumption of the building, and because the first building selected to analyse was very complex and involved many different occupant behaviours, a second experiment was carried out. More details about this first experiment are provided in Section 4.1.

- 2nd Experiment. In a test lab of a second smart building, controlled experiments generated data patterns to be considered during the design of optimum strategies to save energy. Controlled strategies to save energy were implemented taking the environmental conditions and occupants' behaviour as input for the building management. With the aim of translating and evaluating such control actions in a more realistic scenario with a smaller level of automation, more experiments were carried out in a third building in the context of an office. More details about this 2nd experiment are provided in Section 4.3.

- 3rd Experiment. In this third scenario, a building belonged to a Spanish company was selected, where different levels of building management were carried out, and where there is no control of people's attendance. More details about this 3rd experiment are provided in Section 4.4.

Here we summarize the main findings extracted from all the experiments and analyses carried out during this thesis, which are described completely in Chapter 4. In this sense, the main issues evaluated and the results achieved in this work are:

1. **The accuracy of the results obtained from our indoor localization mechanism.** The results obtained from the evaluation of our localization mechanism confirmed the good performance of this solution in terms of location error regarding common target location areas to

provide comfort services in buildings, with a mean accuracy of 1.5 m. More details can be found in Section 4.2.

2. **The success of the results in the mechanism implemented for estimating the comfort preferences of users.** After experimentation and evaluation of our approach to this problem, a successful prediction of customized comfort conditions for occupants of 91% was obtained. More details can be found in Section 4.3.

3. **The energy saving obtained after including user localization data and comfort preferences of users in our building energy management system.** Energy savings in heating of about 20% compared with the energy consumption in a previous month without any energy management was achieved. More details can be found in Section 4.3.

4. **The energy saving obtained after including users in the loop of our building energy management system.** In order to demonstrate the energy saving impact of providing user-centric services in buildings, we show how energy savings of 9% at building level have already been achieved compared with a situation when user participation was not taken into consideration in the building management system. Furthermore, a mean energy saving of 23.12% with respect to the energy consumption of previous periods without any energy management was obtained following this user-centric approach. More details can be found in Section 4.4.

5. **The applicability of the system proposed.** First, experiments were carried out in a large building with a variety of occupant behaviours. The aim of this experiment was to verify the direct relationship between environmental conditions and occupant behaviours, and the electrical energy consumed by comfort appliances distributed in the building. Then, we inferred optimum strategies to save energy, taking into account the effect of such parameters on the energy consumed. These strategies were applied in a test lab of a second building, where a high level of monitoring and automation was available. In this second scenario, controlled experiments were performed, and the results showed that, after applying these strategies, energy savings of between 14% and 30% could be achieved. Finally, and with the aim of validating our building energy management proposal in a more realistic scenario with reduced monitoring and automation capabilities, we selected a third building where different actions to save energy were carried out. From these actions, we achieved energy saving of about 23%. In this way, we demonstrate the applicability of the management system proposed in this work through its installation in different smart buildings. More details can be found in Section 4.1.

3.6. Lessons Learned

The proliferation of ICT solutions (IoT among them) represents new opportunities for the development of new intelligent services, contributing to more efficient and sustainable cities. In this sense, with the increasing urbanization seen in recent decades, there is an urgent need to achieve energy-efficient environments to ensure the energy sustainability of cities. But to achieve this goal, it is first necessary to solve energy efficiency concerns at building level, since this constitutes the cornerstone of the overall problem.

For greater energy efficiency in buildings, smart solutions are required to monitor and control the capabilities offered by wide sensor and actuator networks deployed as part of the system. Furthermore, occupants play an important role in this type of system, since they are the recipients of the indoor services provided by electrical appliances installed in buildings, most of them responsible for providing them with comfort conditions. In this sense, it is required to propose building management systems able to tackle energy efficiency requirements while user comfort conditions are also taken into account. To date, however, the solutions proposed are mainly based on determinist models with few accurate predictions, and are not able to consider real-time data in most cases. Indeed, they do not even come close to reflecting reality.

In this thesis, we propose a building energy management system powered by IoT capabilities and part of a novel context and location-aware system that covers the issues of data collection, intelligent processing to save energy according to user comfort preferences and features that modify the operation of relevant indoor devices. An essential part of our energy efficiency system are the key aspects of **integrating user location and identity**, so that customized services can be provided to them while any useless energy consumption in the building is avoided. Furthermore, another relevant feature is **users involvement** with the system, through **their interactions and their participation** to get **energy savings in the building**.

The applicability of our system has been demonstrated through its installation in different reference buildings. Thus, using user location data, considering target regions of occupancy for comfort and energy management in the building, and finally including users in the loop of the system operation, we show that energy consumption in buildings can be reduced by a mean of about **23%**. If we translate this mean value of energy saving to city level, assuming that buildings represent 40% of the total energy consumption at European level, a reduction of **9%** at city level could be achieved by installing this energy management system in buildings.

