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FACULTAD DE INFORMÁTICA

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

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

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Un Sistema de Gestión de la Información basado en IoT para Eficiencia Energética en Edificios Inteligentes

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.
Me hicisteis construir sobre la realidad como sobre una roca.
Me hicisteis adversaria del malvado y muro del frenético.
Me habéis hecho ver la claridad del mundo,
y la posibilidad de la alegría.

Pablo Neruda

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A mis padres, gracias por haberme dado la vida y mostrarme la integridad de las vuestras. A mis hermanos gracias, por ser como sois y hacerme así sentir tan orgullosa de ser vuestra hermana. A mi tía Elisa por todas las lágrimas que indirectamente te haya podido arrancar. A mis sobrinos, porque sois una de mis mayores fuentes de alegría. Al resto de la familia, gracias por existir. A mis amigos, a todos aquellos que saben que lo son porque así yo se lo haya hecho sentir. A Patri, porque sin serlo, eres la mejor hermana que pudiera tener. A mis directores, Miki y Antonio, gracias por recibirme aquel jueves y la confianza puesta en mí, por haberme hecho sentir parte de, y gracias por ser ejemplos de esfuerzo y dedicación. A mis compañeros de trabajo de la T3, Moragón, Santa, Jara y Cristina, gracias por vuestra compañía diaria y la ayuda prestada. A Manolo, gracias por haberme dejado un día dibujar una flor en tu pizarra. A Miguel, gracias por tantos deseos de buenos días. A mis amigos de la 2.6, porque nada hubiera sido igual sin conoceros, gracias porque además, nada hubiera podido ser mejor. Gracias Jesús por hacer las presentaciones. Y gracias Mayte por ser un enclave de mi admiración. Y con la mayor humildad y la vanidad que no conozco, me doy las gracias a mí misma, por ser mi fiel compañera y quién más valiente me hace ser.

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Capítulo 1

Resumen

1.1. Motivación y objetivos

Durante los últimos años la sociedad ha tendido cada vez más a desplazarse a áreas urbanas para vivir. Tal ha sido esta tendencia que para el año 2050 se espera que más de seis mil millones de personas vivan en ciudades y sus alrededores [42]. Como consecuencia, actualmente existe la necesidad de hacer frente a renovados procesos de urbanización que sean capaces de cubrir un mayor número de necesidades y servicios básicos a ofrecer a los ciudadanos, tales como los relacionados con el suministro de agua, transporte, sanidad, educación, seguridad y energía.

Las ciudades de hoy en día, en comparación a las ciudades tradicionales, han de proporcionar servicios mejorados desde un punto de vista multidisciplinar: combinando la competitividad económica de una ciudad con sus oportunidades de negocio, a través de la disponibilidad social y el capital humano, el gobierno y la participación ciudadana, transporte, uso eficiente de los recursos naturales, y con el incremento de la calidad de vida (ver Figura 1.1)

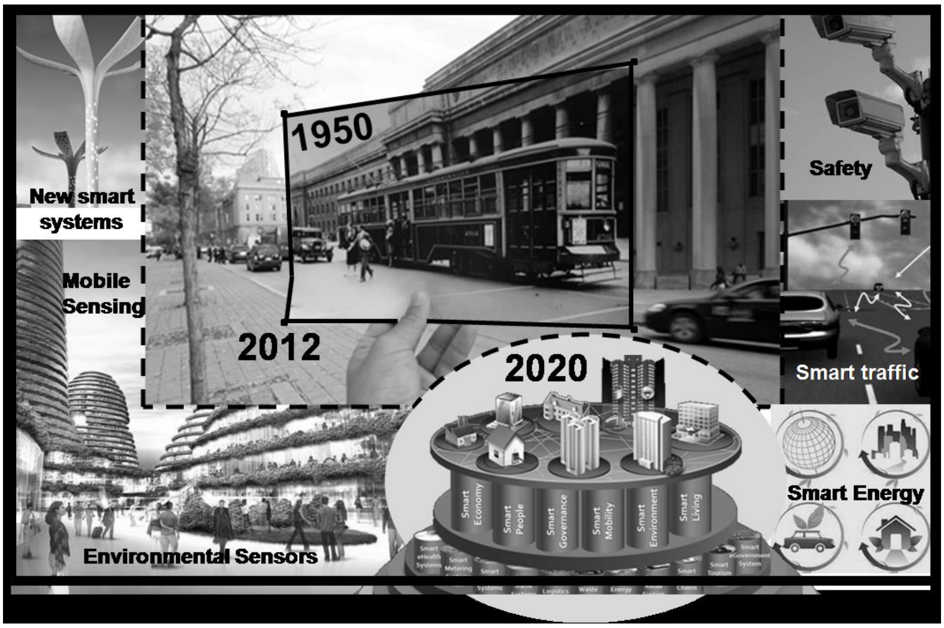

Figura 1.1: Desde el pasado al futuro, hacía las Ciudades Inteligentes

Debido a que los ciudadanos pasan gran parte de su tiempo en espacios de interior, la sostenibilidad de los edificios en términos de su consumo energético y la reducción de sus emisiones de CO_2 representan la piedra angular de la sostenibilidad de las ciudades. Y es que, en contra de lo que mucha gente cree, uno de los mayores consumidores de energía son los edificios, tanto residenciales como comerciales. Esta tendencia se ha pronunciado más en los últimos años, sobre todo entre los países desarrollados, donde entre el 20 % y el 40 % del consumo total de energía proviene de edificios [1].

La reducción de la huella de carbón, así como la eficiencia energética de edificios, son objetivos clave y de alta prioridad entre la comunidad investigadora y expertos en política energética. En esta línea ya se han propuesto acciones internacionales dirigidas a mejorar la eficiencia energética de edificios. Por ejemplo, desde la Comisión Europea se propuso hace unos años la *"Directiva sobre el comportamiento energético de Edificios"* (2010/31/EU) [10]. Esta directiva propone la adopción de medidas para mejorar el comportamiento de las infraestructuras eléctricas instaladas en edificios, tales como aquellas que forman parte de los sistemas de iluminación, climatización, ventilación, etc., con el objetivo de reducir el consumo energético asociado a ellas.

Considerando además la incremental demanda que se ha producido de los sistemas de climatización y ventilación para proporcionar confort térmico en edificios, los cuales llegan a representar el 76 % del consumo energético total de los edificios en muchos países desarrollados [36], existe una clara necesidad de abordar el problema del gran consumo energético asociado a estos. Algunas Organizaciones de estandarización son conscientes de esta necesidad [43], tales como la Organización Internacional para la Estandarización (ISO), la cual ha creado los Comités Técnicos ISO/TC 163 *"Comportamiento termal y uso energético en entornos de edificios"*, y ISO/TC 205 *"Diseño del entorno de edificios"*. A través de ellos, estos grupos reconocen que además de la arquitectura de los edificios, se necesitan **sistemas inteligentes de automatización** que aseguren el **confort en los edificios**, así como la **eficiencia energética** de estos, como por ejemplo recoge la propuesta ISO 16484 *"Sistemas de automatización y control en edificios"*.

En lo que afecta a la normativa española, y como necesidad de transponer la Directiva 2010/31/UE del Parlamento Europeo y del Consejo relativa a la eficiencia energética de los edificios, se propone el Real Decreto 238/2013 del 5 de abril, por el que se modifican determinados artículos e instrucciones técnicas del Reglamento de Instalaciones Térmicas de los edificios. La Directiva 2010/31/UE establece que, a efectos de optimizar el consumo de energía de las instalaciones térmicas de los edificios, los Estados miembros de la UE fijarán unos requisitos en relación con **la eficiencia energética general en edificios**, mediante: **instalación correcta y dimensionado, y la monitorización y control de las instalaciones presentes en los edificios**.

Hasta ahora, la dinámica respecto a la gestión de edificios ha focalizado su interés en materia de eficiencia energética tan solo en el diseño de las instalaciones en condiciones límite o extremas, y se ha prestado muy poco interés a su operación (explotación y mantenimiento). Por esta razón, actualmente el área de los **Sistemas Inteligentes de Gestión Energética en Edificios**, basados en la monitorización y control de sus infraestructuras, no ha hecho más que iniciarse, y está desplazándose rápidamente hacia un estado tecnológico con creciente productividad. Este rápido auge está motivado principalmente por la presión que en materia de ahorro energético se viene ejerciendo desde la Unión Europea. Los Estados miembros de la UE se han comprometido a reducir para 2020 el consumo de energía primaria en un 20 % (Objetivos 20-20-20[2]: -20 % de emisión de gases de efecto invernadero respecto a los niveles de 1990, +20 % en consumo de energías renovables sobre el consumo final y +20 % en el rendimiento energético). No obstante, aún existen numerosos obstáculos para la adopción de medidas efectivas que permitan lograr dichos objetivos en tiempo y forma.

En este contexto, gracias al gran avance en la integración y desarrollo de Sistemas Inteligentes basados en Tecnologías de la Información y las Comunicaciones (TIC) [24], y al extenso despliegue de sensores y actuadores que el paradigma de Internet de las Cosas (IoT) promueve [4], existe actualmente una gran oportunidad de desarrollar sistemas que proporcionen servicios inteligentes y eficientes en el contexto de las ciudades, los edificios, el transporte, etc. En este sentido, el mundo está empezando a ser transformado a tal velocidad, que para el año 2015 se esperan que más de 50 mil millones de

[1] `http://ec.europa.eu/eip/smartcities/`
[2] `http://ec.europa.eu/clima/policies/package/index_en.htm`

dispositivos se encuentren interconectados, formando parte del ecosistema conocido como IoT.

Hasta ahora los dispositivos IoT han sido explotados principalmente por industrias y empresas privadas. Sin embargo, un conjunto de aplicaciones basadas en IoT ha sido ya identificado por el alto impacto que se espera que tengan en beneficios tanto de negocio como sociales. En la Figura 1.2 se muestran algunos ejemplos de aplicación de IoT en el escenario de las ciudades inteligentes.

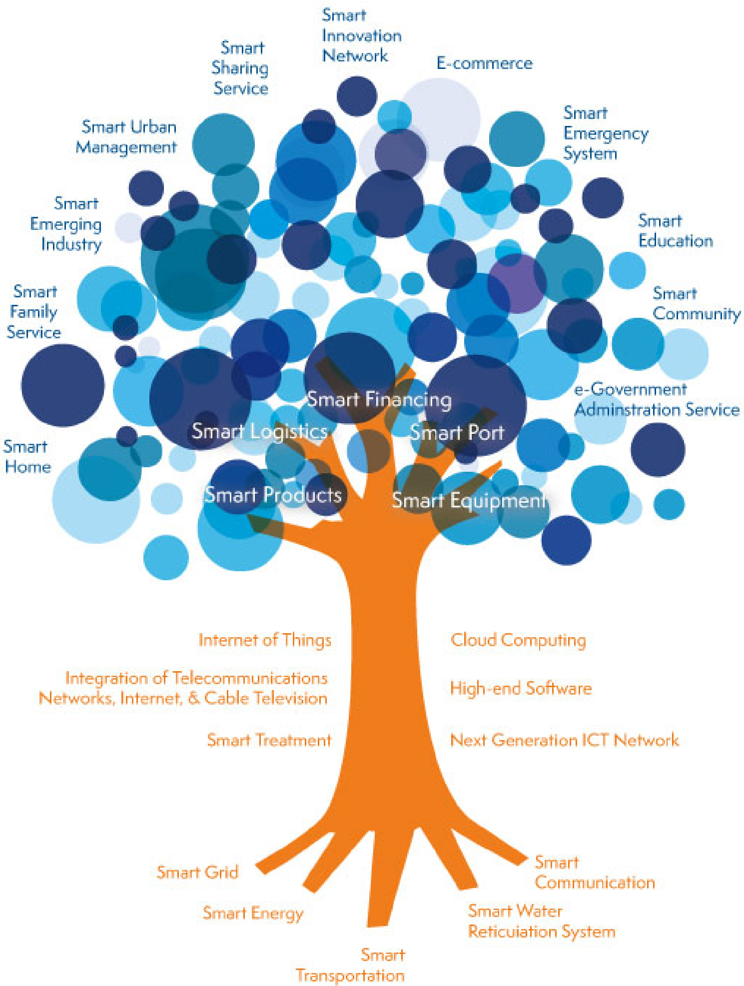

Figura 1.2: Aplicaciones de IoT en las Ciudades Inteligentes

Las tecnologías IoT están basadas en la interacción entre objetos inteligentes y la efectiva integración en el mundo digital de información del mundo real. Los objetos inteligentes están dotados con capacidades de sensado e interacción que permiten capturar información sobre el mundo real con mucho mayor nivel de detalle que nunca antes se haya podido conseguir. Esto representa una gran oportunidad para explotar las múltiples posibilidades que un alto nivel de sensorización y actuación ofrecen. Desde el punto de vista de un ciudadano, la aplicación de tecnologías basadas en IoT en espacios de interior es la de mayor impacto, convirtiendo los edificios en edificios inteligentes.

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 [52], [48]. 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 [65] 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 [50]. 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 [63], [50].

Tras esta fase inicial de análisis, se propuso una arquitectura general para el diseño de sistemas de gestión de edificios inteligentes [55], [54], [50]. Teniendo en cuenta dicha arquitectura, se diseñó nuestro sistema de gestión de la información para eficiencia energética en edificios inteligentes [50].

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 [59] y [62] (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 [51] y [49] se recoge dicha integración, y en el trabajo [64] 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 [58], [53]. 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 [62].

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 [60], [56].

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 [60], [56], [61],

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 [50].

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" [3].

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.

1.3. Conclusiones y Trabajos Futuros

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.

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

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	[50]
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	[63], [50]
3	Diseño de la arquitectura general de los sistemas de gestión de edificios inteligentes basados en IoT	O.3	[55], [54], [50]
4	Diseño de un sistema de gestión de la información para eficiencia energética en edificios inteligentes	O.4	[60], [56], [61], [50]
5	Implementación y validación de un mecanismo de localización para espacios de interior	O.4	[59], [62]
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	[60], [56]
7	Implementación y validación de un mecanismo de gestión de edificios para eficiencia energética incluyendo al usuario como entrada del sistema	O.4	[61], [54], [57], [50]
8	Validación de la propuesta de sistema de gestión de la información para eficiencia energética en diferentes escenarios reales	O.5	[50]

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

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 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 un 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.

El trabajo realizado durante la presente tesis doctoral marca el punto de partida de futuros trabajos que continúen esta línea de investigación. Un ejemplo de trabajo futuro es el de analizar el impacto que cada una de las acciones propuestas por nuestro sistema y que afectan a una zona concreta de un edificio, tiene sobre el comportamiento global del edificio. De esta forma, sería posible convertir el problema de la eficiencia energética de un edificio en subproblemas menores, y por tanto, más fáciles de manejar y gestionar.

Otro trabajo futuro sería el de explotar el uso de técnicas inteligentes de aprendizaje para analizar con mayor detalle cuál es el impacto del comportamiento de los usuarios en el consumo energético de edificios. De esta forma, sería posible dotar al sistema de una mayor capacidad cognitiva que le permitiese, de forma automática, aprender y adaptarse a las condiciones específicas del problema.

Un tercer trabajo futuro es el de extender la validación del sistema propuesto a edificios con un contexto diferente al abordado en esta tesis (edificios residenciales). Por ejemplo, a edificios en un contexto industrial en los que la operación de las máquinas encargadas de la producción son las responsables del mayor consumo energético del edificio. Otra validación de nuestra propuesta sería la llevada a cabo en modelos formados por grupos o bloques de edificios. En este caso, el objetivo sería el de conseguir la eficiencia energética considerando al conjunto de edificios como uno solo, pero en el que será necesario identificar las necesidades a satisfacer de forma individual por cada edificio, convirtiéndose en un problema multiobjetivo.

Y por último, otra interesante extensión del trabajo de esta tesis sería la de automatizar la propuesta de sistemas de gestión en edificios inteligentes atendiendo a su contexto, es decir, desarrollar modelos optimizados adaptados de forma particularizada al contexto y tipología del edificio. Para esto será necesario proporcionar un modelo general que asocie el impacto de cada una de las entradas propuestas del sistema al consumo energético del edificio. Esta última propuesta de extensión ya ha sido iniciada como trabajo de colaboración entre el Departamento de Información y las Comunicaciones de la Universidad de Murcia y el Instituto de Sistemas de Información de la Universidad de Ciencias Aplicadas de Suiza (HES-SO). Esta colaboración surge como consecuencia de la estancia de tres meses que la doctoranda realizó en dicha universidad. El edificio objetivo para eficiencia energética es el perteneciente a la compañía farmacéutica Debiopharm[4].

1.4. Organización de la Tesis

Esta tesis está presentada bajo el esquema de compendio por publicaciones, la cual establece ciertos requerimientos en cuanto al contenido que este trabajo ha de recoger. Según la normativa vigente para la presentación de los trabajos de doctorado, una tesis escrita en un lenguaje diferente al castellano y con la mención de doctorado internacional debe contener un resumen tanto en castellano como en inglés. La normativa también exige que dicho resumen contenga una breve descripción de los objetivos de la tesis y las conclusiones finales de la misma. Por este motivo, la sección de resumen de este trabajo es presentada en dos idiomas, en castellano e inglés respectivamente, y recoge la motivación, objetivos, resultados, conclusiones y trabajos futuros de la tesis.

Dicha normativa también establece que se presente un capítulo introductorio donde se presenten los artículos incluidos para el compendio de la tesis y se justifique la relación entre ellos. Satisfaciendo dicho requerimiento, el Capítulo 3 de la presente tesis presenta los principios fundamentales de los sistemas de gestión para eficiencia energética en edificios inteligentes. En este capítulo además se hace una revisión de las principales limitaciones y restricciones que presentan soluciones previas que han sido propuestas en literatura y que intentan abordar el problema de la eficiencia energética en edificios. Tras esto, se describe la solución propuesta en este tesis a dicho problema. Nuestra propuesta de solución comienza con el diseño de una arquitectura general de sistemas de gestión de edificios inteligentes. Esta arquitectura general es instanciada luego en una solución real y su aplicabilidad en eficiencia energética de edificios inteligentes. Este sistema es llamado "I2ME2 IoT-IBMS", por la abreviación en inglés de *"An IoT-based Information Management System for Energy Efficiency in Smart Buildings"*, y es presentado en forma de módulos abordando cada uno de ellos un subproblema específico. La solución propuesta a cada uno de estos subproblemas es presentada en este capítulo, y una descripción más detallada de las mismas viene recogida en cada uno de los artículos presentados por compendio en la presente tesis.

En este sentido, el Capítulo 4 recoge los cuatro artículos presentados por compendio y que describen gran parte del trabajo desarrollado en el marco de esta tesis. A continuación presentamos brevemente dichos artículos.

El artículo presentado en la Sección 4.1 con título *"How can we Tackle Energy Efficiency in IoT based Smart Buildings"* [50] analiza los requisitos principales de los sistemas de gestión de edificios para eficiencia energética, identificando los parámetros más relevantes a tener en cuenta para su integración en la propuesta de gestión para ahorrar energía en edificios. Este trabajo además presenta una revisión del estado del arte de los sistemas de gestión propuestos hasta ahora en literatura, identificando las principales limitaciones que estos presentan. Luego se describe nuestra propuesta de sistema de gestión, en la cual se hacen visibles los subproblemas identificados como requisitos individuales a resolver y cuyas soluciones componen nuestra propuesta de sistema de gestión para eficiencia energética en edificios inteligentes. Estos subproblemas son: la resolución de la localización en edificios, la integración de información de localización y las preferencias de confort de los usuarios en la gestión del edificio, y por último, la integración del usuario como parte fundamental de la operación del sistema (cada uno

[4] `https://www.debiopharm.com/about-us/debiopharm-group.html`

de estos subproblemas es abordado en el resto de artículos presentados para compendio). Finalmente, en este trabajo se demuestra la aplicabilidad de nuestra solución en diferentes edificios tomados como referencia.

El artículo presentado en la Sección 4.2 con título *"An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings"* [62] presenta la necesidad de disponer de información sobre la localización de los ocupantes de un edificio para que la gestión del edificio sea capaz de asegurar la eficiencia energética del mismo, al tiempo que satisface las necesidades de confort de sus ocupantes. Tras presentar el problema en cuestión, se describe el mecanismo de localización propuesto para abordar dicha necesidad, el cual consigue proporcionar información de localización de los ocupantes con la precisión requerida para satisfacer las necesidades de confort y eficiencia energética del edificio.

El artículo presentado en la Sección 4.3 con título *"User-Centric Smart Buildings for Energy Sustainable Smart Cities"* [56] presenta nuestra propuesta inicial de sistema de gestión de edificios para eficiencia energética, la cual integra información precisa de localización sobre los ocupantes, así como información sobre las preferencias de confort atendiendo al usuario y a las condiciones contextuales del edificio. En este trabajo se llevaron a cabo diferentes experimentos en un edificio tomado como referencia y el cual dispone de una gran capacidad de sensorización y automatización. Tras la evaluación del sistema de gestión aquí propuesto, se consiguió un ahorro medio del consumo energético del edificio de un 20 % en un mes de experimentación.

El artículo presentado en la Sección 4.4 con título *"An IoT Based Framework for User Centric Smart Building Services"* [61] presenta una extensión del sistema de gestión inicialmente propuesto. Dicha extensión consiste en la integración del usuario como parte fundamental de la operación del sistema. La idea de este trabajo es la de involucrar al usuario del sistema con el objetivo de que tras su participación y concienciación del consumo energético asociado a su comportamiento, éste realice los cambios de comportamiento adecuados que permitan un mayor ahorro energético. Tras una fase de experimentación en la que los usuarios formaban parte del sistema, nuestra propuesta de sistema gestión del edificio consiguió un incremento del ahorro energético del 9 % respecto a cuando no se incluía al usuario, consiguiendo por tanto hasta un 29 % de ahorro energético en un mes de experimentación.

El Capítulo 5 recoge las cartas de aceptación de los artículos presentados por compendio en esta tesis.

Finalmente, el Capítulo 6 incluye la bibliografía de este documento. La Sección 6.1 lista los trabajos referenciados en este manuscrito, y la Sección 6.2 presenta la lista completa de todos los trabajos realizados durante el periodo de esta tesis y que son el resultado de la misma.

Chapter 2

Abstract

2.1. Motivation and Goals

In recent years there has been an increasing trend for people to move to urban areas to live; so much so that over six billion people are expected to be living in cities and their surrounding regions by 2050 [42]. The consequent urbanization process has resulted in an urgent need to confront challenges related with the ability of city infrastructures to cover every citizen's needs in terms of water supply, transportation, healthcare, education, safety, and energy.

Compared with the traditional cities of today, modern cities are expected to provide services that are improved from a multidisciplinary point of view, combining the economic competitiveness of a city with its business opportunities, the availability of social and human capital, governance and civic participation, transportation, the efficient use of natural resource and increased quality of life (see Figure 2.1).