Numerous future works taking as starting point the work developed in this thesis are described in Section 2.3. As a summary of them, we propose to analyze each of the different pieces that make up our system - influence of the input data on the system behaviour, validate the suitability of generating power consumption models of buildings given user profiles and current settings of appliances (which results in the energy-efficient performance of the building), assess the capability of the system for auto-assessment and auto-adjustment to changes in the context, and finally, analyze its accuracy in terms of comfort prediction according to user preferences, considering both HVAC and lighting services.

Chapter 4

Publications composing the PhD Thesis

4.1. How can we Tackle Energy Efficiency in IoT based Smart Buildings?

Abstract

Nowadays, buildings are increasingly expected to meet higher and more complex performance requirements. Among these requirements, energy efficiency is recognized as an international goal to promote energy sustainability of the planet. Different approaches have been adopted to address this goal, the most recent relating consumption patterns with human occupancy. In this work, we analyze what are the main parameters that should be considered to be included in any building energy management. The goal of this analysis is to help designers to select the most relevant parameters to control the energy consumption of buildings according to their context, selecting them as input data of the management system. Following this approach, we select three reference smart buildings with different contexts, and where our automation platform for energy monitoring is deployed. We carry out some experiments in these buildings to demonstrate the influence of the parameters identified as relevant in the energy consumption of the buildings. Then, in two of these buildings are applied different control strategies to save electrical energy. We describe the experiments performed and analyze the results. The first stages of this evaluation have already resulted in energy savings of about 23% in a real scenario.

Title	How can we Tackle Energy Efficiency in IoT based Smart Buildings?
Authors	Moreno-Cano, M. Victoria and Úbeda, Benito and Skarmeta, Antonio F. and Zamora-Izquierdo, Miguel A.
Type	Journal
Journal	Sensors
Impact factor (2012)	1.953
Publisher	MDPI AG
Year	2014
ISSN	1424-8220
DOI	`http://dx.doi.org/10.3390/s140609582`
URL	`http://www.mdpi.com/1424-8220/14/6/9582`
State	Published

4.2. An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings

Abstract

Smart Buildings aims to provide users with seamless, invisible and proactive services adapted to their preferences and needs. These services can be offered intelligently by means of considering the static and dynamical status of the building and the location of its occupants. Furthermore, gathering data about the identity and location of users enables to provide more personalized services, while wasted energy in overuse is reduced. But to cope with these objectives, it is necessary to acquire contextual information, both from users and the environment, using nonintrusive, ubiquitous and cheap technologies. In this work, we propose a low-cost and nonintrusive solution to solve the indoor localization problem focused on satisfying the requirements, in terms of accuracy in localization data, to provide customized comfort services in buildings, such as climate and lighting control, or security, with the goal of ensuring users comfort while saving energy. The proposed localization system is based on RFID (Radio-Frequency Identification) and IR (Infra-Red) data. The solution implements a Radial Basis Function Network to estimate the location of occupants, and a Particle Filter to track their next positions. This mechanism has been tested in a reference building where an automation system for collecting data and controlling devices has been setup. Results obtained from experimental assessments reveal that, despite our localization system uses a relative low number of sensors, estimated positions are really accurate considering the requirements of precision to provide user-oriented pervasive services in buildings.

Title	An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings
Authors	Moreno-Cano, M. Victoria and Zamora-Izquierdo, M.A. and Santa, Jose and Skarmeta, Antonio F.
Type	Journal
Journal	Neurocomputing
Impact factor (2012)	1.634
Publisher	Elsevier
Pages	116-125
Volume	122
Year	2013
Month	December
ISSN	0925-2312
DOI	`http://dx.doi.org/10.1016/j.neucom.2013.01.045`
URL	`http://www.sciencedirect.com/science/article/pii/S0925231213005626`
State	Published

4.3. User-Centric Smart Buildings for Energy Sustainable Smart Cities

Abstract

Over six billion people are expected to live in cities and surrounding regions by 2050. Consequently, in the near future, the autonomic and smart operation of cities may be a critical requirement to improve the economic, social and environmental well-being of citizens. Smart urban technologies represent an important contribution to the sustainable development of cities, making Smart Cities a reality. In this sense, the energy sustainability of cities has become a global concern, bringing with it a wide range of research and technological challenges that affect many aspects of people's lives. Since most of the human lifetime is spent indoors, buildings, which make up a city subsystem, require special attention. Indeed, buildings are the cornerstone in terms of power consumption and CO_2 emissions on a global scale. In this paper, we analyze the role that buildings play in terms of their energy performance at city level, and present an energy-efficient management system integrated in a building automation platform based on an Internet of Things (IoT) approach. Occupants play a crucial role in the system's operation to achieve energy efficient building performance, and any impact on self-sustainable smart cities will be a consequence of efficient user-centric smart building designs. Our proposal represents a user-centric smart solution as a contribution to the energy sustainability of modern cities. The building management platform has been deployed in a real (smart) building, in which a set of tests were carried out to assess different concerns involved in the building's infrastructure management. The first stages of this experiment have already resulted in an energy saving in heating of about 20% at building level, which could translate into a reduction of 8% in the energy consumption of buildings at European city level.