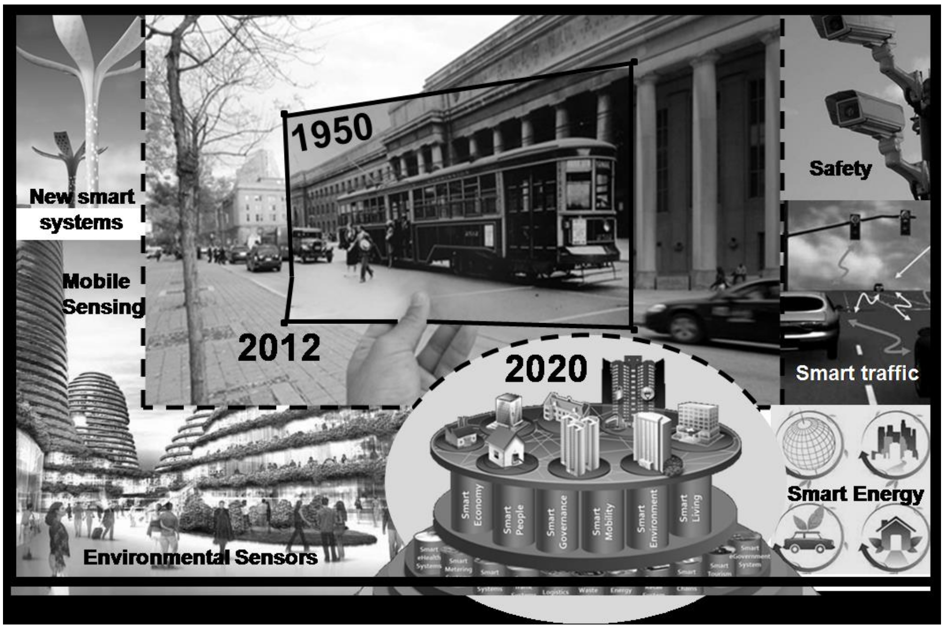

Figure 2.1: from past to future, towards Smart Cities

Since city dwellers spend most of their time indoors, the sustainability of buildings in terms of energy consumption and reduced CO_2 emissions represents the cornerstone of the sustainability of cities themselves. Contrary to what many people think, among the greatest consumers of energy are buildings, both residential and commercial. This tendency has been more pronounced in recent years, above all in developed countries, where between 20% and 40% of the total energy consumed is related with buildings [1].

Reducing our carbon footprint on a global scale and ensuring the energy efficiency of buildings are key high priority goals of the research community and experts in energy policy. International actions to improve energy efficiency in buildings have already been proposed. From the European Commission, for instance, the European Directive concerning *"Energy Performance of Buildings"* (2010/31/EU) [10] was issued few years ago. This Directive proposed the adoption of measures to improve the performance of the electrical infrastructures of buildings, such as those related with lighting, heating, ventilation, etc. with the aim of reducing the associated energy consumption.

The increasing demands being placed on heating, ventilation and air conditioning (HVAC) systems to provide thermal comfort, which may represent as much as 76% of the total energy consumed by buildings in most European countries [36] means there is a clear need to address this problem. Standardization organizations are also aware of this concern [43], such as the International Organization for Standardization (ISO), which has set up the technical committees ISO/TC 163, *"Thermal Performance and Energy Use in the Built Environment"*, and ISO/TC 205 *"Building Environment Design"*. These groups recognize that, apart from the physical building architecture, intelligent automation systems are needed to improve comfort and energy efficiency in buildings, as it is stated for example, in the ISO 16484 proposal, *"Building Automation and Control Systems"*.

As regards Spanish legislation, the need to incorporate European Directive 2010/31/EU proposed by the European Parliament and Council, which is related with the energy efficiency of buildings, Royal Decree 238/2013, of April 5th modifies some technical instructions of the regulation of Thermal Installations of Buildings. The Directive 2010/31/EU proposes that to optimize the energy consumption of buildings infrastructures, European Countries must establish requirements in terms of **general energy efficiency, suitable installation and design, and the monitoring and control of the infrastructures of buildings**.

Until now, trends related with the energy management of building infrastructures have focused on building designs based on extreme conditions, but very little attention has been given to their operation and maintenance. The area of Intelligent Systems of Energy Management in Buildings based on monitoring and control of the infrastructures has only just begun to take off and is moving rapidly forwards. Motivated mainly by the pressure to save energy proposed by European legislation, member states have agreed to reduce energy consumption by 20% by 2020 (Objectives 20-20-20[2]: a reduction by the 20% of the CO_2 emissions in comparison to the levels of 1990, accompanied by a 20% increase in the use of renewable energies, and a 20% increase in energy efficiency). Nevertheless, numerous obstacles remain before effective measures are taken to achieve these objectives.

In this context, due to the advances made in the development and integration of Intelligent Computational Systems based on Information and Communication Technologies (ICT) [24], as well as the widespread deployments of sensors and actuators promoted by the paradigm of Internet of Things (IoT) [4], there is currently a huge opportunity to develop intelligent and efficient services in the context of cities, buildings and transport systems. The world is being transformed at such a speed that by 2015 it is expected that over 50 billion devices will be interconnected in a full eco-system known as IoT.

Until now, most IoT devices have been used by private industry and business. However, a set of applications based on IoT has been identifies for their expected impact in both the business and social context. Figure 2.2 shows some examples of applying the IoT in the scenario of smart cities.

IoT technologies are based on the interaction of 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) will provide the means to capture information concerning the real world in much more detail than ever before. This offers a huge

[1] `http://ec.europa.eu/eip/smartcities/`
[2] `http://ec.europa.eu/clima/policies/package/index_en.htm`

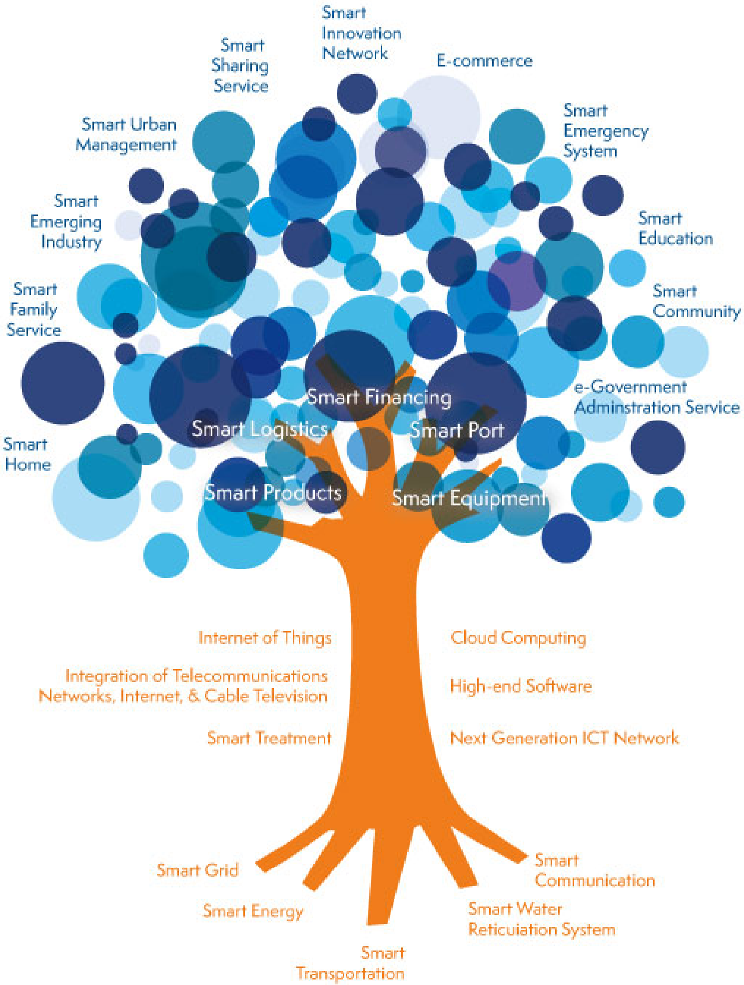

Figure 2.2: IoT applications in Smart Cities

opportunity to exploit the multiple possibilities that a high level of sensing and actuation provides. From the point of view of individuals, one of the most obvious impacts of IoT applications is indoors, since smart buildings are becoming a reality.

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 [52], [48], in which an IoT-based platform is proposed to supply, from a social and collaborative point of view, user-centred smart services. In [65] 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 [50], 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 [63], [50].

After the initial phase of the analysis we proposed a general architecture for the design of smart building management systems (SBMS) [55], [54], [50]. Bearing in mind this architecture, we designed our information management system to save energy in smart buildings [50].

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, [59] and [62] (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 [51] and [49] such an integration is described, and in [64] 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 [58], [53]. 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 [62]. 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 [60], [56].

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 [60], [56], [61].

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 [50].

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" [3].

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.

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[3] 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	[50]
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	[63], [50]
3	Design of a general architecture for management systems of smart buildings based on IoT	O.3	[55], [54], [50]
4	Design of an information management system for energy efficiency in smart buildings	O.4	[60], [56], [61], [50]
5	Implementation and validation of an indoor localization mechanism	O.4	[59], [62]
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	[60], [56]
7	Implementation and validation of a building management mechanism which integrates user behaviour and participation for energy efficiency	O.4	[61], [54], [57], [50]
8	Validation of the proposal, confirming the viability of its integration in different real scenarios	O.5	[50]

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

2.3. Conclusions and Future Work

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 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.

The work carried out to date can be regarded as the starting point of future works on the same research field. One possibility would be to analyse the impact that each of the actions proposed by our system in a given zone of the building has on the overall energy efficiency of the building, thus converting the problem of energy efficiency in a building into a series of sub-problems that would be easier to manage and control.

Another possibility would be to exploit the use of smart learning techniques to analyse in greater detail the impact that user behaviour has on a building's energy consumption. In this way it may be possible to endow the system with a greater cognitive capacity that will permit it to automatically learn and adapt to the specific conditions of the problem.

A third possibility would be to extend the validation of the proposed system to buildings with a context other than that considered in this thesis, for example, residential buildings or industrial buildings in which machinery is the greatest user of energy. Or groups or blocks of buildings, in which case all the buildings would be considered as one but in which the individual needs of each would need to be identified, making it a multiobjective problem.

Lastly, another interesting extension of this thesis would be to automate the management system of smart buildings according to the context, that is, develop optimised models adapted to the particular context and typology of the building. For this, a general model would be needed that associates the impact of each of the inputs proposed by the system with the energy consumed by the building. This last proposal has already begun to be studied in a collaborative project between the Department of Information and Communication of the University of Murcia and the Information Systems Institute of the University of Applied Sciences of Switzerland (HES-SO), set up as a consequence of a three month stay by the author of this thesis in the above university. The building under study for possible energy saving belongs to the pharmaceutical company Debiopharm[4].

2.4. Organisation of Thesis

The present thesis is based on a compendium of publications and must therefore fulfil certain requirements. Accordingly, a thesis written in a language other than Spanish, to be considered "international" should contain an abstract written both in Spanish and English. The norms also mention

[4] `https://www.debiopharm.com/about-us/debiopharm-group.html`

that the abstract should contain as brief description of the aims and the final conclusions concerning the same. In addition to this, we also set out directions which future studies may follow.

The norms also establish that an introductory chapter should be presented that describes the articles that make up the thesis and justifies the relation between them. To satisfy this requirement, Chapter 3 of this manuscript presents the underlying principles of the energy saving management system for use in smart buildings. The chapter also reviews the main limitations and restrictions of previous solutions that have been proposed in the literature. We then outline the solution proposed in this thesis, which begins with the design of a general architecture for smart building management systems. This is then applied to solve a real problem in a smart building. The system known as "I2ME2 IoT-IBMS", for its abbreviation from *"An IoT-based Information Management System for Energy Efficiency in Smart Buildings"*, is presented in modules, each of which looks at a specific sub-problem. The solution for each of these sub-problems are presented in this chapter and a detailed description of the same is provided in each of the articles that conform the thesis.

In this sense, Chapter 4 contains the four articles presented herein and which describe much of the work developed in the thesis. Below, we briefly present these articles.

The article presented in Section 4.1 with title *"How can we Tackle Energy Efficiency in IoT based Smart Buildings"* analyses the main requisites of energy efficiency building management systems, identifying the most important parameters to take into account in such a system. This work also presents a review of the state of the art of management systems, and identifies the main limitations of previous proposals. We then describe our proposal for a management system, in which the sub-problems whose individual solutions make up our energy efficiency management system for use in smart buildings. The sub-problems are: localization in buildings, the integration of localization information and user comfort preferences in the management system, and the incorporation of the users themselves in the operation of the system (each of these sub-problems is tackled in the subsequent articles that make up the compendium). Finally, the applicability of our solution is demonstrated in different buildings taken as reference sites.

The article presented in Section 4.2 with title *"An Indoor Localization System Based on Artificial Neural Networks and Particle Filters Applied to Intelligent Buildings"* highlights the need to have available information on the localization of the building occupants to be included in the energy saving management system while satisfying their comfort requirements. After presenting the problem, the localization mechanism proposed is described and it is demonstrated that the mechanism is accurate enough for providing the information needed for the aims mentioned.

The article tackled in Section 4.3 with title *"User-Centric Smart Buildings for Energy Sustainable Smart Cities"* presents our initial proposal to energy saving management system, which integrates the localization information and comfort preferences of the occupants according to the contextual conditions of the building. Several experiments in a reference building endowed with a great sensor and actuation capacity are described in this article. Application of the system in question is demonstrated to have saved approximately 20% energy in the month that the experiment lasted.

The article described in Section 4.4 with title *"An IoT Based Framework for User Centric Smart Building Services"* represents an extension of the proposed management system, in which users themselves become a fundamental part of the system's operation. The idea behind this is that users become more aware of the energy they consume and modify their behaviour in a way that saves energy. After an experimentation period in which users became part of the system, the proposal was seen to have achieved a 9% increase in the energy saved compared with a period in which users were not included, so that 29% of overall saving was reached in the month of experimentation.

Chapter 5 reproduces the acceptance letters referring to the articles making up this thesis.

Finally, Chapter 6 includes the bibliography relating to this work. Section 6.1 lists the references mentioned in this manuscript, and Section 6.2 presents a list of the works carried out during the time this thesis was being completed and which represent the result of the same.

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 [37]. 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], [38], [26]. 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 [13], [16]. 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 [44].

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 [35], 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 [28], 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 [23] 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* [5], 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 [47].

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 [14]. At this respect, the *1888-2011 IEEE Standard for Ubiquitous Green Community Control Network Protocol* [32] 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% [13]. 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 [11] a comprehensive comparison of existing simulation tools is provided. Among these tools are ESP-r [9] and Energy Plus [12]. 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 [8]. 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 [19], 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 [20], 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 [21], 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 [33] 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 [34], for instance, a reference implementation of an energy consumption framework is provided, but it only analyses the efficiency of ventilation system. In [15] 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 [41], 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 [16] [13]. 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 [22]. 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 [44]. 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.

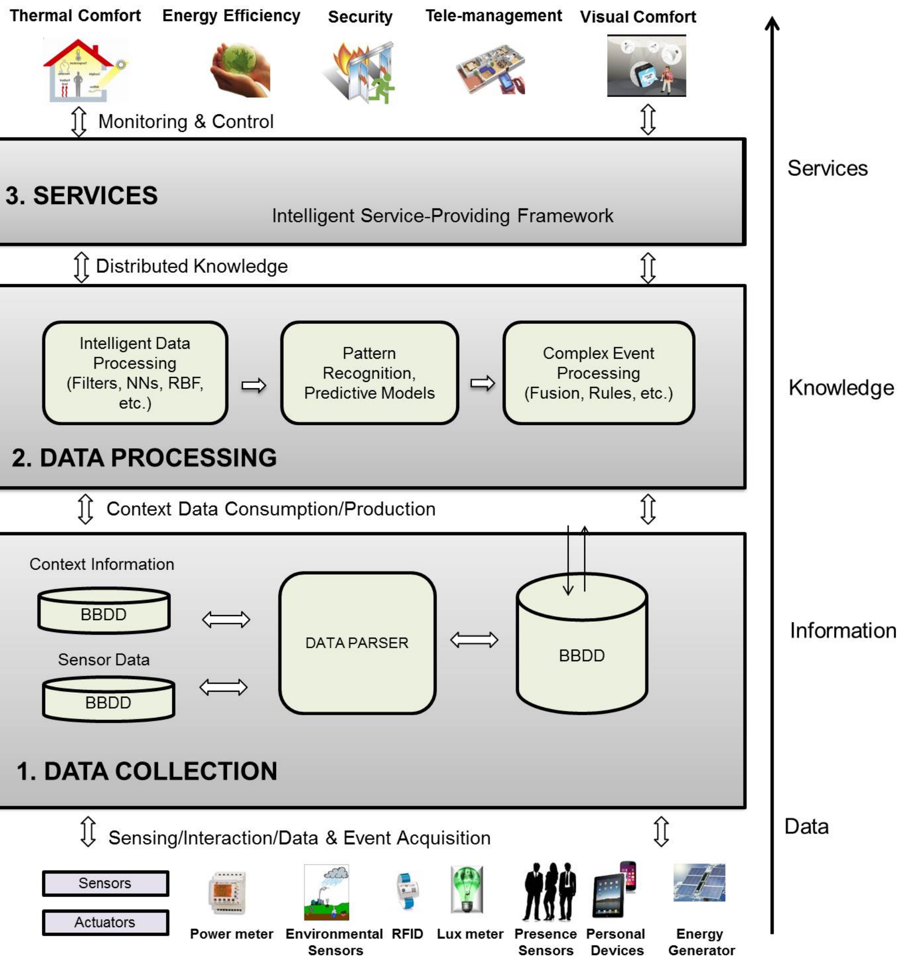

Figure 3.1: Layers of the base architecture for smart buildings

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 [46] [63].

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.

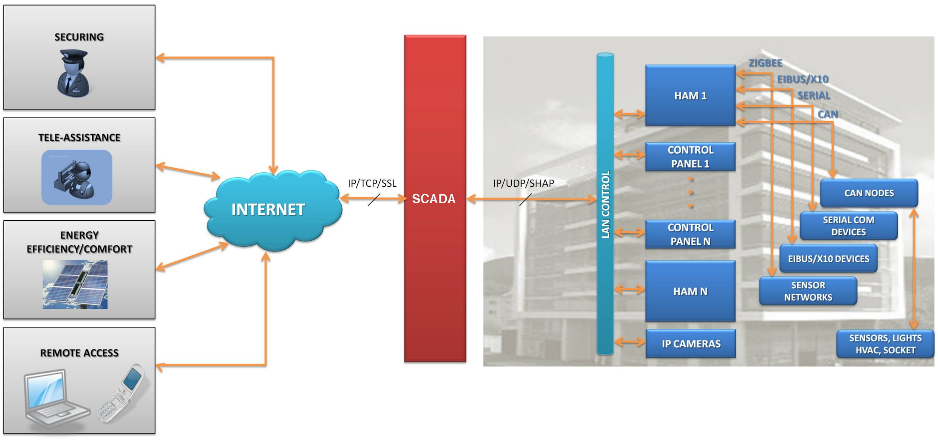

Figure 3.2: City explorer applied to smart buildings

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.

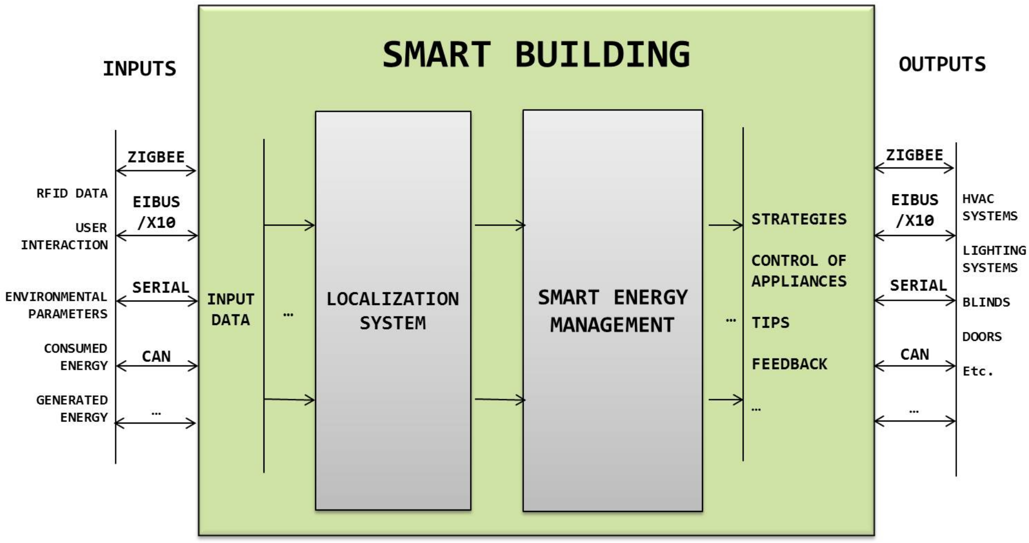

Figure 3.3: Schema of the modules composing the management system in charge of the building comfort and energy efficiency

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 [27]. 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.

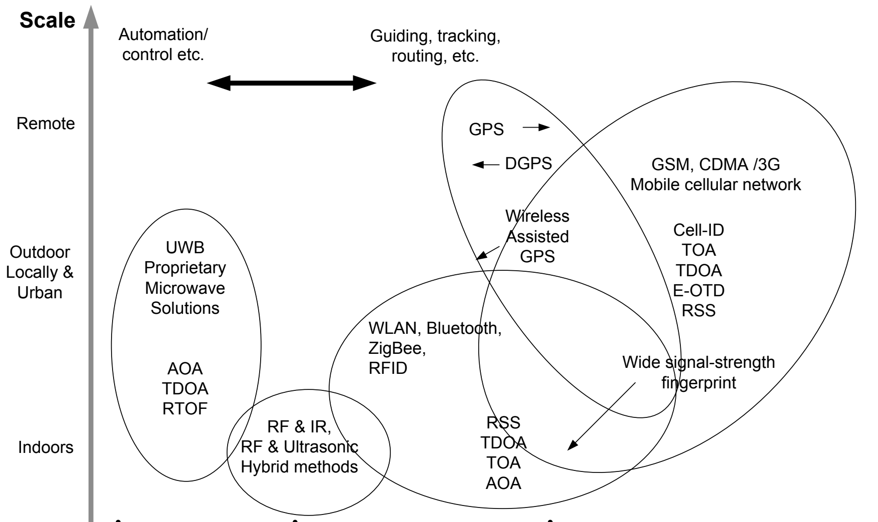

Figure 3.4: Outline of some positioning systems [27]

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	[45]	-	√	√	-
Pressure sensors	[30]	-	√	√	-
Cameras	[25]	√	-	-	-
UWB	[40]	√	√	-	√
Microwave	[39]	√	√	-	-
Ultrasonic	[6]	√	√	-	-
Hybrid RF and non-RF	[29]	√	√	√	√
WLAN	[18]	√	√	√	√
RFID	[31]	√	√	√	√

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.

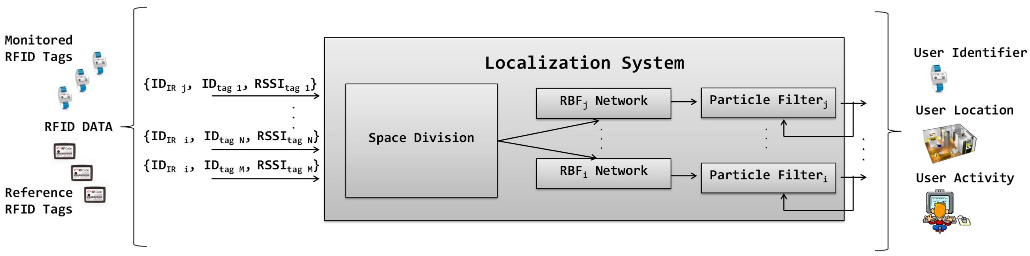

Figure 3.5: Schema of the data processing for position calculation

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 [5], 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) [7], which are usually suitable resolving MOPs because they maintain a population of solutions, enabling solutions to be found in parallel [17]. 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 [5]). 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.