Title	User-Centric Smart Buildings for Energy Sustainable Smart Cities
Authors	Moreno-Cano, M. Victoria and Zamora-Izquierdo, Miguel A. and Skarmeta, Antonio F.
Type	Journal
Journal	Transactions on Emerging Telecommunications Technologies
Impact factor (2012)	1.049
Publisher	Wiley-Blackwell
Pages	41–55
Volume	25
Year	2014
Month	January
ISSN	1524-9050
DOI	`http://dx.doi.org/10.1002/ett.2771`
URL	`http://onlinelibrary.wiley.com/doi/10.1002/ett.2771/full`
State	Published

4.4. An IoT Based Framework for User Centric Smart Building Services

Abstract

Pervasive Future Internet networks enable housekeeping scenarios to provide intelligent real services to a wide population. Among these scenarios, there is a strategy to experiment from the human centric perspective, whereby the users, and not universal procedures, are the owners of the rules operating things. As members of an IoT ecosystem, users inform about their needs and provide feedback within a networked intelligence to jointly improve their individual ability to rule the actuators of the system at their service. Following an IoT approach, we propose a smart building management system, whereby energy savings are achieved because relevant social aspects are considered in the management process of the infrastructures of buildings. An important aim of our user-centric building management system is to raise energy literacy and environmental consciousness by providing personalized steps for saving energy, and by providing users with customized comfort services, control abilities and feedback about their energy consumption. This building management platform has been deployed in a real (smart) building where experimental tests have been carried out to assess the energy savings derived from considering a user-centric management. The first experimental stages of our system operation already reflect energy savings of about 9% at building level when users are included in the loop of the management process of the appliances responsible for their comfort. Furthermore, user feedbacks about their experience and their confidence level in the proposed system were gathered and taken into account for the subsequent adjustment of the system.

Title	An IoT Based Framework for User Centric Smart Building Services
Authors	Moreno-Cano, M. Victoria and Zamora-Izquierdo, Miguel A. and Skarmeta, Antonio F.
Type	Journal
Journal	International Journal of Web and Grid Services
Impact factor (2012)	1.615
Publisher	Inderscience publishers ltd
Year	2014
ISSN	1741-1114
DOI	
URL	
State	To appear

Chapter 5

Acceptance letters

How can we Tackle Energy Efficiency in IoT based Smart Buildings?

Asunto: [Sensors] Manuscript ID: sensors-53089 - Accepted for Publication
De: Lin Li <lin.li@mdpi.com>
Fecha: 21/05/2014 03:39
Para: Victoria Moreno Cano mvmoreno@um.es; Benito Úbeda Miñano <bubeda@um.es>; Antonio F. Skarmeta Gómez <skarmeta@um.es>; Miguel Ángel Zamora Izquierdo <mzamora@um.es>; Sensors Editorial Office <sensors@mdpi.com>

Dear Dr. Moreno Cano,

We are pleased to inform you that the following paper has been officially accepted for publication:

Manuscript ID: sensors-53089
Type of manuscript: Article
Title: How can we Tackle Energy Efficiency in IoT based Smart Buildings?
Authors: M. Victoria Moreno Cano *, Benito Úbeda Miñano, Antonio F.
Skarmeta Gómez, Miguel Ángel Zamora Izquierdo
Received: 14 March 2014
E-mails: mvmoreno@um.es, bubeda@um.es, skarmeta@um.es, mzamora@um.es Submitted to special issue: Select Papers from UCAmI & IWAAL 2013 - the 7th International Conference on Ubiquitous Computing and Ambient Intelligence & the 5th International Workshop on Ambient Assisted Living (UCAmI & IWAAL
2013: Pervasive Sensing Solutions,
http://www.mdpi.com/journal/sensors/special_issues/UCAmI-IWAAL-2013

We will now edit and finalize your paper which will then be returned to you for your approval. The invoice covering the article processing charges (APC) for publication in this open access journal will be sent in a separate e-mail by the Editorial Office in Basel, Switzerland, within the next couple of days.