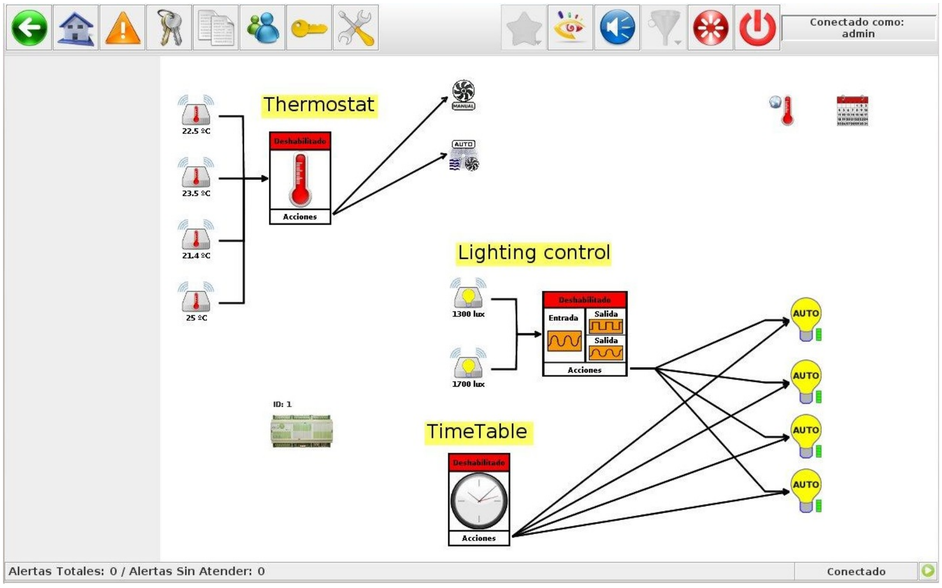

Figure 3.6: Example of rules defined through the City explorer's editor

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

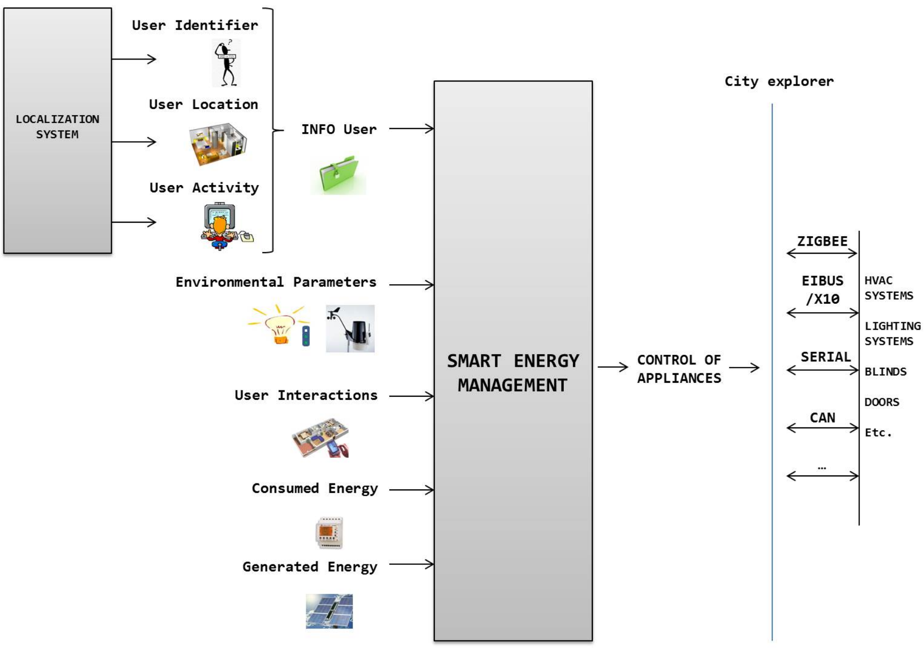

Figure 3.7: Schema of the module of building energy management including information about occupants localization and comfort preferences

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 [16]. 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

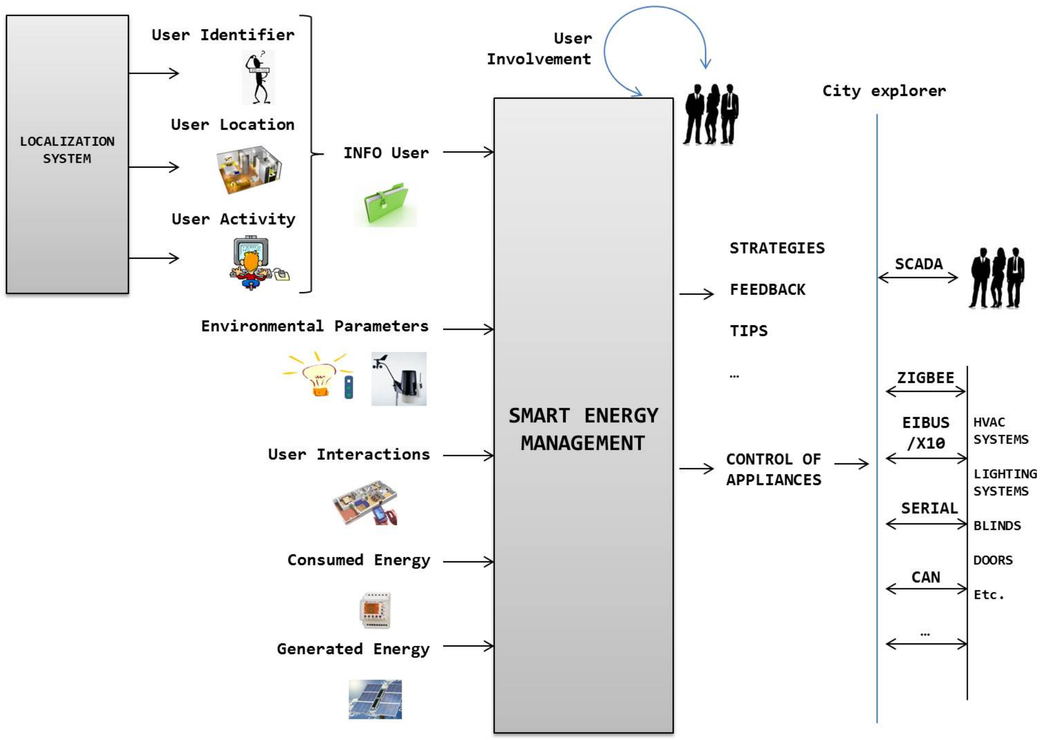

Figure 3.8: Schema of the definitive module of our building energy management system

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?

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.
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Contribution of the PhD student
The PhD student, M. Victoria Moreno Cano, declares to be the main author and the major contributor of the paper *How can we Tackle Energy Efficiency in IoT based Smart Buildings?*

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Article

How can We Tackle Energy Efficiency in IoT Based Smart Buildings?

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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.

Keywords: internet of things; smart building; energy efficiency

1. Introduction

Buildings, both residential and commercial, represent one of the highest energy consumption fields in the world. This tendency is particularly pronounced in developed countries, where between 20% and 40% of the total energy consumed is related with buildings [1]. Reduction of the carbon footprint on a global scale as well as ensuring energy efficiency of buildings are key goals of high priority for multi-disciplinary researchers in the fields of building engineering and energy policy. International actions to improve energy efficiency in buildings have already been proposed. From European Commission, for instance, a recast of the Directive about *"Energy Performance of Buildings"* (2010/31/EU) [2] was issued few years ago. This Directive proposed the adoption of measures to improve the performance of appliances located in buildings, including lighting and, especially, boilers and ventilation systems, in an attempt to reduce their associated energy consumption.

In order to be able to reduce the amount of energy consumed by improving the efficiency of the supply systems, a crucial step is to analyze how energy is currently consumed in buildings. Given the increasing demands being placed upon heating, ventilation and air conditioning (HVAC) systems to provide thermal comfort, there is a clear need to address one of the underlying drivers of energy consumption. Standardization organizations are also aware of this concern [3], such as the International Organization for Standardization (ISO), which has set up the technical committees ISO/TC 163, *"Thermal Performance and Energy Use in the Built Environment"*, and ISO/TC 205 *"Building Environment Design"*. Across them, these groups recognize that, apart from the physical architecture of a building, intelligent and automated systems are needed to improve comfort and energy efficiency, as is stated, for example, in ISO 16484 proposal, *"Building Automation and Control Systems"*.

Analysis of the energy efficiency of the built environment has received growing attention in the last decade [4–6]. Various approaches have addressed energy efficiency of buildings using predictive modeling of energy consumption based on usage profile, climate data and building characteristics. On the other hand, studies about the impact of displaying public information to occupants are shown useful to modify their individual behavior in order to obtain energy savings [7,8]. 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 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 [9]. Therefore, there is a lack of analysis to indicate the steps required to find solutions to energy efficiency in buildings.

The need for robust characterization of energy use in buildings has gained attention in light of the growing number of projects and developments addressing this topic. Bearing in mind that 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 to the operation of industrial machinery and infrastructures dedicated to production processes.

In this context, the integration and development of systems based on Information and Communication Technologies (ICT) and, more specifically, the Internet of Things (IoT) [10], 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.

In this respect, there is a huge opportunity to improve the most competitive actors to offer more cost-effective, user-friendly, healthy and safe products for buildings. In Europe, for instance, the area of energy management systems in buildings has only just started, but is rapidly moving towards a technology-driven status with rising productivity. This is mainly due to the need to reduce energy and greenhouse gas (GHG) in line with the EU 2020 and 2050 objectives [11]. This will ultimately create a solid foundation for continuous innovation in the building sector through sustainable partnerships, fostering an innovative eco-system as a fundamental corner-stone for smart cities.

In this work, we talk about what are the main drivers of the energy consumed in buildings, and 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 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. With the aim of validating our approach to achieve significant energy savings, we carry out different experiments following this approach, which demonstrate the need to consider holistic solutions to the problem of energy efficiency in buildings. For this, we select three reference smart buildings, 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%.

The rest of the paper is organized as follows: Section 2 reviews previous solutions presented in the literature to the problem of energy efficiency in buildings. Section 3 makes a general description of the problem of optimizing energy consumption in buildings, and analyze the main parameters identified as relevant for inclusion in any building management system to save energy. Section 4 describes our proposal of a smart building based on an automation platform in charge of monitoring, managing and controlling the building infrastructures, and explains our strategy of optimum energy management. Section 5 presents some experiments carried out in three buildings used as reference. For this, Section 5.1 describes the deployments carried out in these buildings, and Section 5.2 details the experiments performed and which shows the suitability of our solution when energy savings are to be achieved. Finally, Section 6 concludes the paper and presents possible future lines of work.

2. Related Work

Although much interest has been put into smart building technologies, the research area of using real-time information has not been fully exploited yet. In order to obtain an accurate simulation model, a detailed representation of the building structure and the subsystems is required, although it is the integration of all systems that requires the most significant effort. 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 [12] or [13] a comprehensive comparison of existing simulation tools are provided. Among these tools are ESP-r [14] or Energy Plus [15]. 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 [16]. 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 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 behavioral changes. The solutions based on these approaches are aimed at providing models based on real data sensor 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 energy savings, whilst an excessively fast response could produce inefficient actions. These monitoring systems, while contributing towards energy efficiency, require significant investment in 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 technology would provide a cheaper alternative to building energy management. On the other hand, building energy management must face up the inaccuracy of sensors, the lack of adequate models for many processes and the non-deterministic aspects of human behavior.

In this sense, there is an important research area that proposes to implement artificial intelligence techniques to process all data related with the problem, and as a way of providing intelligent building management systems 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.

On the other hand, and 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 [20] 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 in buildings using automation platforms is more limited. In [21], for instance, a reference implementation of an energy consumption framework is provided, but it only analyzes the efficiency of ventilation system. In [22] 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 [23], 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.

In this work we present a solution that involves collecting and analyzing information from heterogeneous sources, and propose 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 gathered information, which is provided by, among others, the users themselves. This generic and interoperable smart building automation proposal addresses the problem of energy efficiency of buildings, comfort services for occupants, environmental monitoring and security issues, among others. It uses a flexible IoT approach, 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 analyzes all monitored data provided by automated devices and, depending on the required operation mode and considering the energy balance status of the building, takes real-time decisions to improve energy efficiency, while retaining conditions at different user-acceptable comfort levels.

In the next section we review different aspects that need to be analyzed before a solution can be proposed to save energy in buildings. Additionally, we describe the steps that are essential for providing optimum solutions that address energy efficiency in buildings based both on real data sensors and data prediction.

3. Towards Smart Buildings: Optimization of Energy Efficiency

Optimizing energy efficiency in buildings is an integrated task that comprises the whole lifecycle of the building. According to the literature [21], the main stages are:

- Design, using simulations to predict the energy performance.
- Construction, testing individual subsystems.
- Operation, monitoring the building and controlling actuators.

- Maintenance, solving infrastructure problems due to energy deficiencies.
- Demolition, recycling materials and usable elements.

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. If we take as reference the energy performance model for buildings proposed by the *CEN Standard EN15251* [24], 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 energy consumption of buildings. Given each building has a different static model according to its design, we try to provide a solution for energy efficiency focusing on analyzing how dynamic conditions affect energy consumed in buildings. Thus, we propose an initiative for the challenges involved in the living stage of buildings *Performance monitoring and management* from the before list. In this stage, we need to identify what are the main drivers of energy use in buildings. Because after monitoring these parameters and analyze the energy consumed associated to them, we can model the impact of each one in the energy consumption, and then, propose strategies of control that let save energy in the target building. The main idea of this approach is to provide anticipated responses to ensure energy efficiency in buildings.

Bearing in mind all these concerns, following we describe the stages [25] that must be carried out to realize energy-efficient buildings.

3.1. Monitoring

During monitoring phase, information from heterogeneous sources is collected and analyzed before proposing concrete actions to minimize energy consumption considering the specific context of buildings. Bearing in mind that 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 to 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* [26], we describe below the main parameters that must be monitored and analyzed before implementing optimum energy building managements. In this way, from this set of parameters affecting energy consumption in buildings, we can extract the input data to include in the proposal of solution.

1. **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 this represents 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 consumed. This value will be included as an input to the final system responsible for estimating the daily electrical consumption of the building.
2. **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 behavior of the occupants; for example, in the context of a factory or an office where there are schedules and rules. Whatever the case, a 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 of a household or an industrial site over time, cost effective and readily available solutions include Non-Intrusive Load Monitoring (NILM) techniques [27].

3. **Occupants' behavior.** Energy consumption of buildings due to the behavior of their occupants is one of the most critical point in every building energy management. This is mainly because occupant behavior is difficult to be characterized and controlled due to its uncertainty and dynamic. First of all, it is necessary to have solved the occupants' localization before behavior models associated to them can be provided. Depending on the building context, the impact of occupants behavior on the total energy consumption is different. For example, in residential buildings the impact of occupants behavior in the energy consumed is one of the greatest, followed by environmental conditions. However, in buildings with productive goals, the electrical consumption due to the appliances and devices working for such goals is usually the main contributor to the total energy consumed in the building. Therefore, it is required to monitor and analyze this issue to be able to provide behavior patterns that will be included in the final estimation of the daily energy consumption of the building. Occupants' behavior can be characterized for features such as:
   - Occupants localization data
   - Activity level of occupants
   - Comfort preferences of occupants
4. **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.
5. **Information about the energy generated.** 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 daily. This information allows us to design optimal energy distribution or/and strategies of consumption to ensure the energy-efficient performance of the building.
6. **Information about total energy consumption.** Knowing the real value of the energy consumed hourly or even daily permits the performance and accuracy of the energy building management to be evaluated, and make it possible to identify and adjust the system in case of any deviation between the energy consumption predicted and the real value. Besides, providing occupants with this information is crucial, making them aware of the energy that they are using at any time, and encouraging them to make their behavior more responsible.

3.2. Information Management

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

3.3. Automation System

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 with energy efficiency requirements [28].

3.4. 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% [7]. As can be deducted, a set of subsystems should be able to provide consumption information in an effective way. These subsystems are: electrical lighting, boilers, heating/cooling systems, electrical panels, *etc*.

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 provide users with increased awareness (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 users involvement, through their interactions and their associated data (identity, location and activity), so that customized services can be provided.

4. City Explorer: A Holistic Platform for Smart Buildings

A smart building provides occupants with customized services thanks to the intelligence of their contained objects, be it an office, a home, an industrial plant, or a leisure environment. Since the building environment affects the quality of life and work of all citizens, buildings must be able of not only providing mechanisms to minimize their energy consumption (for instance, integrating their own energy sources to ensure their energy sustainability), but also of improving habitability and productivity.

Sensor and actuator deployments in buildings need to be optimized in such a way that the associated cost is offset by the economic value of the energy saving. Note that monitoring the whole area of large buildings is not feasible nor realistic. Moreover, to the behavior patterns obtained after data monitoring, real sensor data about such inputs should be considered in the final energy management system. In this way, the system is able to adapt itself to changes in the building context as well as to new situations not included in the initial models.

On the other hand, it is possible to make a spatial division of the building according to the energy consumption of each area, so that different levels of monitoring and management can be applied. For example, while denser sensor deployments may be required to provide data about energy consumption in some zones of the building, in others, very few sensors or even none may be necessary when the energy consumption of these areas is negligible compared with the total.

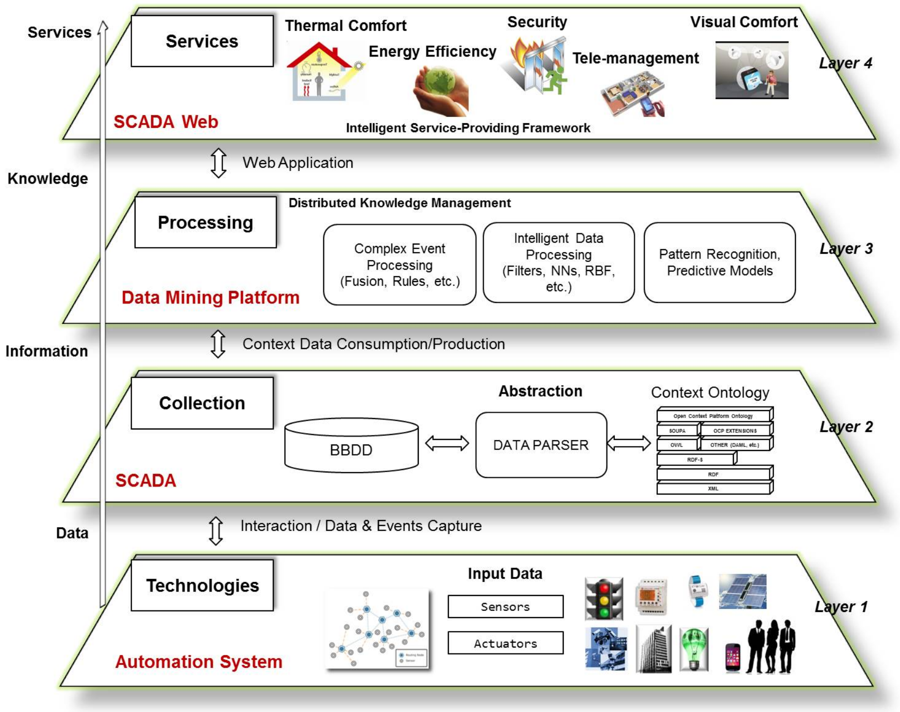
Following this approach, an optimum design for the building energy management can be provided by: (i) considering many data sources and the characterization of the building context; (ii) applying appropriate techniques of data fusion and intelligent data processing to take decisions to save energy in an efficient way.

In this section we present our core platform for smart buildings, and describe our proposal for energy building management, which includes as input data the variables mentioned above as relevant in the energy consumption of buildings.

The automation platform integrated in our smart building proposal is based on the *City explorer* system, whose main components are described in details in [29]. This automation platform composes all internal equipment installed in the building and all the external connectivity infrastructure required to provide remote access, technical tele-assistance, security and energy efficiency/comfort services.

The architecture of this platform is modeled in layers, which are generic enough to cover the requirements of different smart environments, as addressed in the context of smart buildings. Figure 1 shows the layers structure which is fully detailed in the previous work [30]. Basically, it consists of a first layer of data sensing able to manage multiple data sources as well as heterogeneous technologies. The second layer is dedicated to data processing to convert all collected data into a common format. To do this, some relevant works on energy efficiency with building automation systems employing semantic technologies can be found in [31,32]. Nevertheless, in this work the semantic perspective is not the main goal up to this moment for the data processing in our proposed system, although we consider this as a key and very critical aspect from an architecture point of view, and certainly it is in our next step of the evolution of our platform. Thus, currently we are implementing a common language format to represent all data sensed by sensors deployed in buildings and available through City explorer, taking as reference the ontologies already proposed in the literature. The next layer consists of applying data processing techniques and intelligent rules according to the final application or service selected for each specific building context (a home, an office, an factory, *etc.*). In this way, for example, a mechanism for solving the indoor localization problem has been implemented. This mechanism is explained with detail in the previous work with reference [33]. As a summarize, the main techniques implemented for this mechanism are based on an estimator based on Radial Basis Function Networks (RBF) and a tracking technique based on a Particle Filter (PF). Another example of data processing technique implemented is an optimization technique based on Genetic Algorithm in charge of providing optimal comfort conditions to the occupants of buildings. In the previous work with reference [30] more details about the mining data algorithms implemented in this layer are described. Finally, as can be seen in the last layer depicted in Figure 1, services such as thermal comfort, security, tele-management, energy efficiency, *etc.* can be provided in the context of smart buildings.

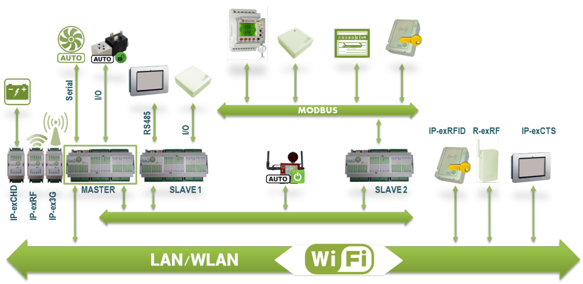
Figure 1. Layers of the base architecture of our smart building management system.



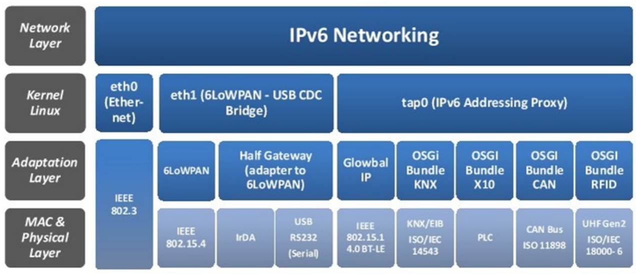
The City explorer system is composed of two main subsystems: a network of Home Automation Modules (HAMs) and the Supervisory Control and Data Acquisition system (SCADA). Each HAM is an embedded system based on a low consumption CPU (32bits 4 MB) and connected to all the appliances, sensors and actuators installed in the building. These devices centralize the intelligence of each space, controlling the configuration of the installed appliances. The HAM includes an optional human-machine interface (HMI). In addition, several control panels can be spread throughout the building to control specific parts. These include an embedded solution with an HMI adapted to the controlled devices. For example, in a three-story office building, each floor could have a control panel set to automatically open windows, turn the air conditioning to the desired temperature, or open and close the blinds according to the desired light intensity before using artificial lighting. These examples are developed case studies that diminish the power consumption and contribute to environmental preservation. The local gateway offers value-added services for managing and monitoring tasks, but it does not directly control appliances or actuators. Instead, this gateway communicates with the HAM using a UDP-based protocol.

City explorer bets on current specifications to connect the HAM with appliances and the remaining devices, and it proposes a novel communication protocol that connects the architecture's IP-based elements through UDP. IP-based elements are considered the local gateway; control panels and architectural elements outside the building are the remote gateway. Sensors and actuators can be self-configured and controlled remotely through the Internet, enabling a variety of monitoring and/or control applications. Each HAM of City explorer supports most extended communication protocols, enabling it to connect with a wide range of external devices. In addition to wired buses, wireless IP connectivity is provided by standards such as ZigBee (or 6LowPAN) and Bluetooth in order to allow an IoT approach to connect SCADA and all sensors and actuators. Controller Area Network (CAN) bus may also be used to extend the operation range or provide a more distributed wiring solution. X-10 connections over the power line (PLC) are also available for low-cost domotic installations, whereas the KNX-EIB controller offers a powerful solution for connecting with more complex appliances. Devices based on the RS-485 protocol can be connected, and the Modbus protocol is also supported. In Figure 2a a schema showing the integration of different components in the City explorer platform is depicted, and in Figure 2b a schema of the technologies integration is showed.

Figure 2. Schemas of integration in City explorer. (**a**) Schema of components integration in City explorer platform; (**b**) Schema of technologies integration in City explorer platform.



(**a**)



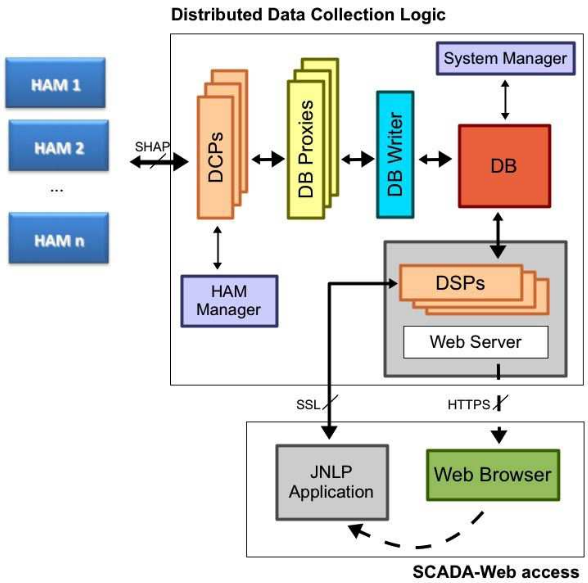
(**b**)

We use the OSGi (Open Services Gateway initiative) framework in the gateway to manage the life cycle of services that cover these features. Thus, a service that implements the underlying UDP protocol to connect with the HAM enables the implementation of more complex applications; and the HTTP service that the OSGi framework offers is used by a Web application to provide local and remote management capabilities through a 3D interface. In addition, the building owner can also use an SMS-based remote control strategy if the wired Internet access is out of service.

A SCADA platform acts a as gateway to offers value-added services for management and monitoring, but it is not in charge of performing any control over appliances or actuators directly. Instead, this gateway communicates with the HAM using a UDP-based protocol later explained. This SCADA will be usually provided remotely in a high-end server. Some other solutions leave these control actions to a local PC-based gateway, which is understood as a not appropriate strategy. A SCADA-based solution is used in City explorer to give extra services to inhabitants, and perform networking tasks from the transport to the application layer in the OSI stack.

A remote data and request processing management system is proposed. The SCADA has been designed on the basics of a distributed data collection logic. It collects building data, sensor measurements and energy efficiency information from buildings in a reliable way, and provides processed information to users/administrators through a SCADA access. Its architecture is shown in Figure 3. As can be seen, data from HAMs is collected by a set of Data Collection Points (DCPs) by means of the SHAP protocol. HAMs choose one of these DCPs according to the observed performance and an initial priority list. All data collected by DCPs is then sent to Data Base Proxies, in charge of turning HAM measurements into data records. Several Data Base Proxies provide reliability to the system for accessing the database. Finally, an intermediate stage for providing a buffered and synchronized access to the database is provided by DB Writer. All this information flow provides a fault-tolerant design against eventual problems in the different modules.

Figure 3. Architecture of the SCADA distributed logic.



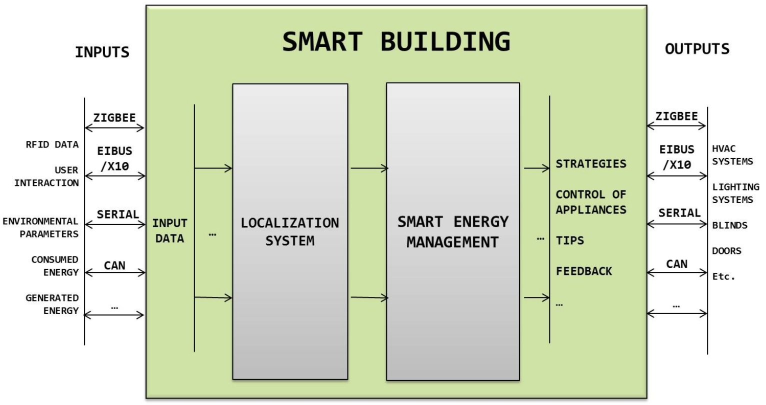
As can be seen in Figure 3, two management modules have been included in the data collection system: HAM Manager and System Manager. HAM Manager is used to keep track of all building connections, and it enables administrators to check the HAM firmware. System Manager is an always-on service that monitors the operation of all modules. It periodically reads status information of all modules (DCPs, DB Proxies, *etc*.) from the database, since each new record also includes status stamps of each system module.

All collected information from HAMs is finally provided to users/administrators (and the rest of building-external entities) through a SCADA access (called SCADA-Web). This is also illustrated in Figure 3. By means of a PC platform, a common Web Browser can be used to access a URL of the system. After the user is authenticated, a secure HTTPS link is established. At this moment, a JNLP (Java Networking Launching Protocol) application is automatically downloaded. This software operates at the client side, and provides a graphical front-end to access building information of all the monitored HAMs. This information is available for the JNLP application by means of an SSL (Secure Socket Layer) link with a Data Server Point, which access the database. This feature also improves the system reliability when the building information is accessed. Moreover, the JNLP technology offers flexibility to the system, since external entities dynamically download the Java (platform-independent) application from a Web server, but only when it is accessed for the first time or a newer version is available at the SCADA server.

Our energy saving strategy in building infrastructures includes a first phase of sensor deployment (*layer 1* of the architecture shown in Figure 1 and data monitoring (*layer 2*)). The monitoring phase is dedicated to registering the evolution of the parameters identified as relevant in the task of saving energy in any building or specific context. Such parameters may be building occupancy, behavior patterns, electrical devices, environmental conditions, *etc*. The data collection proposed in this work needs to be properly referenced to specific contextual conditions, since this association will help us to evaluate and validate our building management approach. After data collection, data processing techniques are applied to identify optimal control actions for energy saving in the building (*layer 3*). Apart from energy efficiency in buildings, additional services like thermal and visual comfort, security, *etc*. can also be provided following this same approach (*layer 4*).

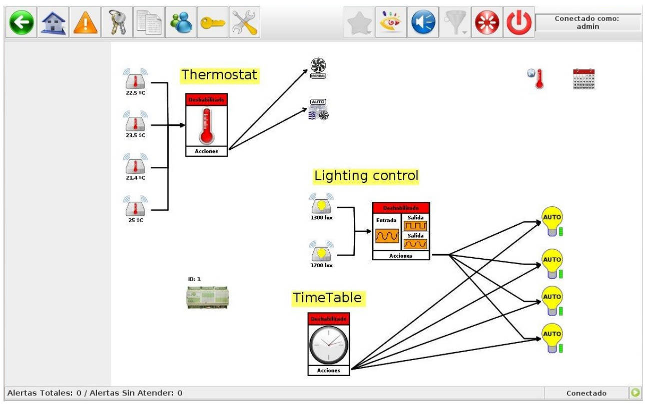
Our building management proposal to increase energy efficiency has the capability, among others, to adapt the behavior of the automated devices deployed in the building in order to meet energy consumption restrictions. Figure 4 shows a schema of the different subsystems comprising the intelligent management system integrated in City explorer, where the outputs of the system are forwarded to the actuators deployed in the building. We can see the variety of input data related with the parameters described as being relevant for energy savings. The output data of the system are different depending on the final aims depending on the context of the target building. 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 measures for saving energy. For example, identifying possible oversize in the contracted power tariff with the energy provider, defining optimized strategies of energy distribution in cases where alternative energy sources are integrated, proposing specific breaks in the daily load curves of the overall energy consumption of the building, *i.e.*, avoiding abrupt changes in energy demand, *etc*. More details about the data processing techniques implemented in each of the subsystems showed in Figure 4 were collected in previous works. Specifically, in [33] is explained the localization system implemented, and in [30] and [34] is described the building management system.

Figure 4. Our Energy Management Platform for buildings.



The overall system can set by users of City explorer, and with no any need to program any controller by code. In this way, it is possible to set up the whole system by just adding plans, drawings 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 how 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, in which some rules are defined for the management of lighting and HVAC appliances, is shown in Figure 5. Currently, we define the optimum rules to implement based on analysis of data already collected and available in our system. Another approach to generate such rules is that proposed by the reasoning over the ontologies containing all knowledge about the problem, as in the work [35] is carried out. Including in City explorer a semantic perspective to represent the contextual information of buildings is a current work line, then context-based rules can be generated automatically.

Figure 5. Example of rules defined through the City explorer editor.



As mentioned in a previous section, to implement any energy building management, it is first necessary to contextualize the target building and identify the most relevant parameters which affect its energy consumption. Then, joint strategies for saving energy are implemented in the light of the requirements of the target building. Following this approach, next section describes the analysis carried out in a reference smart building where comfort and energy efficiency are the target goals to achieve. And then, from this analysis we extract the main strategies to be implemented and assess them in different smart buildings to save energy.

5. Deployment and Experimental Analysis

In this section we present three examples of smart buildings in which City explorer has been deployed. The target services to provide in the context of these buildings are comfort and energy efficiency. In general, to provide both services in any buildings it is necessary to satisfy the following requirements:

- 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.
- Tele-monitoring of any parameter of interest.

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.
- Windows 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.
- Electrical devices and appliances.

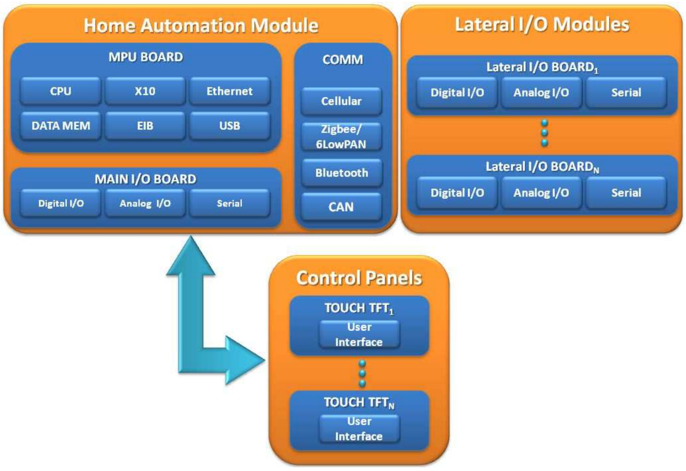
5.1. System Deployment

The HAM of City explorer is based on the SIROCO 3.0 (System for Integral contROl and COmmunications) hardware architecture, designed at the University of Murcia for automation purposes. The first generation of the SIROCO platform was presented in [29]. The different modules that comprise the unit can be seen in Figure 6. SIROCO is a modular system highly adaptable that gives a self-sufficient platform to perform management and monitoring tasks. It offers the option of installing a low-cost solution or a complex one, extending the base system with the required modules.

The third generation of SIROCO hardware MPU series is based on a 32-bit microcontroller. The MPU (Main Processor Unit) Board is equipped with a set of I/O channels:

- 16 basic I/O ports (analog and digital).
- Communication ports: Ethernet, USB, CAN 2.0B, RS-485 and three RS-232.
- Possibility of adding extra memory through microSD card or USB flash drive.

Figure 6. Logical diagram of the home automation module and its communication capabilities.



The HAM is additionally provided with extended networking capabilities. Specific domotics communications are provided by an X10 module and an EIB controller, connected both through a serial interface. Furthermore the MPU board can be extended with additional communication boards (if needed) through the serial and USB ports. The CAN bus support offers an alternative to EIB when a more flexible communication channel with wired sensors is needed.

The main I/O board provides extra wired interfaces with appliances, sensors and actuators adding up to 16 lateral I/O boards connected to the main I/O board. With this configuration, complex control schemes can be tackled.

The hardware unit developed following the previous design can be seen in Figure 7. The main I/O ports are visible (CAN/serial, Ethernet and USB), and it can be observed the compacted case chosen, as compared with the former prototypes described in [29]. As a summarize, following we enumerate the main features of the HAM modules acting as master units:

- 32bit CPU, 4MB expandable by microSD.
- Interfaces: Ethernet, USB, CAN, 3xRS232, 1xRS485 (Modbus support).
- 16 I/O ports as:
  - Digital inputs.
  - Analog inputs (0–10 V or 4–20 mA).
  - Digital outputs (for relays).
  - Analog outputs (0–10 V).
- Up to 16 additional slave units.
- Extra communication ports: 3G, RF 433/868Mz, 6LowPAN/Zigbee, DALI, KNX.

The second generation of control panels are based on the MPU board of the previous SIROCO architecture and have been upgraded to include a TFT 7 touch screen, as compared with the first units presented in [29]. They guarantee a familiar HMI limited to automated devices in the surroundings (connected to the same HAM). Users can define configuration profiles, which contain a set of device states and actions to be performed under certain conditions. Moreover, the building alarm can be armed/disarmed by a defined control panel. Any panel, however, can be used to activate panic, security or fire alarms at any time. Additionally, when an alarm is activated by the HAM (due to sensor measurements) or manually, control panels warn users via acoustic and visual messages.

Figure 7. Home automation module developed.

Figure 8a shows the control panel developed, while Figure 8b shows a screenshot of the HMI integrated, where the user is reviewing the configuration of the HVAC system of a laboratory of one reference building.

Control panels provide a local management of certain spaces in the building, but remote access to the whole system is also possible through the SCADA-Web application. This software can be used to monitor and control indoor spaces, but also to store incidents, manage machinery services, access control and system status reporting.

Users, administrators and technical personnel, by using this JNLP application, obtain an personalized 3D view of the building depending on their access type, and can manage the automation systems as if he/she were physically there. Figure 9a shows a screenshot of the application when a technician is accessing the main view of the building. Here the five different administrative domains can be accessed by pressing on the desired floor. Moreover, important events are listed on the left part of the window and the user can click on them to directly access the device emitting the alert.

In Figure 9b it can be seen the view for both a common user (e.g., the caretaker of the building) or a technician. The application is showing the status of the bathroom available in the first floor of the building (a map view is depicted on the bottom right part of the window). The status of the lighting system and the information provided by the presence and flooding sensors are showed here. Apart from the monitoring features, the user can press on the different subsystems (e.g., lighting) for changing the current state; thus, this view also serves for managing automated devices.

Security staff receive fire alarms from the building through the SCADA-Web application, and they can monitor in real time the fire sensor deployment along the building. In case of fire, an effective and timely response is possible thanks to the precise information about the incident given by the platform.

Figure 8. Control panel prototype. (**a**) Control panel installed in the reference building; (**b**) HMI of the integrated software.

(**a**)

(**b**)

When accessing the SCADA, if the user authenticates as an administrator, the JNLP application downloaded provides additional functionalities for allowing specialists to access the building configuration. Figure 10 shows a screenshot of the application while the administrator is establishing the keys to be used in the communication with one of the HAMs installed in the reference building. The software also monitor X10, EIB and UDP communications with the HAM.

The software enables the installer to configure the different partitions and zones of the building domain managed by the HAM, set the devices connected to the system, and define the remote accesses allowed from outside. All this information is stored in the HAM database, and then replicated in the SCADA logic. The HMI allows the installation of initial profiles and actions to be performed under certain events detected by sensors. All settings can also be saved for application to other HAMs.

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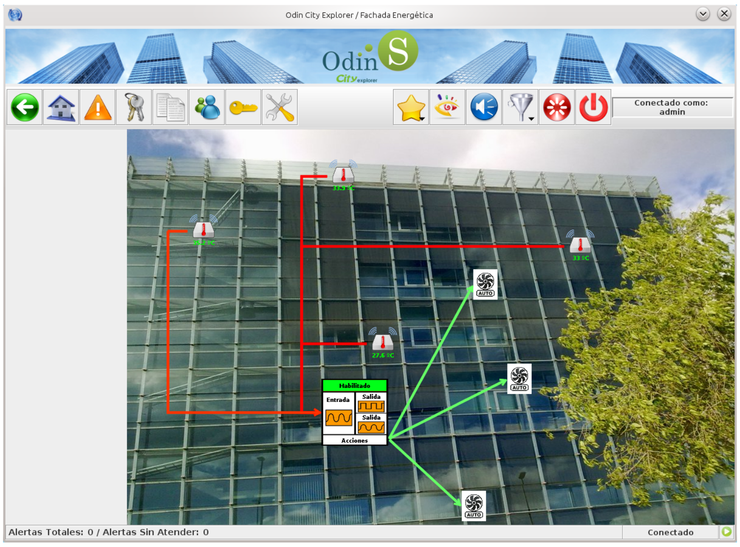
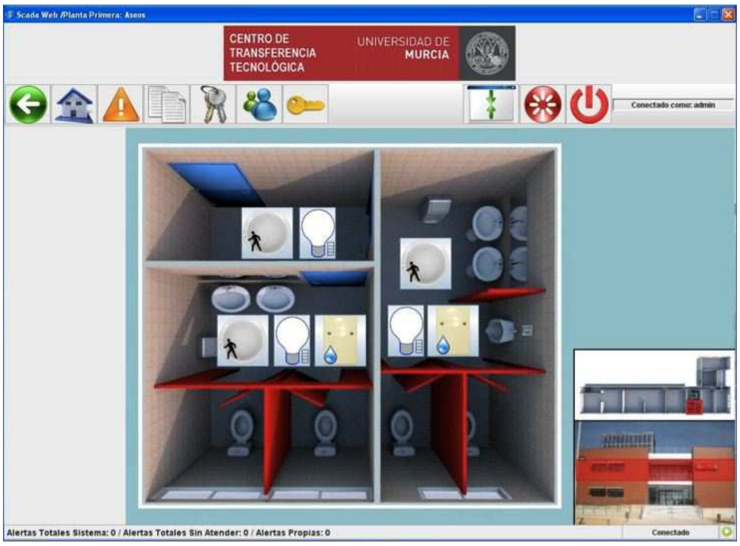
Figure 9. JNLP application with 3D HMI for local/remote management through the SCADA-Web access. (**a**) Overall building view; (**b**) Monitoring the bathroom of the 1st floor.

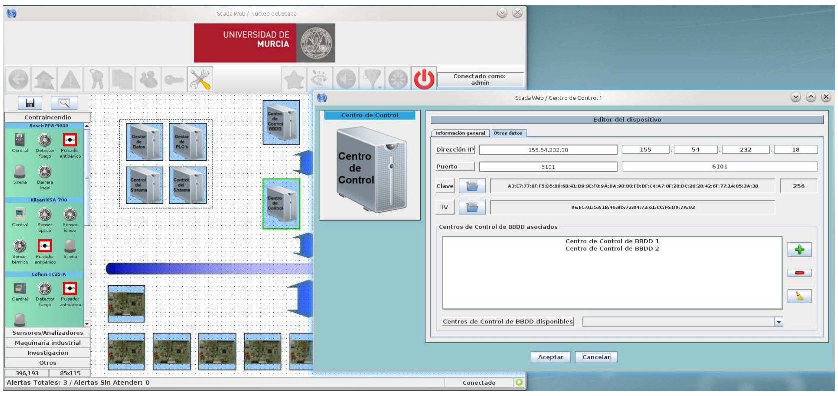


(**a**)



(**b**)

Figure 10. Screenshot of the HAM set-up software.



5.2. Experimental Analysis

As a starting point, we focus on the management of lights and HVAC subsystems since they have the highest energy consumption at building level [36]. On the other hand, user interactions have a direct effect on the whole system performance, because occupants can take control of their own space at any time. Thus, combined control of the system requires optimal operation of every subsystem (lighting, HVAC, *etc*.), under the assumption that each operates normally in order to avoid conflicts arising between users' preferences and the simultaneous operations of these subsystems.

During our experiments, the building's occupants could define their own strategies to control any appliance and/or monitor any specific parameters captured by City explorer. As regards users interactions with the system to communicate their energy control strategies or even their comfort preferences, City explorer lets users explore monitored data by navigating through the different automated areas or rooms of the building, and 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.

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 occupant's behavior. To analyze 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. The different experiments carried out were as follows:

- First Experiment. A representative building was selected where people usually spend long periods of time and different occupant's behaviors are evident. We chose a large building of the University of Murcia, which we consider an example of a scenario where energy efficiency could be achieved given the large amount of energy consumed. After demonstrating and analyzing the impact of such inputs on the energy consumption of the building, and because the first building selected to analyze was very complex and involved many different occupant's behaviors, a second experiment was carried out.

- Second 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' behavior as input for the 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.
- Third 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.

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.

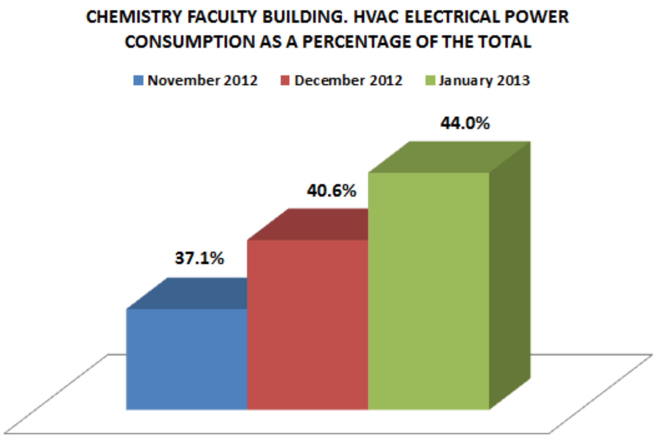
5.2.1. Use Case 1: Smart Campus Building

For this first experiment, the Chemistry Faculty of the University of Murcia (Murcia is near to Mediterranean coast of SE Spain) was chosen since it provides different functionalities and was thought more likely to demonstrate a distinguishable energy usage profile. It is predominantly composed of classrooms, offices and an open receptacle, and its characteristics and size serve as indicators of the range of buildings contained within the campus of this university. In Figure 11 we show a picture of an automated floor of this building, such picture is obtained from our SCADA web.

Figure 11. Use case 1: Smart campus building.

We analyzed the total energy consumption of this building and compared it with the energy consumption only related with thermal comfort, *i.e.*, the HVAC system. In this way, the impact of thermal comfort on the total energy consumption of this building could be estimated. We decided analyze this consumption first because it is known that HVAC systems are responsible for 50% of the total energy consumption in buildings. In many developed countries, even it represents 20% of the total energy consumption [37]. In the three months considered for our analysis, and Figure 12 shows, the mean consumption of HVAC represented 40.5% of the total. Given this high percentage, we focused on monitoring consumption patterns associated to the main parameters involved in order to identify strategies that could improve energy usage.

Figure 12. Percentage of energy consumption involved in thermal comfort.

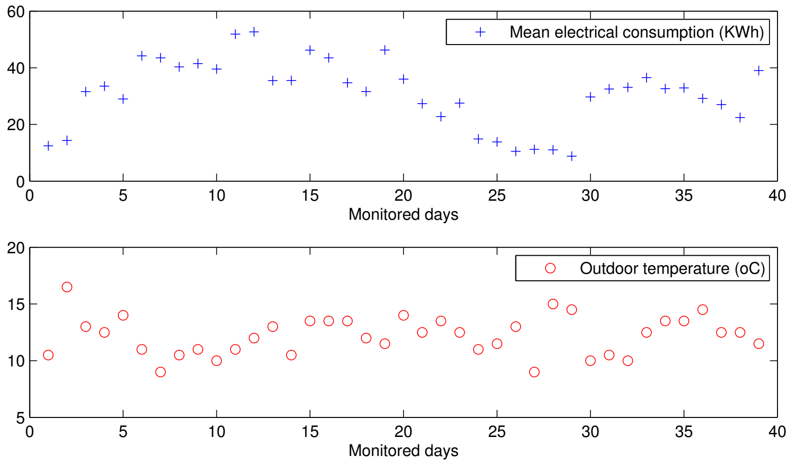


The selected parameters with the greatest impact on energy consumption due thermal comfort were the outdoor environmental conditions and the occupancy of the building. By taking into account the distribution of the individual HVAC appliances in the building as well as the monitoring data about what individual appliances are in operation at each time, we can extract a general picture of the minimal occupancy level and its daily distribution in the building, *i.e.*, how many people are in the building at specific hour, on which floor, even in which zone of the floor. Information about the outdoor temperature for each monitoring day was also available. Using these data we analyze the impact of both parameters on the total energy consumption related with thermal comfort in the context of a University building, where occupancy profiles have unique features such as high variability within small time intervals and often periods of low but non-zero occupancy.