Kind regards,

Lin Li
Assistant Editor
E-Mail: lin.li@mdpi.com
Sensors (http://www.mdpi.com/journal/Sensors/)
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Figure 5.1: Acceptance letter from Sensors

Full reference:

Moreno-Cano, M. Victoria and Úbeda, Benito and Skarmeta, Antonio F. and Zamora, Miguel A. *How can we Tackle Energy Efficiency in IoT based Smart Buildings?*. Sensors, 2014. no. 6: 9582-9614. Impact factor (2012): 1.953.

An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings

Asunto: Article tracking [NEUCOM_13411] - Accepted manuscript available online
De: Author Services <support@elsevier.com>
Fecha: 13/06/2013 20:06
Para: mvmoreno@um.es

Article title: An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings
Reference::NEUCOM13411
Journal title: Neurocomputing
Corresponding author: Ms. M.V. Moreno-Cano
First author: Ms. M.V. Moreno-Cano
Accepted manuscript (unedited version) available online: 11-JUN-2013
DOI information: 10.1016/j.neucom.2013.01.045

Dear Ms. Moreno-Cano,

We are pleased to inform you that your accepted manuscript (unformatted and unedited PDF) is now available online at:

http://authors.elsevier.com/sd/article/S0925231213005626

You might like to bookmark this permanent URL to your article.

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http://authors.elsevier.com/TrackPaper.html?trk_article=NEUCOM13411&trk_surname=Moreno-Cano

Yours sincerely,
Elsevier Author Support

Figure 5.2: Acceptance letter from Neurocomputing

Full reference:

Moreno-Cano, M. Victoria and Zamora-Izquierdo, M.A. and Santa, Jose and Skarmeta, Antonio F. *An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings*. Neurocomputing, 2013. Pg. 116-125, Vol. 122. Impact factor (2012): 1.634.

User-Centric Smart Buildings for Energy Sustainable Smart Cities

Asunto: ETT-13-0229.R2 - Decision
De: onbehalfof+mischa.dohler+kcl.ac.uk@manuscriptcentral.com; en nombre de; mischa.dohler@kcl.ac.uk
Fecha: 29/10/2013 18:10
Para: mvmoreno@um.es; mzamora@um.es; skarmeta@um.es

29-Oct-2013

Dear Miss Moreno-Cano,

It is a pleasure to accept your manuscript entitled "User-centric Smart Buildings for Energy Sustainable Smart Cities" in its current form for publication in Transactions on Emerging Telecommunications Technologies. For your records the comments of the referees are included at the foot of this letter.

Unless already done, we would like to ensure that you have already searched the ETT database for related prior art. To this end, please, take your time and search under http://onlinelibrary.wiley.com/advanced/search for (keywords related to your paper in "All Fields") AND ("Telecommunications" in "Publication Titles") AND (between the past 3 years). If you find papers that are related to your work, and of sufficient quality to add to the validity of your 'related work' section, we kindly suggest to position them. Thank you!

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Thank you for your contribution.

Yours sincerely,

Prof. Mischa Dohler
Transactions on Emerging Telecommunications Technologies mischa.dohler@kcl.ac.uk

Referee's Comments

Figure 5.3: Acceptance letter from Transactions on Emerging Telecommunications Technologies

Full reference:
Moreno-Cano, M. Victoria and Zamora-Izquierdo, Miguel A. and Skarmeta, Antonio F. *User-Centric Smart Buildings for Energy Sustainable Smart Cities.* Transactions on Emerging Telecommunications Technologies, 2013. Pg. 41-55, Vol. 25. Impact factor (2012): 1.049.

An IoT Based Framework for User Centric Smart Building Services

Asunto: Refereeing Decision IJWGS_60438
De: Submissions <submissions@journalservice.net>
Fecha: 22/03/2014 12:01
Para: mvmoreno@um.es; mzamora@um.es; skarmeta@um.es

Dear author(s) M. Victoria Moreno, Miguel A. Zamora, Antonio F. Skarmeta,

Ref: Submission "An IoT Based Framework for User Centric Smart Building Services"

Congratulations, your above mentioned submitted article has been refereed and accepted for publication in the International Journal of Web and Grid Services. The acceptance of your article for publication in the journal reflects the high status of your work by your fellow professionals in the field.

You need now to login at http://www.inderscience.com/login.php and go to http://www.inderscience.com/ospeers/admin/author/articlelist.php to find your submission and complete the following tasks:

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Finally click on the "Notify Editor" button to let the editor know that you have completed the six tasks.

Your continuing help and cooperation is most appreciated.
Best regards,

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Figure 5.4: Acceptance letter from International Journal of Web and Grid Services

Full reference:

Moreno-Cano, M. Victoria and Zamora-Izquierdo, Miguel A. and Skarmeta, Antonio F. *An IoT Based Framework for User Centric Smart Building Services.* International Journal of Web and Grid Services, 2014. To appear. Impact factor (2012): 1.615.

Chapter 6

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