In total, there are 158 individual HVAC systems distributed on the 5 floors of the building. On each floor there are different identified zones with different requirements in terms of occupant distribution and the activities carried out. The configuration of each HVAC appliance is free to be changed by any individual. But minimum comfort levels are provided automatically by the system for each specific building zone. These minimal levels are different depending on the expected activities carried out in such spaces. Thus, after data analysis, it was thought what activities involve a higher energy consumption, in order to define strategies to save energy considering the behavior patterns of occupants.

To analyze the monitored data we chose the period between 18 November 2012 and 20 January 2013, representing 64 complete days monitored in two seasons: autumn and winter. The evolution of the mean electrical power consumption associated to the HVAC system of this building is presented in Figure 13, which also shows the evolution of the outdoor temperature in the geographical area of this building. The week of highest consumption during the monitored period of time was that running from 2 December to 6 December 2012, when the outdoor temperature ranged from 8 °C to 11 °C. Therefore, during this week electrical consumption was due to the heating service. Besides, only during week days was electrical consumption associated to the HVAC system, since only during such days was the building officially open. From the evolution of electrical power consumption and outdoor temperature, we can deduce that both parameters are related since the days with extreme temperatures (both the highest and lowest) are associated with increasing values of energy consumed, both in heating and ventilation.

Figure 13. Evolution of the consumed electrical power and the outdoor temperature.



Considering now the evolution of the occupancy in the building during the monitored days (see Figure 14), we can see that when the number of occupants is high, the electrical power consumption derived from HVAC systems is also high. This figure also shows the dispersion of both parameters. The positive relation between them, with a specific correlation value of 0.89, confirms the close dependence of the electrical energy consumption on the occupancy level of the building.

Another aspect related to the level impact of building occupancy on the energy consumed for thermal comfort is that related with the distribution of occupants in the building. When occupants are distributed across many different building zones, more HVAC systems are in operation, and so the occupancy pattern represents one of the main factors affecting the total electrical energy consumption of this type of building related with thermal comfort.

For instance, Figure 15 shows the distribution of the electrical power consumed during the day with the highest consumption (3 December 2013 with 53 KW/h and 12 °C), and the number of different HVAC appliances turned on at each time along the "productive" timetable of this building. We can see that the time period with the highest consumption is associated with the period with the highest number of HVAC appliances that are turned on. Specifically, during the time period that runs from 09:30 A.M.

to 12:30 P.M. the electrical load curve increases, since 09:30 A.M. is the approximate time when people are usually enter this building. On the other hand, the highest consumption was not the academic day with the lowest temperature of the period considered in our analysis (26 November 2012 with 9 °C). Therefore, the electrical energy consumed on this day would have been due to the high occupancy level of the building.

Figure 14. Evolution of the electrical power consumption and the occupancy level.

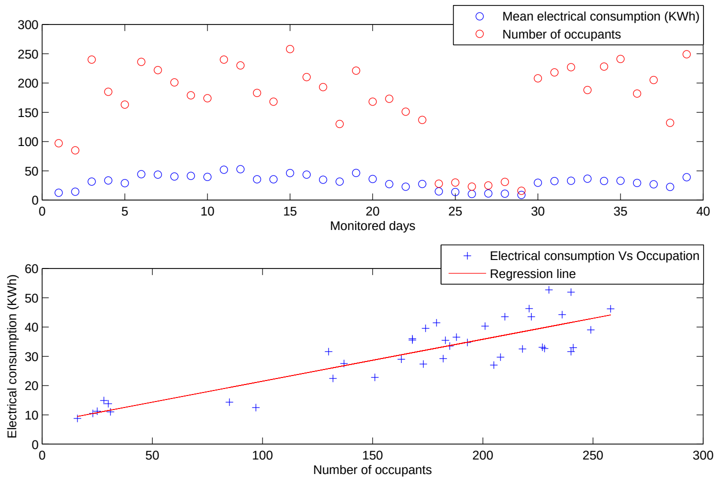
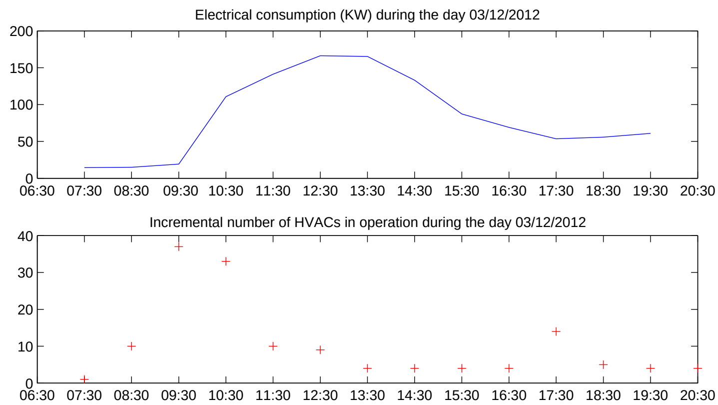


Figure 15. Evolution of the electrical power consumption and the incremental number of HVAC systems in operation.



From this analysis we can observe how it is crucial to consider both parameters, *i.e.*, outdoor temperature and occupancy levels of the building, for inclusion as input data of the building management proposed to save energy. Therefore, in defining optimum strategies for energy savings, it is necessary to provide specific behavior patterns of both parameters, above all of occupancy for its high impact and its high variability. In this sense, the occupancy levels of buildings can be deduced from localization data about occupants as and the usage of the building can be foreseen.

5.2.2. Use Case 2: Test Lab of Smart Building

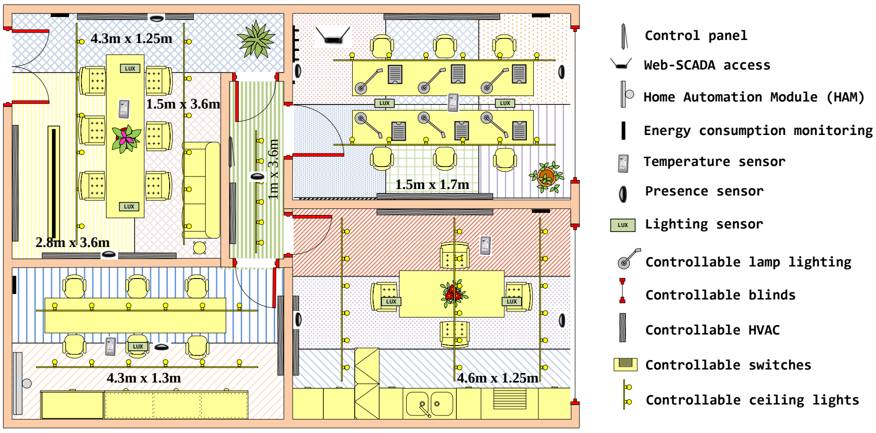
The test lab selected for this use case is located in the Technology Transfer Centre of the University of Murcia (www.um.es/otri/?opc=cttfuentealamo), where City explorer is installed and working. Figure 16 depicts one of the floors of the building where a set of laboratories can be seen on the lower part of the map.

All the rooms of the building have been automated (a HAM unit in each one) to minimize energy consumption according to the actions suggested by the management system. On the other hand, user comfort preferences are communicated to the system through user interaction with the control panel or user restricted access to the SCADA. We have taken the second laboratory starting from the left as the reference testbed to carry out our experiments.

In this test lab we have defined different room spaces in which the sensors have been installed. All input data involved in energy and comfort services are available in real-time through the SCADA access. Finally, separate automation functions for managing lighting, HVAC, switches and blinds are also provided in these spaces. Figure 17 shows an overview of this deployment.

Figure 16. Use case 2: Test lab.

Figure 17. Reference scenario with the deployed sensors and actuators.



For the analysis carried out in this case, we focus on the energy saving associated with occupant localization data as well as environmental conditions. Taking into account the HVAC appliance distribution in this testbed, different target regions can be identified, where user location data must be estimated and considered to provide occupants with customized thermal conditions according to both their preferences and needs. For such a spatial division, it is also necessary to consider features such as: (1) user activities expected to be carried out; and (2) thermal requirements. Therefore, we define different target regions where localization must be solved to provide the occupants located there with the most suitable comfort services. These target regions are shown in Figure 17. In this sense, since it is able to consider scenarios with different contextual needs and features, our system is able to adjust its operation mode to ensure a suitable response to different situations. For this reason, the characterization of such contexts was carried out after analysis of the data collected.

Because our goal was to provide this scenario with user-centric comfort services while considering energy saving, the localization system providing occupant location data must be capable of providing location estimations with a mean error smaller than the surface of the mentioned target zones. The technological solution to cover our localization needs is based on a single active RFID system and several IR transmitters. Integration of these two technologies in a final 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, and each RFID tag indicates to the reader its identifier, as well as the identifier of its associated IR transmitter. In a previous work [33] we described with more detail this localization system and evaluated its behavior. The results obtained confirmed the good performance of this solution in terms of location error regarding common target location surfaces to provide comfort services in buildings. But, here we analyze its behavior in terms of accuracy, considering the scenarios of this use case, and show the results obtained.

It is important to note how the chosen scenarios are representative for the localization problem dealt with in this work (with their comfort appliances, device distributions and target regions), and how they cover almost all location needs (in terms of target regions) presented by other indoor environments (such as hospitals, schools, *etc*.). In this way, we can extend the validation results obtained in these representative scenarios to other similar indoor environments. Among the target regions shown in Figure 17, we highlight the case defined by the service area of individual lamps in a typical office, which can be considered as one of the most restrictive location problems (with a mean accuracy of 1.5 m.) for providing users with customized comfort services in buildings.

Below we demonstrate the benefits of considering accurate user positioning information (including user identification) and user comfort preference during the management process of HVAC appliances, showing how energy wastage derived from overestimated or inappropriate thermal settings is avoided. Taking into consideration these scenarios, environmental conditions, occupant locations data and comfort preferences, smart rules are designed to take intelligent decisions about the operation and configuration of the automated appliances with the aim of saving energy while they are kept at an acceptable comfort level.

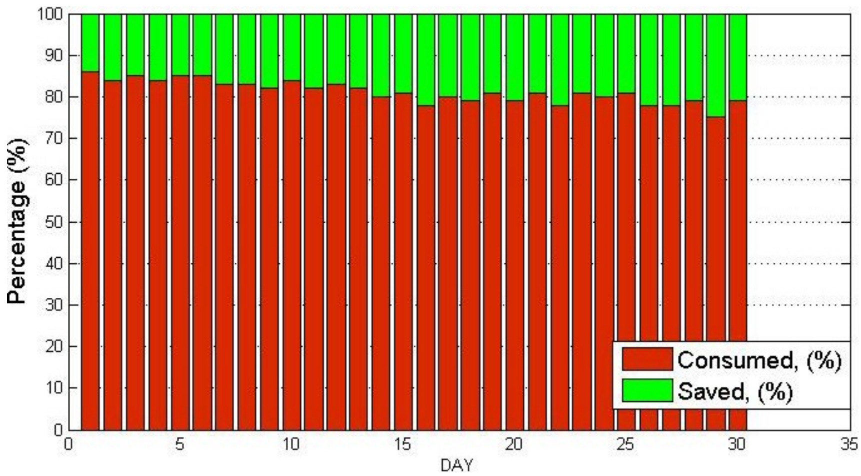
Fifteen monitored people (all postgraduate students from the Information and Communications Engineering department of the University of Murcia) were asked to carry out their normal every day tasks of working and interaction among themselves during both months. During the data collection process, the subjects were asked to walk along a set of paths involving different directions and transitions among the environments considered (living room, bedroom, corridor, office and dining room), and to work or relax in the areas designed specifically for such purposes (see Figure 17). These experiments were repeated over two consecutive months (3 hours per day) in different conditions of user paths and activities, environmental conditions, *etc*.

For the evaluation of energy savings, a comparison was performed between consecutive months in 2013: February, without energy management, and March, with intelligent management. It is clear that environmental conditions cannot be repeated exactly, but even so, during both months the daily routines were very similar, and the weather conditions did not suffer any abrupt change. However, worth mentioning is the fact that the month of experimentation with the management platform in operation was cooler than the previous month, and hence the energy needed for heating would presumably have been higher. We compared the energy consumption value for each day of March with that for the same day of the previous month. The maximum registered outdoor temperature difference during the selected time period was 9 °C, which can not be considered as extreme, while the mean difference was only 3 °C, so no great environmental difference occurred.

The daily energy saving values achieved during the month of operation of our energy management system compared with the previous month is shown in Figure 18. As we can see in this figure, energy savings varied between 14% and 30%. Therefore, the experimental results obtained to date reflect energy savings in heating of about 20%, compared with the energy consumed in a previous month without any energy management. More information about the experiments and analysis for energy efficiency carried out in this reference building can be found in the previous work with reference [30].

Finally, having achieved energy savings after applying specific actions in a totally automated scenario in which controlled experiments were carried out, we wished to validate our proposal of energy management in a third building representing an office scenario (a Spanish bank), with only partial automation capabilities available. In this way, we provide a complete picture of the applicability of our proposal to energy building management.

Figure 18. Percentage of energy saved in heating, considering user location data.



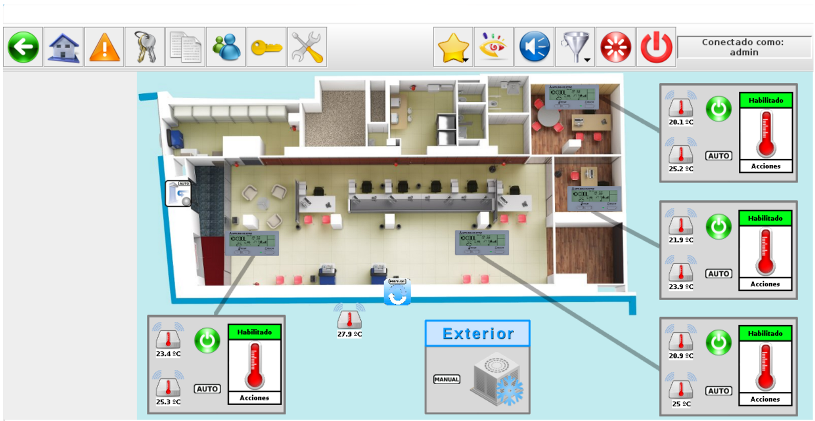
5.2.3. Use Case 3: Smart Company Office

The reference building selected to evaluate our energy management proposal in the context of a company was an office of a Spanish bank, where energy saving and tele-monitoring goals have to be achieved. The main management actions focused on controlling HVAC and lighting appliances, since both services were identified with the highest impact in the total energy consumption of the building. Figure 19 depicts the automated floor of the reference building. This screenshot was obtained from the SCADA-web integrated in City explorer, which offers the possibility of consulting any monitored data from the different sensors deployed in the building.

Taking into account the lights and HVAC appliances distribution in this scenario, we can distinguish different target regions where user location problem must be solved to provide occupants with customized comfort conditions according to both their needs and preferences. For such zonal division, it is necessary to identify the office spaces where people stay and, depending on the expected activities carried out there (customer waiting to be attended, office tasks, *etc.*), estimate the associated lighting and thermal requirements. Therefore, lighting and HVAC appliances installed in the office must be managed according to the information provided by the user allocated to each target zone and the environmental parameters collected in the room (lighting, temperature, ventilation and humidity for this use case). All the information sensed is gathered in real-time, and is available through City explorer system. Finally, our intelligent system controls the settings of the appliances which provide service in each specific zone where occupants are located.

As for the previous use case, the environmental conditions and user behavior during the two time periods selected (the months of April and May of 2013) were not exactly the same, so there is a degree of uncertainty concerning the results. But during both periods considered, the occupants' daily routines were very similar and the weather conditions did not suffer any abrupt change, with external temperature values between 22 °C and 28.5 °C. Bearing in mind all these aspects and despite the relatively short time of evaluation, we achieved mean energy saving of 23.12% associated to the cooling and lighting services.

Figure 19. Use case 3: Company office.



It is important to highlight that our energy efficiency system needs a long evaluation period to extract relevant figures of merit regarding energy saving, and each simplification or adjustment in the system (different input data, rules, locations, comfort conditions, *etc.*) requires extensive testing and validation with respect to the environment chosen to carry out the evaluation. In addition, system validation must cover different seasons for its performance, to be analyzed in different weather conditions during a whole year. More information about the experiments and analysis for energy efficiency carried out in this reference building can be found in the previous work with reference [38].

6. Conclusions

In this work we have broken down into separate areas how energy is usually consumed in buildings. To do this, we analyze the main parameters affecting energy consumption of buildings considering different contexts. Such an analysis permits us to propose an optimum prediction concerning the daily energy consumed in buildings by integrating the most relevant input data in such models. Once energy usage profiles have been extracted, we can design and implement actions to save energy, for instance, proposing strategies to adjust the operation time and configuration of the involved appliances or devices, selecting the optimal distribution of energy to maximize the use of alternative energies, *etc*.

After the analysis described in first sections of the paper, we have described our proposal for energy efficient building management. Firstly, we presented our building automation platform for collecting and monitoring all data involved in the problem of energy consumption in buildings, as well as the control of the actuators integrated in the system. Then, we studied three different use cases in which this platform was deployed. These buildings were automated to gather data from their context (sensors, user interaction, data bases, *etc*.).

First experiments were carried out in a large building with a variety of occupant behavior. The aim of this experiment was to verify the direct relationship between environmental conditions and occupant behaviors, 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 is 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 energy building 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.

At present we are carrying out more experiments to analyze each one of the different pieces that make up our building management system based on the kind of analysis described here: influence of the rest of the parameters identified as relevant in energy consumption of buildings (see Section 3.1); the effect of including data predictions and behavior patterns in the management of the building; the capability of the system for auto-assessment and auto-adjustment to changes in the context; and finally, the semantic perspective of technologies to translate data into a common language format considering related ontology already proposed in this field, as well as the automatic generation of intelligent rules obtained from the ontology reasoning. On the other hand, note that more experimental tests and evaluations are needed to provide a system able to respond to different conditions that cover different seasons, different users and different indoor contexts, for example in contexts like industries and shopping centers. Moreover, we are experimenting with mobile crowd-based sensing techniques for gathering data from occupants' devices, since this information will be able to complement the data obtained by the infrastructure-based system.

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Author Contributions

Ma. Victoria Moreno is the author with the main contribution to the paper. Benito Úbeda has been in charge of the mathematical analysis about the energy consumption in the buildings used as reference. Finally, Antonio F. Skarmeta and Miguel A. Zamora have been the responsible for reviewing the work and the paper's preparation.

Conflicts of Interest

The authors declare no conflicts of interest.

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An indoor localization system based on artificial neural networks and particle filters applied to intelligent buildings

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ABSTRACT

Smart Buildings aim 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.

1. Introduction

Over the last few years, researches on Smart Buildings have evolved in real solutions that improve the indoor life of people thanks to innovations on sensors/actuator integration and control processes, among others, but more recently, thanks to Information and Communication Technologies (ICT). Another great contributor for all these changes has been the Internet of Things (IoT) approach [1], which considers pervasive infrastructures of fixed and mobile heterogeneous nodes designed to obtain a greater integration and accessibility.

According to experts in this field, an intelligent building is one that provides people with a productive and cost-effective environment, through optimizations based on three basic elements: people (considering owners, occupants, visitors, etc); products (standing for materials, fabrication, structure, facilities, equipments and services); and processes (composed of automation, control systems, maintenance and performance evaluation) [2].

In addition, it is important to consider that buildings are one of the most critic energy consumption areas, both residential and commercial [3]. Thus, achieving energy efficiency is the cornerstone of many administrations around the world nowadays. It implies improving the interaction between building systems and users, reducing energy consumption, and therefore, CO_2 emissions.

Automation Systems are essential for these issues, as it is remarked in [4]. These systems take input data from sensors deployed in corridors and rooms (presence, light, temperature, etc) and use this information to control certain subsystems, such as heating, ventilation and air conditioning (HVAC) or security [5]. For that, an intelligent management system must provide the proper adaptability to both the environment and users, to cope with the most important comfort and energy efficiency requirements in buildings [6].

As can be noted, location plays an important role in this kind of context-aware applications, since for a vast number services provided in a smart building, it is a necessary information about the presence and location of users, and their identities could be also needed to deploy customized services. However, depending on service requirements in terms of accuracy in the location data about users, a different localization scheme could be applicable, varying the number of sensors needed and the algorithms used.

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In recent years, there has been a great technological progress on indoor localization systems, but most of the proposals do not still fully solve some problems, such as the time required in the calibration process, poor robustness or high installation and equipment costs [7].

Bearing all these aspects in mind, the work presented in this paper proposes a low-cost and nonintrusive solution for the localization data needs of the most important subsystems of a smart building, i.e. lighting and HVAC, with the goal of achieving to provide occupants with personalized and smart services in sustainable buildings. The proposed location mechanism integrates RFID (Radio-Frequency Identification) and IR (Infra-Red) data for computing user position. A Radial Basis Function Network has been developed to carry out the estimation of user locations, for that, the RSSI values are used for estimating inter-tag distance. And on the other hand, a tracking method based on a Particle Filter algorithm has been developed to infer the next positions of users. Along this paper, it can be tested how this localization system meets the accuracy, cost and complexity requirements of our indoor services, while the number of devices used by the location mechanism is optimized.

The content of this work is structured as follows: in Section 2 background information about intelligent buildings, energy efficiency and indoor positioning is reviewed. Section 3 presents the proposed indoor localization system based on artificial neural networks and particle filters. The experience deploying the system and the tests performed, as well as the analysis and discussion are shown in Section 4. And, finally, the conclusions are given in Section 5.

2. Background

As has been said, we focus the indoor localization problem on the context of intelligent buildings. Thus, given that the final purpose of our work is coming up with an intelligent and energy efficient building, our localization mechanism must meet certain requirements in terms of position data accuracy, cost, flexibility and scalability.

In the first point of this section we speak about the problem context and its location data requirements. And in the last part of this section, we review the most relevant localization technologies treated in the literature, which serve us to present our location solution.

2.1. Building management systems for energy efficiency

It is clear that to cope with most important comfort and energy efficiency requirements in buildings, an intelligent management system must be able to provide monitoring and automation capabilities [6]. In addition, in these environments, a suitable comfort level is desired for guaranteeing thermal, air quality and luminance needs of occupants. Thus, energy savings should be addressed by establishing a trade-off between comfort measures and the energy resources that are required. The aims of these systems are, first, offering a real solution to monitor energy consumption of the most important subsystems of buildings (i.e. lighting, HVAC and most energy consuming appliances); second, assess energy efficiency by computing significant parameters based on the collected monitoring data; and, third, achieving a comfort level committed to energy efficiency requirements. This last part is essential, and it is carried out by taking intelligent decisions.

During these phases it is necessary to continuously re-engineer in real time the index that measures energy efficiency to adapt the model to the building conditions. However, the optimization of these parameters comprises a complex task, full of variables and constraints. For instance, a multi-criteria decision model to evaluate the whole lifecycle of a building is presented in [8]. This problem is tackled from a multi-objective optimization viewpoint in [9], and it concludes that finding an optimal solution is unreal, an approximation of it being only feasible.

Although there are many works related to Building Management Systems (BMSs), a lot of them have failed to fully optimize energy consumption in real time, and when the BMS is not working adequately, a great amount of energy could be wasted due to excessive heating or cooling, for instance. In [10], an examination of the main issues in adaptive BMSs is carried out, however, as it is stated, there are still few works dealing with this problem completely.

The impact of the HVAC consumption in the total energy used in buildings is extremely important, comprising 50% of the building energy consumption, and in many developed countries it represents 20% of the total energy consumption [11]. The European Commission issued a recast of the Directive about Energy Performance of Buildings (2010/31/EU) [12], which pushes for the adoption of measures to improve the performance of the energy used in building appliances, lighting and, above all, HVAC systems. The CEN's standard EN 15251 [13] specifies the design criteria to be used for dimensioning the energy system in buildings and how to establish and define the main input parameters for building energy estimation and long term evaluation of the indoor environment (thermal and visual comfort, and indoor air quality). Among others, several parameters involved are location data about occupants, user activity level, total number of occupants per room, temperature, humidity and natural light. Therefore, all these variables need to be measurable and available from the automation system deployed in the building.

With this discussion it is reflected that, for making reality smart and energy efficient buildings, an important issue to solve previously is the localization problem presented inside buildings, since having in real-time information related to user location, human activity level and number of occupants results indispensable.

Besides, we must take into account the user identity data so that the intelligent system can learn and manage devices according to the behavior of users. Although solving the user identification issue in smart buildings is a key objective, privacy should be considered. Thus, some sensors cannot be installed in buildings. For instance, in Spain, video cameras could not be used in offices. These problems cause some localization systems to be unsuitable in buildings where nonintrusive, ubiquitous and cheap systems are needed. On the other hand, maintaining an updated image of the operation environment is essential for indoor localization systems.

For all these reasons, and given the context of our problem, the localization system presented here must be able to locate a user among the various areas of a building to provide optimum comfort and energy efficiency services, and thus, each user position can be calculated within the different target areas considered.

2.2. Indoor localization problem

There is a common classification of indoor localization solutions in the literature: those based on RF and those using other technologies. Among RF-based techniques we could cite those based on GPS, wireless local area network (WLAN), and RFID localization, whereas non-RF-based techniques include audio, visual, ultrasonic, infrared and laser sensors. By nature, RF signals have certain advantages over non-RF signals, as it is explained in [14], since, despite on the fact that non-RF-based localization techniques are relatively mature, they are vulnerable to environment disruptions.

In [15], for instance, a localization mechanism based on cameras is proposed. Wearable devices are not needed using this technology, but a high cost and a delicate calibration process are its main drawbacks. In general, depending on the accuracy needs of the final localization application, a specific technological solution should be chosen to solve the problem.

Regarding RF-based solutions, in [16], for instance, a localization mechanism based on 802.11 and RADAR technologies is presented. Its main advantage is the easy deployment, but a delicate calibration process is needed. In [17] an RFID localization mechanism is proposed, enabling 3D localization, but presenting important errors due to the RFID signal variations during its indoor transmission. In [18] a fusion of infrared and active badge data is used to calculate the position. Although this is a low-cost solution, an imprecise location estimation is obtained using this type of localization technology.

Since each localization technology has its pros and cons in terms of accuracy, cost and complexity, the fusion of several of these technologies should improve the overall system performance. Apart from considering this approach in our solution, the localization system proposed must deal with the identification and privacy issues, avoiding the common intrusion problem of cameras.

Among the various technologies previously mentioned, RFID and infrared (IR) have been chosen for solving our indoor localization problem due to the reasons presented in the following. RFID provides identification capabilities inherently and extra security features could be added to deal with the privacy issue. Furthermore, the relatively low cost of RFID tags makes this solution a popular candidate to deal with localization and tracking needs, despite the drawbacks of imprecise location estimate due to RFID signal variations, as it is indicated in [19]. Additionally, a lot of public and private buildings already provide access control through personal identification based on RFID, which implies a cost reduction in the system deployment. The same applies to the IR technology, used in automatic control in alarm systems. Using any of these two technologies to solve the indoor localization problem means a cost saving, since no additional devices are needed in those buildings where these devices are already presented. Additionally, using IR sensors we can provide stability to the localization solution since it is a non-RF based technology, and thus it is not influenced by the losses caused by reflection, diffraction and absorption in walls, floors, etc.

Location technologies based on RFID can be classified into three categories [20]: tag-based, reader-based and hybrid. In a previous work [21], we presented a theoretical study about the indoor transmission of RFID signals given a real distribution of reference tags. Taking this work into account, we now propose to carry out the fusion of RF and non-RF-based data in order to solve the large variability problem of the RFID signals in indoor environments. Furthermore, using these theoretical analysis, it is possible to optimize the number of devices needed to solve our location problem.

In contrast to many RFID location-based works, where it is common to use information from several RFID readers to improve robustness (through integrating beaconing information from multiple sources [22]), our localization system can work with a single RFID reader to reduce cost. Then, location robustness is offered by a mechanism that combines RFID and IR data in an effective way. Here, it is important to note that IR devices are cheaper than RFID readers. In [19], for example, a solution that also combines RFID and seamless sensors solves the localization problem by means of an agent-based virtual architecture that considers human-centric needs. It calculates the probabilities of possible user paths choosing a locator region to represent the user position. In contrast to this paper, our work is based on estimation and tracking techniques that let us achieve an efficient solution, while cost considerations are also taken into account through the optimization of the number of sensors used.

3. An indoor localization system based on artificial neural networks and particle filters

This section explains the studies and analysis performed to provide an efficient solution for the indoor localization problem, as well as the algorithms used to process the gathered data from the RFID and IR systems to compute the user positions.

3.1. Theoretical distribution of the RFID signals in indoor environments

The large variability problem of the RFID signals in indoor environments is well-known [22], which implies that solving the indoor localization problem using RFID data may derivate in inaccurate estimations of the user positions. Despite this, as mentioned above, RFID systems are relatively cheap and they are already deployed in many modern buildings (mainly to provide access control). This makes them a good solution to deal with indoor localization and tracking needs in a direct way.

Before taking our final technological decision, a previous theoretical and simulated study about RFID signals transmission is performed, in which a real distribution of RFID reference tags is considered. We aim to analyze the RFID power distribution in indoor environment, i.e. the RFID power losses through reflection, diffraction and absorption, and then, provide the most suitable technological solution for our localization problem.

This theoretical study is carried out using a radio planning software tool, which is able to consider different propagation models to simulate the RF signals transmission. In this study, we have considered an indoor RFID signal transmission based on the application of Geometrical Optics (GO) and Uniform Theory of Diffraction (UTD) using ray tracing techniques. With this method it can be predicted that the electric field is created by the direct, reflected and diffracted contributions of RFID signals. Then, parameters required to carry out these simulations are the reflection, diffraction and absorption coefficients of walls, ceiling and floor. Different values for these coefficients have been used. More details about this theoretical study can be found in [21].

Analyzing the results of these theoretical studies, the RSSI variability problem in the simulated indoor environment is clearly reflected. Thus, we propose to perform the fusion of RF-based data and non-RF-based data to try to solve this problem. For that, we locate the non-RF-based devices in such a way that the reference regions are splitted into subareas where the RFID distribution is uniform, choosing the best locations for non-RF-based devices according to these distributions. Therefore, the RFID reference tags are installed in the ceiling of each subarea, and then, the RFID information of each one is used to further localize the user located inside of it, being possible to implement a regression or classification technique to estimate the location data of occupants taking into account these regions.

In the following subsections, the different data processing techniques of the localization mechanism proposed are explained in detail.

3.2. Scenario of the localization system

As already mentioned above, the technological solution to cover our localization needs is based on a single active RFID system and some IR transmitters. The RFID technology provides cost and identification advantages, while the IR technology provides stability to the localization mechanism.

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, as well as the identifier of its associated IR transmitter.

Fig. 1 illustrates the data exchange of our localization system, where the RFID reference tags are placed in the ceiling of the room, the IR transmitters are placed on the walls, and the target user wears the RFID monitored tag.

In detail, the process is as follows: the RFID reader receives a data vector from the IR-enabled RFID tags periodically (after several seconds), this vector contains $[ID_{ir}, ID_{tag}]$, where ID_{ir} is the identifier of the IR transmitter that is read by the RFID tag with identifier ID_{tag}. Additionally, the reader is able to provide us with the Receive Signal Strength Indication (RSSI) related to this tag. These data are continually updated, hence, the dynamics of the environment can be modeled continuously. Then, the input data of our localization mechanism are vectors in the form: $[ID_{ir}, ID_{tag}, RSSI_{tag}]$, which are obtained from the RFID reader.

Fig. 2 shows a schema of the data processing implemented to solve the indoor localization problem, which can be split into three stages that are explained in the following subsections.

3.3. *Space division into uniform RFID distributions*

Our goal is to get an easily trainable localization model to compute the relationship between the RSSI values and the objects positions. Since the RSSI data are not robust (due to the multi-path phenomenon), we first bound the area in which the user stands by dividing the space in IR zones. This is performed according to the ID_{ir} values received. Each of these ID_{ir} values is associated with some ID_{tag} and $RSSI_{tag}$ values coming from several deployed active RFID reference tags installed in the ceiling of each subarea. Then, the information inside the subarea to which the monitored tag belongs to is used to further localize the object.

3.4. *Location estimation through radial basis functions*

The following step consists of exploiting the RSSI database of the reference tags selected in the previous mechanism stage to approximate the function that maps the reference information from the signal space to coordinates in the plane by interpolating the collected data.

A widely used practice is applying the *Nearest Neighbors Technique* to choose the reference tags used to estimate the target position, but this technique provides a poor estimation due to the great variability of the RFID signals. An alternative solution for that purpose is using *Artificial Neural Networks* (*ANN*) [23,24], where localization can be viewed as an approximation function problem. Thus, for instance, in [25] a modular classification model based on modular multilayer perceptron (MLP) networks is presented to develop large scale and highly accurate signal strength based location systems.

For the localization mechanism presented in this work we propose to use the *Radial Basis Functions* (*RBF*) technique, which is a special class of ANN. The main advantages of RBF for our problem are its scalability and easy deployment for different RFID system setups, where a variable number of RFID readers or reference tags (fingerprints) may be available. Then, in our case, for each previous space division performed according to the ID_{ir} values received in the reader, a radial basis functions (RBF) network can be implemented as a regression technique to estimate the position of the monitored tags. This mechanism can be summarized mathematically as follows.

The input space P of our RBFs is the vector of RSSI values received in the RFID reader. These data can be denoted as

$$P \in R, P = \{p_i\}, \quad \forall p_i = [p_1, p_2, \ldots, p_n] \tag{1}$$

where n is the number of reference tags within the chosen subarea. The target class Z represents the position of the reference tags. This is denoted as

$$Z \in R^k, Z = \{z_i^k\}, \quad \forall z_i^k = [z_1^k, z_2^k, \ldots, z_n^k] \tag{2}$$

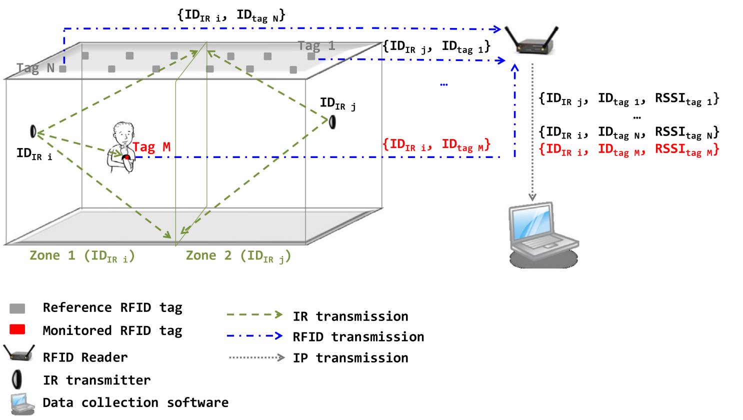

Fig. 1. Scenario of the localization solution using RFID and IR devices.

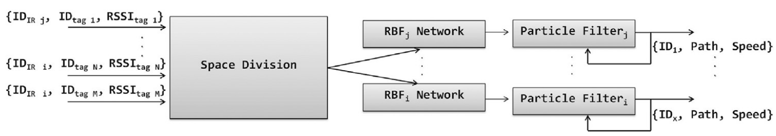

Fig. 2. Schema of the data processing for position calculation.

where k is the dimension of the position. In our case, we assume a value of k=2, then given the training values $\{(p_i, z_i^k),\ldots,(p_n, z_n^k)\}$, our goal is to find a function that let us classify the monitored tag position ($z_i=[x_i, y_i]$) knowing its RSSI tag value (p_i).

The RSSI tag value p_j is provided as input to all functions of our RBF classifier, and the output $f(p_j)$ is given by

$$f(p_j)=\sum_{i=1}^{c} w_i \cdot \varphi(\|p_j-c_i\|) \tag{3}$$

where $\|p_j-c_i\|$ is the Euclidean distance between p_j and the RBF function with center c_i. The number of RBFs is C, and w_i are the weights of the network. Gaussian radial basis functions are usually used to represent the RBFs. However, other types of functions are common, such as thin-plate splines, multi-quadratic, linear polynomial bi-harmonic splines, etc. [26]. The poly-harmonic splines are softer, and we use these functions for our RBFs. The equation that represents to this type of functions is

$$\varphi(\|p-c_i\|)=\|p-c_i\|^{\beta}\log(\|p-c_i\|) \tag{4}$$

The value of β specifies the width of the basis functions and allows their sensitivity to be adjusted. As β decreases the basis functions become wider and there may be more overlap among them. An appropriate value of β is usually selected experimentally based on the reference data, and can be further adjusted when testing data are available. A common practice is to use a heuristic method to set the width β according to Eq. (5), where $d_{max}=\|p_j-c_i\|$ for $i=1,\ldots,L$.

$$\beta=\frac{1}{2\cdot d_{max}} \tag{5}$$

From this equation, it is detected that when the distance among centers in the n-dimensional signal space increases, the value of β is reduced to ensure that the basis functions still overlap enough to produce accurate location estimates. With this scheme, the value of β can be easily adjusted to provide a high level of accuracy when a variable number of reference tags are used.

The proper values for C and the centers c_i are not trivial. These values affect the performance of the RBF network. A common practice is using each reference RSSI value to define the centers, so if there are L reference tags, there will be L basis functions. However, this architecture has high memory requirements when there are a lot of reference fingerprints and more than one RFID reader. In these cases the computational complexity is high, both for the calculation of w_i and location estimation. In our problem, the number of reference tags per each space division performed is low and a single RFID reader is used, therefore there are no problems related to computational complexity, and it is possible to use the reference RSSI data as the center of our basis functions. For this reason, our RBF system has a unique solution and its design guarantees the exact fitting for all reference data.

The reference RSSI values and their corresponding coordinates (x_i, y_i) are employed to train the network and adjust the weights accordingly. Thus, given a RSS target p_j measured at location $z_j=(x_j, y_j)$, the output of the RBF network may be expressed as a weighted sum of normalized basis functions:

$$z(p_j)=\sum_{i=1}^{c} w_i \cdot \frac{\varphi(\|p_j-c_i\|)}{\sum_{k=1}^{c}\varphi(\|p_j-c_k\|)} \tag{6}$$

where w_i are 2-dimensional weights. The parameter w_i may be determined to obtain a good approximation by optimizing the fit represented by the difference between the RSSI values of the reference data and the RSS targets (Eq. (6)). Thus, we form the following set of equations:

$$z(p_k)=\sum_{i=1}^{c} w_i \cdot u(\|p_k-c_i\|),\quad k=1,\ldots,L \tag{7}$$

We calculate w_i by solving the system of linear equations based on Eq. (7) using the reference RSSI values of the database and their corresponding coordinates. Therefore, our resulting RBF avoids over-fitting.

Subsequently, the weights w_i are used during localization process to obtain a location estimate $\hat{z}$ given a new RSSI value p'_j according to

$$\hat{z}(p'_j)=\sum_{i=1}^{c} w_i \cdot u(\|p'_j-c_i\|) \tag{8}$$

During this process, every T seconds it is evaluated whether there are new sensor data to estimate the target position using the RBF network. If there is updated information, the RBF network performs the estimate of the target position, but if it is not the case (loss of signal, different sampling times of the RFID system), the particle filter is applied to estimate the next position based on the prior state of the target.

Finally, for each RBF network implemented, a tracking algorithm is applied after to estimate the next position of the target user. This is the third and the last step of the localization mechanism proposed in this work. Its features are explained below.

3.5. Tracking process through particle filters

As tracking technique we implement a *Particle Filter (PF)*, which is a powerful tool to construct a probability distribution over the target area representing the environment [27]. This approach uses recursive *Bayesian Filters* based on *Sequential Monte-Carlo Sampling* to compute a posterior distribution of the target's location using another distribution that can be arbitrary a priori.

This algorithm is less computationally intensive than other probabilistic methods. In addition, contrarily to *Kalman filters* [27], PF avoids any assumptions about intrinsic features of the process and the uncertainty about the sensor data is dealt.

PF starts with the particle set initialized uniformly. Then, all particle positions are updated according to a motion model. In our case we consider a movement in the space (x,y) that follows a *random walk* model [28] to represent the human motion. Eq. (9) shows the random user paths, where Φ is the random parameter that represents the probability of following a determined direction in the next step of the tracking process (given the time interval τ). This movement model also takes into account the error model in the obtained measures from the deployed RFID tags

$$X(t+\tau)=X(t)+\Phi(\tau) \tag{9}$$

During the correction stage of the filter, particle weights are modified according to their distances to the real measurement as

$$w(\vec{x}_t)=w(\vec{x}_{t-1})\cdot\frac{p(\vec{y}_t|\vec{x}_t)\cdot p(\vec{x}_t|\vec{x}_{t-1})}{q(\vec{x}_t|\vec{x}_{t-1},\vec{y}_t)} \tag{10}$$

where $w(\vec{x}_t)$ represents the weights of the set of particles at instant t, $p(\vec{y}_t|\vec{x}_t)$ and $p(\vec{x}_t|\vec{x}_{t-1})$ denote, respectively, the probabilistic behavior of the output model and the state model of the system, and $q(\vec{x}_t|\vec{x}_{t-1},\vec{y}_t)$ is the approximation of the belief function.

It is important to note that the areas in which we want to solve the localization problem are defined by dividing the space into IR zones (according to the theoretical RSSI distribution map), and several active RFID tags are deployed in each subarea. Therefore, the information inside each subarea is used to further estimate the user localization and carry out his/her tracking process. Thus, an RBF network and a Particle Filter are defined for each subarea, and then, the amount of data to process for each region only depends on the number of reference tags deployed there. Thus, the resulting RBFs and PFs are small enough, easy to train and offer good performance, satisfying the requirement of providing user location data in real-time. At the same time, statistical values of

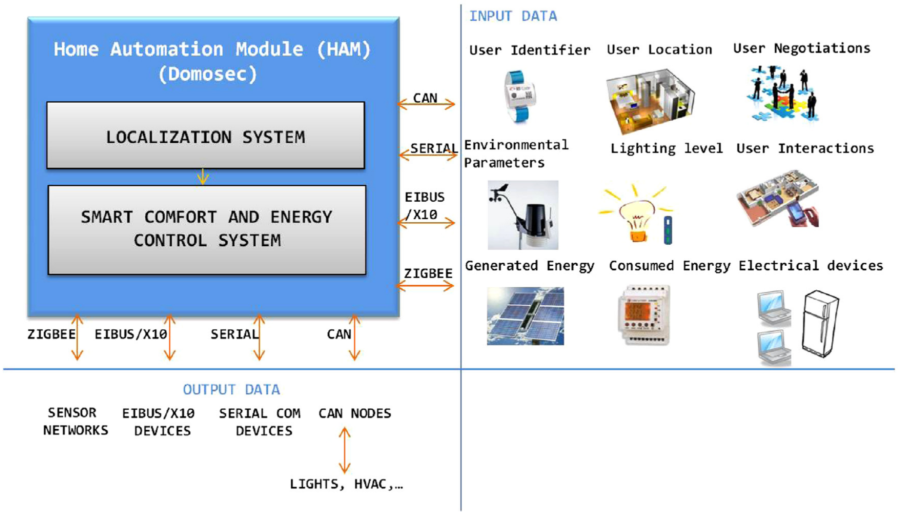

Fig. 3. Distributed data collection architecture.

velocity can be calculated continuously using the particle filters results, being available later to determine the user activity level and adapt comfort services according to the his/her needs.

In summary, combining these two algorithms, a radial basis function network as an estimation technique and a particle filter as a tracking method, a good estimate of the motion of the monitored RFID tag is obtained, while a minimum number of sensors are required.

4. Experience deploying and testing the system

4.1. Deployment of the system

The reference building where our localization system has been evaluated is the Technology Transfer Center at University of Murcia,[1] which was designed as a smart environment since its early stages of design.

The hardware Architecture (Domosec) developed and deployed in this building (Fig. 3) was toughly presented in [29]. The main components of this architecture are the network of Home Automation Modules (HAM) and the building gateway. All the environmental and location data measured by the deployed sensors are available in each of these modules. In Fig. 3 we show all the inputs involved in our overall system, as well as the different types of connections with sensors and actuators.

In this reference building, smart services are provided, such as the control and regulation of the lighting and HVAC appliances. In our work, different house spaces have been simulated in a test lab of this building, such as a living room, a corridor, a bedroom, an office and a dining room. Each space has been provided with a different distribution of HVAC and lighting appliances, according to the features of the space (such as natural light, indoor space activities and occupants' differences) and the expected comfort requirements.

Fig. 4 depicts the test lab of the Technology Transfer Center at University of Murcia where we have allocated different rooms/areas that represent a home environment and have carried out the essays described in the following subsection.

Fig. 5 shows a possible distribution of the different target location surfaces, taking into account the distribution of lighting and HVAC appliances, as well as the user lighting and climate needs depending on the activities expected to be performed in each region (which are determined in accordance to the different work areas). Therefore, to satisfy the location requirements imposed by potential context-aware services, our localization system must be able to locate a user within these different space surfaces.

In this lab an RFID system is already available for access control, and various IR transmitters are already installed for the alarm system. Therefore, it does not require any additional equipment.

The RFID system used in our tests is based on IR-enabled RFID tags which initiates communication with the RFID reader, sending their data every 10 s using the frequency band of 433 MHz. The transmission power of RFID tags is 28 μW, and the RFID reader has two radios, a channel with a maximum sensitivity of −58 dBm and another channel with −108 dBm, so that it is possible to configure various ranges of detection.

The RFID reference tags are placed in the ceiling of the test lab, and one IR transmitter is placed on the wall for every floor surface of 9 m^2 to optimize the total number of IR transmitters needed (according to the theoretical study of the RFID power distribution in this indoor environment [21]).

The distribution of reference tags is crucial to reach the accuracy requirements in the desired zones. For this reason, in the following subsections we analyze how it affects the accuracy of the location data obtained when different RFID reference tag distributions are given.

4.2. Experimental tests

Firstly, it is important to bear in mind that the minimum accuracy achieved in the location data must be lower than the IR transmitter coverage. Consider that a single IR transmitter can be used to estimate the user location within a target area of 9 m^2.

In the previous work presented in [21], a distribution of tags in a grid of 1 m × 1 m was considered. Using this distribution, a 77% success in estimated positions with an error lower than 1.5 m is

[1] http://www.um.es/otri/?opc=cttfuentealamo

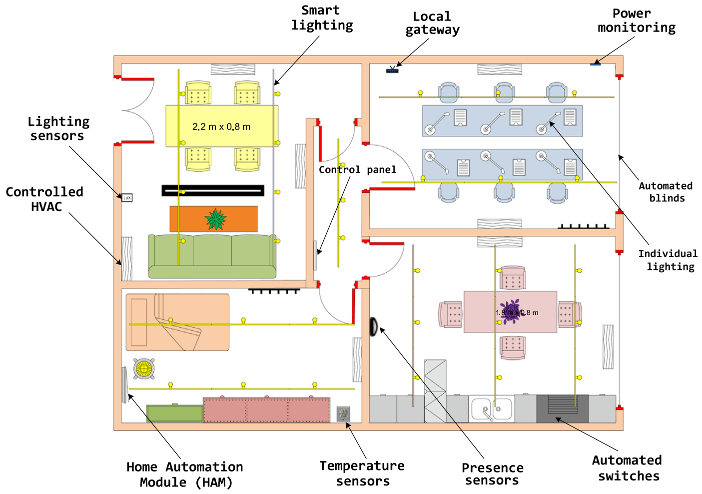

Fig. 4. Distribution of space to simulate a home environment.

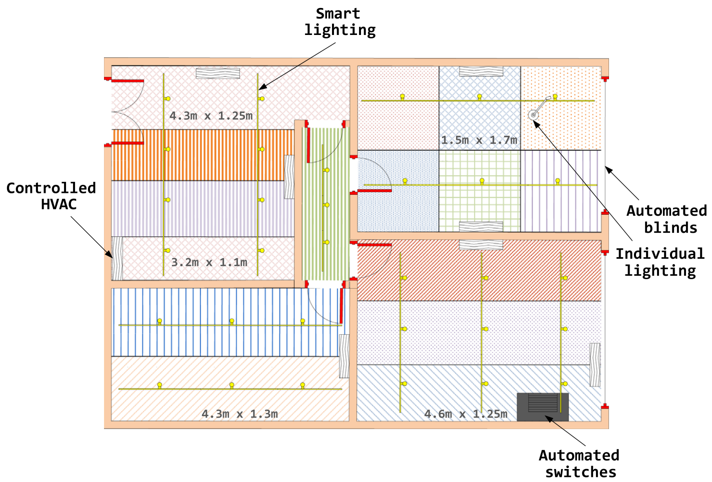

Fig. 5. Target location surfaces according to the offered services.

Table 1
Statistical values of localization error for different distributions of the reference tags: me (mean error), mxe (max error) and mne (min error).

Location surface	me (m)	mxe (m)	mne (m)
1 m × 1 m	1	2.6	0.3
1 m × 1.5 m	1.8	2.7	0.3
1 m × 2 m	1.2	2.9	0.3
1.5 m × 1.5 m	1.3	2.7	0.4
2 m × 2 m	1.6	3.1	0.6
2 m × 2.5 m	1.9	3.3	0.6

Table 2
Success rate in the localization mechanism given a mle (maximum location error).

Location surface	mle < 1 m (%)	mle < 1.5 m (%)	mle < 2 m (%)	mle < 2.5 m (%)
1 m × 1 m	65	77	96	98
1 m × 1.5 m	51	73	88	92
1 m × 2 m	45	72	81	85
1.5 m × 1.5 m	42	69	75	82
2 m × 2 m	38	64	66	78
2 m × 2.5 m	37	64	65	76

reached. However, in practice it is not feasible to equip a whole building with tags placed at 1 m of distance from each other, due to cost implications and the amount of data to process. Moreover, it is clear that an accuracy of 1.5 m is not always needed to provide us with individual lighting and HVAC services, for instance.

The results obtained from the tests performed in our test lab are collected as statistical values of the error achieved in the estimated positions, considering different RFID reference tag distributions. The tests performed represent different users behavior and different conditions of context, such as a very crowded or few people spaces,

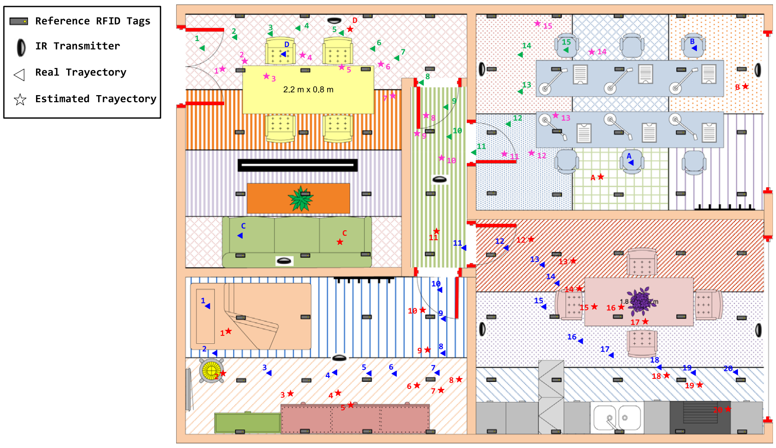

Fig. 6. Tracking process using a reference tag distribution of 1 m × 1 m.

different numbers of obstacles, changes in the human activity, etc. Table 1 shows the results corresponding to several days' monitored. As can be seen, they are quite accurate according to the location requirements of lighting and HVAC services, giving an acceptable error even though a low number of reference tags are used.

In Table 2 we collect the successful cases related to the same previous distribution of reference tags, and given a maximum error in location estimation. These results allow us to analyze the general behavior of the proposed localization system.

As can be seen, with a distribution of tags of 1 m × 1 m it is possible to obtain a 65% success rate in localization with an error less than 1 m, while a 98% of the cases have a maximum error distance less than 2.5 m.

These results ensure a good performance of our solution in terms of location error, given common target location surfaces to provide comfort services in buildings, such as those shown in Fig. 5. In the environment shown by this figure, the worst case corresponds to solve localization within an area of 1.5 m × 1.7 m to provide individual lighting in an office space. This means to have location data with a mean error lower than 1.5 m. Therefore, with three of the five reference tag distributions analyzed in this work (1 m × 1 m, 1 m × 2 m and 1.5 m × 1.5 m), we can solve one of the most restrictive location problems in a home environment.

Regarding cost terms, contrasting with previous works that also use RFID systems for indoor localization, such as those collected in [22] (Landmarc, SA-Landmarc and SA-SVR), our work clearly reduces the final cost of the technological solution chosen, while the mean error in the location estimation is acceptable given our requirements in terms of accuracy in location data. Our investment in equipment is reduced due to a single RFID reader is used, and this is the most expensive device involved in these localization systems. Besides, the technology chosen to fuse with RFID data (and in this way providing stability to the localization mechanism) is IR, which is a low-cost choice.

In Fig. 6 an example of some tracking processes carried out in our test laboratory is shown, given a distribution of reference tags of 1 m × 1 m and several IR transmitters. As can be noted, our localization system is able to monitor the users locations with a high accuracy (taking into account the target location surfaces involved in the main comfort services provided in the different work areas).

For maximum errors greater than 1 m in the location data provided, our system assures a good performance even when the surface covered by reference tags is higher, being 62% the lowest value of successful cases in location for a target surface of 2 m × 2.5 m and with a mean error of 1.9 m. Furthermore, for location surfaces greater than 1.5 m × 1.5 m, the success cases obtained with different maximum errors are similar. This shows a stabilization of the location error. Therefore, among these tags distributions, we can choose those requiring a lower number of reference tags, i.e. the distribution of 2 m × 2.5 m with a 64% of successful cases providing an error lower than 1.5 m, which is quite suitable considering the location requirements of our problem.

4.3. Analysis and discussion

From the results of our tests, we can assert that using an IR transmitter per each 9 m^2 of location surface and a single RFID system with different distributions of reference tags, our localization mechanism ensures an adjustable location error, taking into account the location requirements of the pervasive services analyzed in this work.

The test lab where our assays have been performed is designed to provide flexibility in the distribution of space and appliances, using for this moving and fixed walls made of different materials. Therefore, these experimental results are also satisfactory in those cases in which the RFID signal shows a large variability; for instance, when the user location must be determined through walls of different materials, i.e. with different coefficients of reflection, diffraction and absorption (which was already proved theoretically in a previous work [21]).

An important consideration to bear in mind is the appropriate places to install the IR transmitters, since they need direct line of sight with the RFID tags. In case of not having line of sight with the monitored tags, despite the RBF cannot be applied to estimate the positions, the PF is able to provide the users positions using previous information about their paths. However, the line of sight of the IR transmitters with the reference tags is a key requirement in this localization system, since it affects directly in the accuracy achieved in the location data provided by our mechanism.

And finally, to choose the most appropriate distribution of reference tags, we recommend defining priorities among the different zones of a building regarding the duration and frequency of use. Thus, it may be possible to reach a tradeoff between the energy and hardware cost and the position accuracy. For example, in an office building where users stay for a long time daily, some accurate localization information is needed in order to not waste energy with inappropriate settings of comfort appliances. In contrast, in a dining room where sporadic users appear, the energy wasted due to localization errors may be lower, because a poorly setup of comfort appliances may be applicable during a short period of time.

Hence, after the evaluations performed, we can state that this indoor localization system is both a cost effective and a realistic solution to provide positioning data for context-aware services oriented to smart energy management in buildings.

5. Conclusions

In this paper a hybrid RFID/IR mechanism to solve the indoor localization problem is proposed. The localization solution is focused on satisfying the accuracy location requirements needed to provide context-aware and customizable services in buildings, such as those involved in lighting and HVAC.

Our mechanism is based on a regression method implemented using the RSSI values available in an RFID reader in order to estimate the location data of those users who wear a monitored RFID tag. Then, a particle filter is applied as a tracking technique to estimate the user path. This filter eliminates those estimated positions that do not fit with a realistic movement pattern. This localization system is easily configurable, and totally embeddable in an automation platform.

This system has been tested in real scenarios where a smart energy control wants to be performed depending on the presence and identification of users. The results obtained are satisfactory, covering the accuracy requirements of localization data for pervasive indoor services. Therefore, we present it as both a cost effective and realistic solution for solving the indoor localization problem.

Although this paper is based on a specific case of study and on applying the localization mechanism proposed to smart buildings, it can also be applied in different scenarios where an RFID system and some IR transmitters are available or easily installed, and where target users to be monitored only need to wear an RFID tag.

The current working line is testing this indoor localization system taking into account the different floors of a building, as well as other types of buildings (for instance, in a campus, a shopping mall, etc.) to verify its performance. In future works we will develop energy models and compute indexes that reveal the energy saved and the comfort services that can be adapted to the human activity, considering location data about occupants.

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

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SPECIAL ISSUE - SMART CITIES

User-centric smart buildings for energy sustainable smart cities

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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. Because 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 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 a European city level. Copyright © 2013 John Wiley & Sons, Ltd.

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1. TOWARDS THE CITIES OF THE FUTURE

The increasing trend for people to move to urban areas [1] and the associated urbanization process have resulted in an urgent need to confront to challenges related with the ability of city infrastructures to cover every citizen's needs in terms of water supply, transportation, healthcare, education, safety, and, most importantly, energy. In this context, the integration and development of systems based on Information and Communication Technologies (ICT) [2] and, more specifically, the Internet of Things (IoT) [3], are important enablers of a broad range of applications, both for industries and the general population, helping make smart cities a reality. In [4] is researched the emergence of new business process management and of novel service-oriented architectures focused on the development of electronic services available to customers.

In this respect, there is a huge opportunity to improve the most competitive worldwide actors to offer more cost-effective, user-friendly, healthy, and safe products for smart cities. In Europe, for instance, the area of energy management systems in buildings has only just started but is rapidly moving towards a technology-driven status with rising productivity. This is due mainly to the progress in the need to reduce energy and greenhouse gas (GHG) in line with the EU 2020 and 2050 objectives*. This will ultimately create a solid foundation for continuous innovation in the building sector through sustainable partnerships, fostering an innovated ecosystem as a fundamental corner-stone for smart cities.

Within the worldwide perspective of energy efficiency, it is important to highlight that buildings are responsible for 40% of total European energy consumption and

*www.ec.europa.eu/clima/policies/package/index_en.htm.

generate 36% of GHG [5]. 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 work, we focus on analyzing the important role that buildings represent in terms of their energy performance at city level, and even at world level, where they represent a cornerstone for the energy sustainability of the planet.

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 in smart systems, (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. To help fill this gap, we present our proposal for smart buildings to collect and analyze information in an effective way, and propose specific actions for the control of building infrastructures. Our approach is based on the optimal integration and use of information provided by, among others, the users themselves, that is, although a large part of the IoT infrastructure is composed of wired and wireless sensors and actuator networks embedded in the environment, the occupants also play a key role through their interaction with the system. We show how, despite the relatively short time our system has been operative in a real smart building, energy saving is already a reality thanks to accurate user location data and the user-customized control of appliances to provide comfort at specific target locations.

The structure of this paper is as follows: Section 2 describes the problems related with the huge energy impact that buildings represent at city level. Section 3 reviews related works tackling the problem of energy building management systems. Section 4 presents our proposal for an intelligent management system of building infrastructures aimed at achieving energy sustainability, while ensuring the quality of life of its occupants. Section 5 presents the scenario chosen to deploy our system, and the first evaluation tests performed and results obtained. Finally, Section 6 concludes the paper with conclusions and a description of possible future directions of our work.

2. SMART BUILDINGS FOR ENERGY SUSTAINABLE CITIES

A city can be seen as a network of public and private spaces, transport infrastructures, buildings, essential user-centric services (such as electricity, heating, cooling, water and waste-water, etc.), and citizens. Six dimensions where ICT can be applied to provide 'smartness' in a city are the economy, people, governance, mobility, environment, and the living[†]. A city becomes a smart city after investment in human and social capital, sustainable transport and modern ICT infrastructures, fuel sustainability, economic development, and improvements in the quality of life of its citizens. To cover all these dimensions, natural resources (such as energy) must be wisely managed, and this management must be provided by the governments, researchers, renovated business models and citizens. In this approach, IoT represents a key enabler for smart cities, permitting 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 radio-frequency identification (RFID) will provide the means to capture information about the real world in much more detail than ever before, which will enable to influence real world entities and other actors in a smart city ecosystem in real time.

In [6], for example, the authors explore the concept of sensing as a service and how it fits with IoT. They investigate the concept of sensing as a service model from technological, economic, and social perspectives and identify the major challenges and issues. [7] presents an approach for telecoms to take advantage of the upcoming machine-to-machine markets and defines an advanced architecture able to withstand the demands of a new plethora of evermore clever and useful services.

Bearing all these aspects in mind and focusing on the requirement for energy-efficient environments, energy building performance monitoring and management are recognized[‡] as fundamental components for accelerating the reality of smart cities wherein ICT will play a dominant role. As mentioned, buildings are one of the major contributors to energy consumption within cities. According to a study by the *Gesi Climate change group* [8], the worldwide energy consumption of buildings will grow by 45% from 2002 to 2025, which includes a reduction of 15% by different ICT domains. The study emphasizes that the biggest impact could come for ICT tools for the improvement of energy efficiency in buildings in the design phase (0.45) and smart building management systems (BMS) (0.39). Embedded systems, as part of ICT tools, will play a relevant role in the energy efficiency of buildings, and, indeed, represent the main part of the domains shown in Figure 1. Thus, taking part in 0.8, approximately half of the potential energy consumption reduction comes from ICTs (7.5%).

Summarizing all these aspects, the left side of Figure 1 depicts the expected reduction in total emissions that can be achieved by smart building (1.68), and the right side shows the expected impact that each dimension could achieve within the reduction target. In this paper, we pay

[†]FP7 Artemis Project: http://www.artemis-ia.eu/project/index/view?project=35.

[‡]http://setis.ec.europa.eu/implementation/technology-roadmap/european-initiative-on-smart-cities.

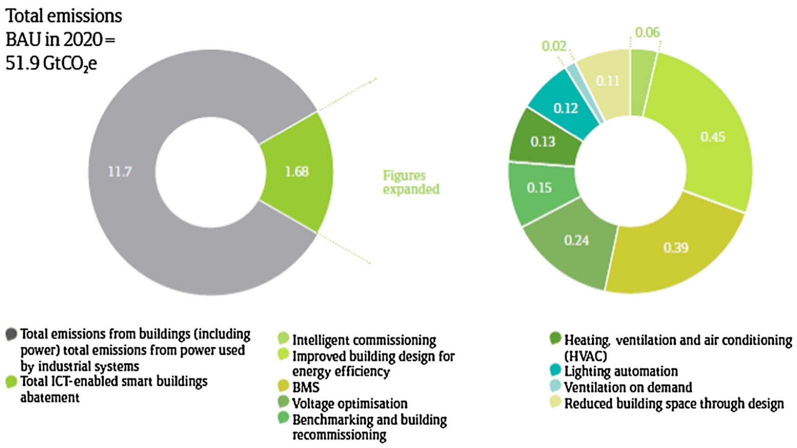

Figure 1. Potential of information and communications technology enabled smart buildings for greenhouse gas emission reduction (BAU, Behaving As Usual) [8].

special attention to the significant role played by BMS in the expected total emission reduction of 0.39, which is part of our motivation for the efforts applied to this specific dimension.

Nevertheless, novel technologies and systemic solutions are still needed to expand the research capabilities provided by paradigms such as the Future Internet. In [9], for example, *Schonwalder et al.* define the Future Internet as a composition of an increase in the available content, the definition of new services that are centralized and personalized for users, accompanied by an increase in their management capabilities. In this respect, to date, building users have had very few possibilities for the energy control of their own facilities, devices, and so on. Information in real-time about building energy consumption has been largely invisible to millions of users who have had to settle for traditional energy bills that throw little light on the problem. Therefore, it is necessary to provide users with increased awareness (especially concerning the energy they consume), and permit them to act as input in the underlying processes of energy building management systems.

There is another direct impact stemming from the fact that users have little awareness of the energy consumption associated with their energy wastage behaviour, and this is partly because of the fact that most people do not actually know what the optimum comfort conditions are according to the environmental features and their needs. Although each person has his/her own comfort preference, these preferences are strongly conditioned by subjective concerns, whereas there are a minimum and a maximum set of comfort conditions recognized as common to ensure the quality of life of every occupant [10]. Furthermore, it is necessary to increase the energy-awareness of society, where energy consumers will be able to differentiate between different energy providers and/or sources, and develop their own strategies for energy saving. Thus, human-centric BMS can be considered smart in the sense that BMSs are able to learn and adapt their performance according to each user.

In [11], the authors of provide a general perspective on the contrasting issues of privacy and efficient utility management of services provided in smart cities, by surveying the main requirements and tools, and by establishing exploitable connections.

Bearing all these aspects in mind, and for buildings to have an impact at city level in terms of energy efficiency, different challenges have been identified[§] 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-targeted.
(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

§http://www.ectp.org/.

on sustainable generation as well as on heat recovery. Among these systems, thermal storage (including both heat and cold) is recognized as a major breakthrough in building design. Distributed/decentralized 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 [12] 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.

(5) *Construction processes*. These should consider ICT-aided construction, improving the energy performance delivered, and using 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 modeling, 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.

In this work, we propose an initiative for the challenges involved in the living stage of buildings: *Performance monitoring and management*. In Section 4, we describe the initiative, which is presented as a solution to the energy efficiency problem of buildings. It is based on an automated IoT platform, where interoperability is addressed, and a building management system, which takes into account the huge amount of input data sensed, as well as the occupants' interaction with the system, makes intelligent control decisions and even plans economic strategies for minimizing the energy consumption of the building while ensuring occupant comfort.

3. SOLUTIONS TO ENERGY EFFICIENCY IN BUILDINGS

Although much effort has been put into smart building technology, the research area of using real-time information has not been fully exploited. In [13], for example, an intelligent agent-based approach for energy management in commercial buildings is presented, in which static and dynamic information, as well as objectives concerning energy saving and user comfort, are jointly considered to accomplish a successful design. Currently, devices are being developed that support energy efficiency (E2) in functional (e.g. energy harvesting devices) and conceptual (e.g. smart metering devices) aspects. Therefore, at building level, the construction of E2 buildings (E2B) is possible. Embedded devices are integrated to address the more complex problems of comfort and energy efficiency in the building as a whole, taking into account the users and indoor environmental conditions. Furthermore, new models, methods, and tools are required to integrate and manage the large amount of information available regarding the status of the building and user intentions. In this line, some work has already been carried out, for example, the *eDiana project*¶ proposes models, methods and tools developed at building level, which can serve as a know-how and as an initial step for developing energy-efficient buildings.

Nevertheless, most of the previous approaches to the problem of energy efficiency in buildings present partial solutions regarding monitoring, data collection from sensors, and control actions. For instance, in [14] the main issues involved in adaptive building management systems are examined, and, as the authors state, few works have dealt with this problem completely.

There are many works on building automation systems, which extend the domotics field originally used only for houses. A relevant example is the proposal [15], where the authors describe an automation system for smart homes based on a sensor network. However, the system proposed lacks automation flexibility, because each node of the network only offers limited I/O capabilities through digital lines, that is, there is no friendly local interface for users in the house, and, what is most important, the integration of energy efficiency capabilities is weak. The work presented in [16] 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. But the authors do not propose any control application to improve energy efficiency, security, or living conditions in buildings.

The number of works concerning energy efficiency in buildings by using automation platforms is more limited. In [17], for example, a reference implementation of an energy consumption framework is given, but it only analyzes the efficiency of a ventilation unit. In [18], 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 [19], but with the main difference that it is less focused on efficiency indexes and more on cheaper and practical devices to cope with a broad pilot deployment to collect the feedback from users and address future improvements for the system.

¶http://www.artemis-ediana.eu/.

Our work presents a solution that involves collecting and analyzing information, and proposes concrete actions, which can be applied in the management of any smart city infrastructure. For this, we propose a platform based on the optimal integration and use of gathered information, which is provided by, among others, the users themselves. This general and interoperable smart building automation proposal addresses the problem of energy efficiency of buildings, comfort service for occupants, environmental monitoring, and security issues, among others, by means of a flexible IoT approach, which allows data to be gathered from a plethora of different sources, and which controls a wide range of automated parts of the building. Apart from presenting the architecture of this general framework, we show how our system provides a real solution to the requirements of a net-zero/positive energy building (NZEB/PEB) [20], where the final goal is to achieve null (or even negative) consumption of non-renewable energy. Thus, our smart energy BMS analyzes all monitoring data provided by automated devices, and then, depending on the required operation mode and considering the energy balance status, takes real-time decisions to improve energy efficiency while retaining building conditions at different user-acceptable comfort levels.

4. HOLISTIC SYSTEM FOR ENERGY-EFFICIENT BUILDINGS

According to [21], achieving energy efficiency in buildings requires solutions in the following fields:

(1) *Automation systems*. Automation systems in smart buildings take inputs from the sensors installed in corridors and rooms (presence, light, temperature, humidity, etc.), and use these data to control certain subsystems such as heating, ventilation and air conditioning (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.

(2) *Monitoring and consumption feedback*. Monitoring energy consumption and providing users with feedback is necessary for energy saving and should be used as a learning tool. As can be deduced, a set of subsystems should be able to provide consumption information in an effective way. Such subsystems include the following:

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

(3) *Economic strategies*. Finally, an intelligent management system must provide proper adaptation countermeasures for both automated devices and users, with the aim of satisfying the most important comfort and energy efficiency requirements. On the one hand, a suitable comfort level involves ensuring the heat, air quality, and lighting requirements of occupants. Whereas on the other hand, energy savings need to be addressed by establishing a tradeoff between comfort, energy resources, and associated costs.

For a building to be considered energy-efficient, it must be able to minimize conventional energy consumption (i.e. non-renewable energy) with the goal of saving energy and using it rationally. Optimizing energy efficiency in buildings is an integrated task that covers the whole lifecycle of the building [17], and during these phases, it is necessary to continuously adapt the operation of its subsystems to optimize energy performance indexes. However, this process is a complex task with a lot of variables and constraints.

Bearing these aspects in mind, we present in the succeeding text the base platform of our proposal for a smart building, which includes an energy building management system that will be described subsequently.

4.1. IoT platform applied to smart buildings

Our base platform used for integrating energy efficiency features is based on the *CityExplorer* solution (formerly called *Domosec*), whose main components were presented in detail in [22]. This platform is based on an architecture modeled in layers, which is sufficiently generic to be applicable in different smart environments such as intelligent transport systems, security, health assistance, and smart buildings among others, promoting high-level interoperability at the communication, information, and service layers. The layers of this architecture are depicted in Figure 2.

As can be seen from the lower part of Figure 2, input data are acquired from a plethora of sensor and network technologies such as Web, local and remote databases, wireless sensor networks, and others, all of them forming an IoT framework. 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 case of energy efficient buildings, the platform CityExplorer is responsible for gathering information from the sensors and actuators deployed in the building following an IoT approach. Furthermore, it is in charge of monitoring environmental parameters, collecting data about occupants, detecting anomalies (such as fire and flooding among others), and it is able to take the actions concerning key efficiency requirements, such as saving energy or water consumption.

The main components of CityExplorer are the network of Home Automation Modules (HAM) and the supervisory control and data acquisition (SCADA). Each HAM module comprises an embedded system based on a CPU (32 bits 4 MB) connected to all the appliances, sensors, and actuators of the various spaces of the building. These devices centralize the intelligence of each space, control-

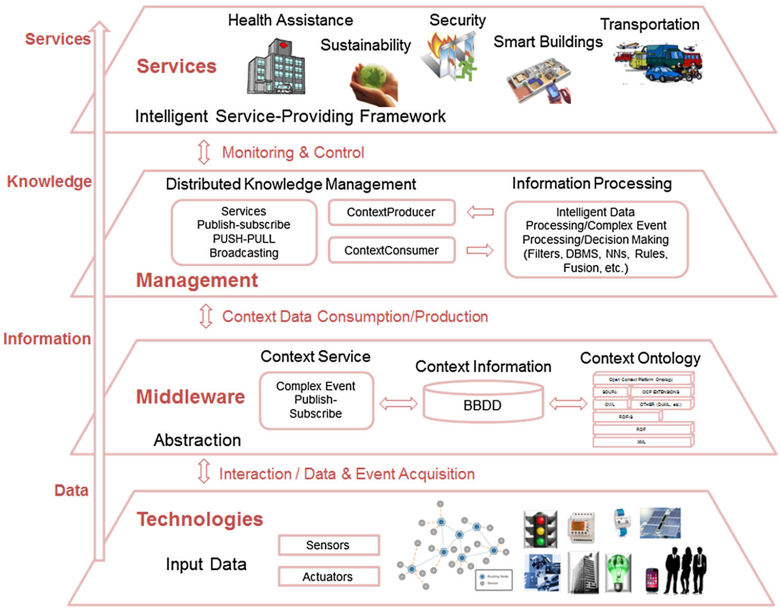

Figure 2. Layers of the base architecture of our building automation platform.

ling the configuration of the installed devices. Additionally, the SCADA offers management and monitoring facilities through a connection with HAMs. Thus, all the environmental and location data measured by the deployed sensors are first available in the HAMs, and are then reported to the SCADA, which therefore has a global view of the whole infrastructure.

Sensors and actuators can be self-configured and controlled remotely through the Internet, enabling a variety of monitoring and/or control applications. Each HAM unit of CityExplorer supports several communication protocols, enabling it to connect with many devices. By complementing the direct digital and analog I/O through common wiring, ZigBee (or 6LowPAN), and Bluetooth connections are available to support direct IP access to sensors and actuators through the SCADA as proxy, following an IoT approach. A controller area network (CAN) bus can be used to extend the operation range or provide a more distributed wiring solution. X-10 connections over the power line are also available for low-cost domotic installations, whereas the KNX-EIB controller offers a powerful solution for connecting with more complex appliances. Finally, Serial-485 devices can be connected, and the Modbus protocol is also supported.

In addition, a LAN installation in the building is available to connect all Internet Protocol based elements with the HAMs, whereas changeable communication technology can be used to connect the in-building network with the Internet. Optical fiber, common ADSL, ISDN, 3G, or cable-modem connections should be sufficient to offer remote monitoring/management and a basic security system. Given the heterogeneity of data sources and the need for the seamless integration of devices and networks covered by the technology layer of the proposed architecture, a middleware mediator is needed (second layer shown in Figure 2). Therefore, the transformation of the collected data from the different data sources into a common language representation is performed in this layer. We use the Open Context Platform (OCP) developed by the University of Murcia and further described in [23]. OCP is a middleware to develop context-aware applications based on the paradigm of producer/consumer. It is responsible for the management of the information flows provided by different sources, which may include the following: sensors, data bases, and web pages. These data sources can be queried through several coordination mechanisms, for example, through publisher/subscriber methods. Hence, the producer (in our smart building CityExplorer is the producer) collects information from the automated devices and adds information to OCP. Meanwhile, consumers interested in some specific context parameters are notified about any change. The context information is collected in an ontology defined according to the model that represents the knowledge of the application domain, whereas, finally, a service to manage all this information is used by consumers and producers of context information.

The management layer (third layer shown in Figure 2) is responsible for processing the information extracted from the middleware and for making decisions according to the final application context. Then, a set of information processing techniques is applied to fuse, extract, contextualize and represent information for the transformation of massive data into useful knowledge that can be distributed. In this layer, two phases can be distinguished: (1) the first acts as context consumer of the middleware, where intelligent data processing techniques are implemented over the data provided by the middleware; and (2) the second phase acts as context producer, where complex event and decision making processes are applied to support the service layer with useful knowledge. During this stage, new context information can be generated, which is provided to the middleware for registration in the ontology context (acting as context producer). Therefore, different algorithms must be applied for the intelligent processing of data, events, and decisions, depending on the final desired operation of the system (i.e. the addressed services).

As regards, the specific application of this architecture in smart buildings, the management layer applies data processing techniques to cover, among others, security, tele-assistance, energy efficiency, comfort, and remote control. Figure 3 shows a schema of the automation platform offering ubiquitous services in the smart buildings field. In this context, intelligent decisions are made through behaviour-based techniques to determine appropriate control actions, such as appliance and lights control, power energy management, and air conditioning adjustment.

Finally, the specific features for service provisioning (which are abstracted from the final service implementation) can be found in the upper layer shown in Figure 2. Our approach offers a framework with transparent access to the underlying functionalities to facilitate the development of different types of applications. Furthermore, in order to provide a local human-machine interface, several control panels are placed throughout the building to manage the automated indoor spaces. This represents an embedded solution with a friendly human-machine interface adapted to the controlled devices. For example, in a three-story office building, each floor could have a control panel to set the automatic opening of windows, switch on the air conditioning to obtain the desired temperature, or close/open the blinds according to the desired light intensity before using artificial lighting. These are just some examples that will reduce the power consumption and contribute to environmental preservation.

Taking into account the services cited in the smart building context, we describe in the succeeding text details of our proposal to address energy efficiency, which is intended to be integrated in the back office part of the City-Explorer platform, with the SCADA acting as data source and gateway to control appliances and machines.

Our proposal for an intelligent management system has the capacity to adapt the behaviour of the automated devices deployed in the building in order to meet energy consumption restrictions while maintaining comfort conditions at the levels desired by the occupants. The outputs of our system (such as the regulation of heating/cooling systems and electric lighting) are forwarded to the actuators deployed in the building. We base our energy performance model on the *CEN standard EN 15251* [24], which specifies the design criteria to be used for dimensioning the energy system in buildings, establishing and defining the main input parameters for estimating building energy requirements and evaluating the indoor environment. The model implemented to manage comfort conditions is based on models for predicting the comfort response of occupants described by the *ASHRAE* [25]. Taking into account all these criteria, we can define the input data of our system (Figure 4).

4.2. Energy building management system

As can be seen, apart from environmental data, user location data are also required to provide customized services

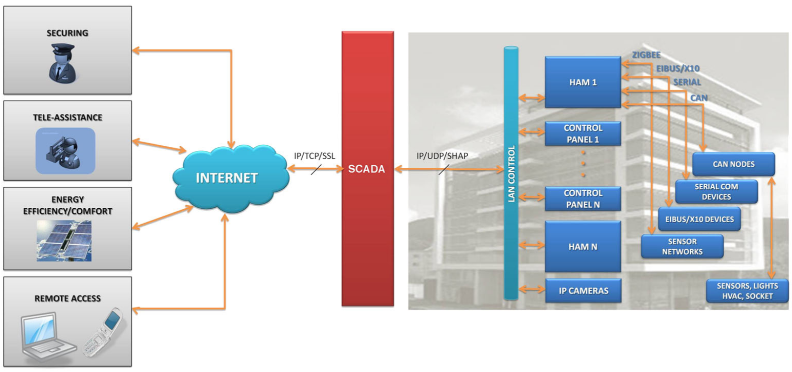

Figure 3. Automation platform applied to smart buildings.

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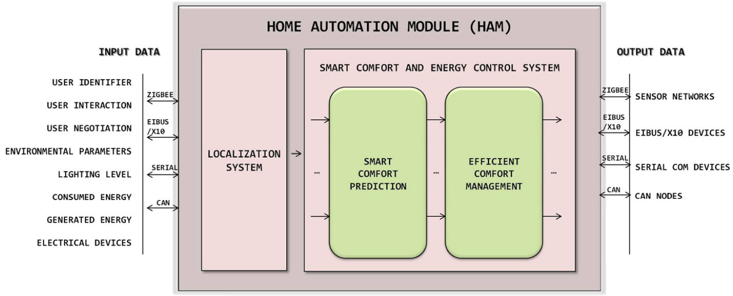

Figure 4. Schema of the modules composing the management system in charge of building energy efficiency.

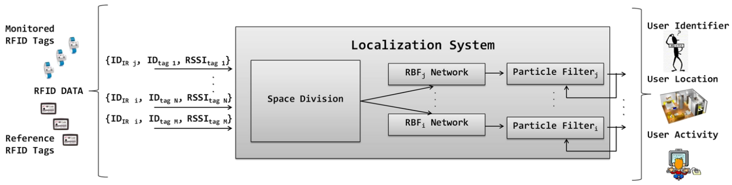

Figure 5. Schema of the data processing for location estimation.

in smart buildings. Information about the number and location of occupants, and even on their activity levels is needed because, depending on this, the comfort requirements may differ, and appliances responsible for providing occupants with such services can be identified individually. In this way, overuse or wastage associated with inappropriate service supply is avoided. User activity levels are defined through models that represent user behaviour patterns under different indoor contexts, such as daily activity in the office and in the home. Therefore, depending on parameters such as user identifier, date, time, and user localization, the associated activity levels can be estimated. On the other hand, user identities are relevant when customized services have to be deployed according to user preferences. For this reason, we have implemented a mechanism which provides identification and localization data of occupants using RFID and Infrared (IR) sensors deployed in the building [26]. In this way, it is possible to carry out control decisions and define strategies to minimize the energy consumption of the building while satisfying comfort requirements depending on occupant location. A schema of this indoor localization system is given in Figure 5, where we can see that this is able to provide information regarding user identifier, location, and activity.

The second system integrated in CityExplorer is responsible for managing comfort appliances (like lights and HVAC devices) in such a way that they provide occupants with the optimum comfort conditions according to their preference as well as the energy consumption of the building. This overall system can be split into two stages: (1) the subsystem responsible for providing comfort preferences to the occupants (module labeled as *Smart Comfort Prediction* in Figure 4), and (2) the subsystem in charge of estimating the energy wastage associated to such preferences, and according to which it chooses the optimum comfort setting (module labeled as *Efficient Comfort Management* in Figure 4). The first one provides the optimum comfort conditions according to the occupants, their activities, their location, and their individual comfort preferences.

As starting point, user comfort preferences are acquired and learned by the system once the user has interacted directly with the system through SCADA and/or using the control panels distributed through the building. Then, these preferences are recorded in a data base, after which, as long as users do not interact again to change their initial preferences, the system is able to provide users with their comfort preferences after detecting each user presence and estimating their location. User interaction is the associated input data related with this aspect.

Once the comfort conditions for each location/region of the building have been estimated, the second subsystem estimates the optimum comfort settings for the involved appliances that ensure minimum energy consumption. For that, the following are taken into account: comfort preferences provided by the first management stage, a forecast of environmental parameters, and the energy consumption measured and generated by alternative energy sources installed in the building.

The management building system presented here implements a combination of techniques based on behaviour-

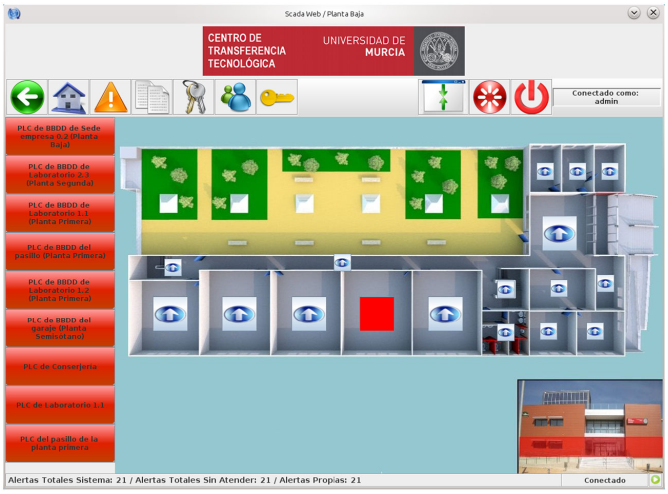

Figure 6. View of the ground floor of the reference test-bed building.

centered mechanisms and computational intelligence [27]. 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 self-adjusts according to such changes and to the control comfort/energy strategies defined by users using the graphic editor of CityExplorer. Therefore, it is necessary for the system to auto-adjust during its operational life. On the other hand, our system must consider user feedback received through user interaction with the system. For these reasons, and as an extension, machine learning algorithms can be used as a solution for learning the parameters of our fuzzy system and to adapt the system to the dynamic conditions and changes of the environment and users over time [28].

5. DEPLOYMENT AND RESULTS

5.1. Deployment

The reference building where our smart system is deployed is the Technology Transfer Centre of the University of Murcia[‖], where CityExplorer is already installed and working. Figure 6 depicts one of the floors of the reference building where a set of laboratories can be seen on the lower part of the map. This screen-shot was obtained from our web SCADA view, which offers all collected data from the heterogeneous sensor network deployed in our building. All the rooms of the building have been automated (through a HAM unit in each one) to minimize energy consumption according to the actions suggested by the management system. On the other hand, user comfort preference are communicated to the system through user interaction with the control panel or user restricted access to the SCADA. We have taken the second laboratory starting from the left as the reference testbed for carrying out the energy efficiency experiments. In this test lab we have defined different room spaces in which sensors are distributed. All input data involved in energy and comfort services are available in real-time through the SCADA access. Finally, separate automation functions for managing lighting, HVAC, switches, and blinds are also provided in these spaces. Figure 7 shows an overview of such deployments.

5.2. System evaluation

For the tests described here we focus on analyzing and showing the energy saving associated with thermal conditions because of the high impact that HVAC appliances have on the energy consumption of buildings. For example, it has been stated that the impact of HVAC on the energy consumption of a building represents 76% of the total in European countries [29]. Therefore, taking into account the HVAC appliance distribution in the testbed under study, we can distinguish different target regions where user location data must be estimated and considered to provide occupants with customized thermal conditions according to both their preferences and needs. For such a regional division, it is also necessary to consider features such as the following: (1) user activities expected to be carried out; and (2) thermal requirements. Therefore, we define different target regions where localization must be solved to provide the occupants located there with the most suitable customized comfort services. These target regions are shown in Figure 7. In this sense, because it is able to

[‖]www.um.es/otri/?opc=cttfuentealamo.

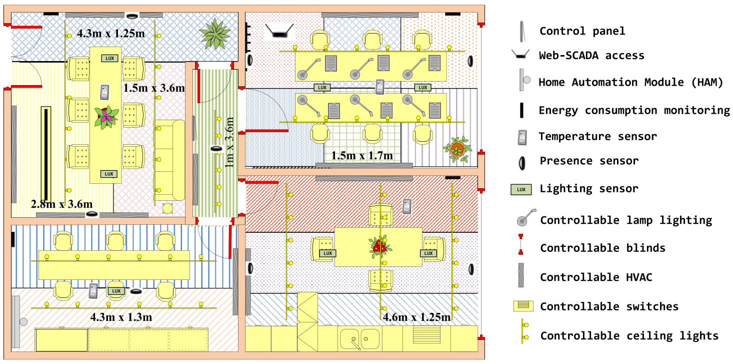

Figure 7. Scenarios of test of the selected laboratory of our reference smart building.

consider scenarios with different needs and features in context, our system is able to learn and adjust its behaviour to ensure a suitable response to different situations.

In the following sections, the tests performed to evaluate three relevant aspects involved in the energy saving associated with thermal comfort services are described.

5.2.1. System evaluation for the identification and positioning of occupants.

Because our goal is to provide user-centric comfort services while considering energy saving, we must ensure that the localization system providing occupant location data is capable of providing location estimations with a mean error that is smaller than the mentioned target regions.

As mentioned earlier, the technological solution to cover our localization needs is based on a single active RFID system and several IR transmitters. 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, and each RFID tag indicates to the reader its identifier, as well as the identifier of its associated IR transmitter. In a previous work [26], we described this system and evaluated its behaviour. The results obtained confirmed the good performance of this solution in terms of location error regarding common target location surfaces to provide comfort services in buildings. But, here we analyze its behaviour in terms of accuracy, considering the scenarios introduced in the previous section, and show the results obtained.

It is important to note how the chosen scenarios are representative environments of the localization problem dealt with in this work (with their comfort appliances, device distributions and target regions) and how they cover almost all location needs (in terms of target regions) presented by other indoor environments (such as hospitals, schools, etc.). Hence, the different target service regions considered in these tests make up the sample of the confidence test performed as part of our evaluation process. This confidence study is described in a subsequent section. In this way, we will be able to extend the validation results obtained in these representative scenarios to other kinds of indoor environment. Among the target regions shown in Figure 7, we highlight the case defined by the service area of individual lamps in an office environment, which can be considered as one of the most restrictive location problems (with a mean accuracy of 1.5 m.) for providing users with customized comfort services in buildings.

Considering transitions between different spaces of such scenarios (more specifically, the two paths represented by numbers: one in blue/red; other in green/pink) as well as some specific positions (those represented by letters in blue/red: A, B, and C), we show in Figure 8 the tracking processes carried out, where the real positions of users (represented by stars) and the locations estimated by the system (represented by triangles) are shown together with the sensor deployment (the reference RFID tags and the IR transmitters). The mean error obtained in this tracking scenario is 1 m, which is sufficient to provide users with individualized comfort conditions. Hence, for instance, considering that the worst case corresponds to solving localization within an area of 1.5 x 1.7 m to provide individual lighting in an office space (as is shown in Figure 8), it would be necessary to have location data with a mean error lower than 1.5 m. Therefore, it can be safely said that our localization system is able to track users with a sufficient level of accuracy and precision for the location requirements associated with the comfort and energy management problem in buildings.

5.2.2. System evaluation for user-centric service prediction.

Taking this as starting point, the suitability of the localization system integrated in each room's HAM, which provides the user location data as input for the energy and comfort management subsystem, here we assess the prediction process in charge of providing the optimum comfort conditions according to the occupants and their

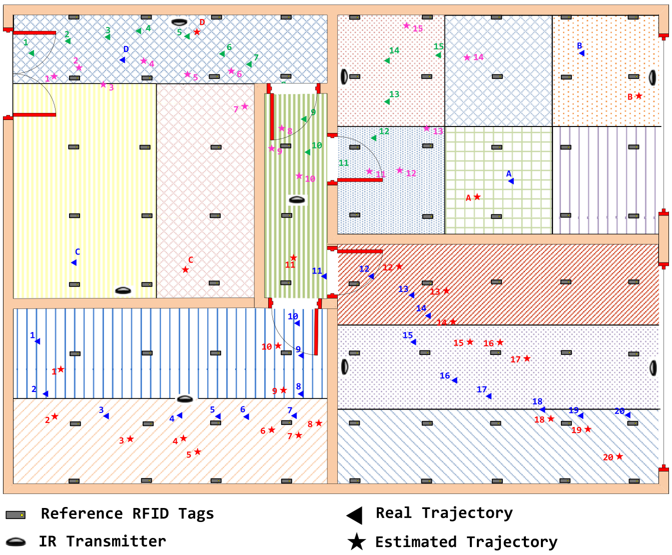

Figure 8. User tracking carried out by the localization subsystem integrated in our building management solution.

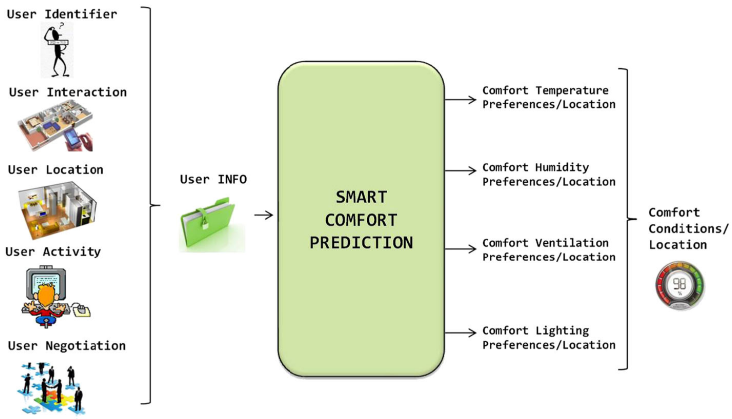

Figure 9. Input and output data of the smart comfort prediction module.

needs. This prediction process is carried out by the module *Smart Comfort Prediction* described in Section 4.2. Figure 9 shows the input and output data of the module.

The HVAC appliances installed in our scenario (Figure 7) are managed according to information provided by the user located in each target region, and the environmental parameters sensed in the room (temperature and humidity in this case). Thus, our intelligent energy management process can communicate different settings to the corresponding HVAC appliances. All the information sensed is gathered in real-time and is available through CityExplorer.

For the comfort prediction implemented, maximum and minimum indoor temperatures were established as control points to ensure minimal thermal conditions in each space. For this purpose, we take into account the comfort models proposed in [25]. Moreover, after identification and localization of occupants, different comfort profiles for each

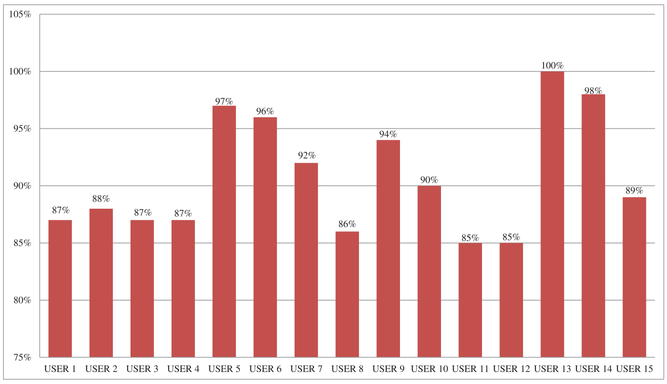

Figure 10. Percentage of success in the estimation of optimal thermal comfort according to user preferences.

user are generated, assigning default settings to their preferences. But occupants are free to change these default values for their own preference when they do not feel comfortable. For this, they can communicate their preferences to the system through the control panel of the HAM associated to their location, or the user access to the SCADA.

In this way, our management system must be 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 given by the features and parameters of the environment. On the other hand, when occupants are distributed in the scenario in such way that the same appliance provides comfort conditions to more than one occupant, our module of comfort prediction must be able to provide them with comfort conditions that satisfy the greatest number of them (always considering minimal levels of comfort). When users interact with the system to change the automatic comfort conditions provided by the system and indicate their preference, the system considers that it is because they are not satisfied with its response,F but if they do not communicate any feedback about this aspect, then our system considers that it is because they feel satisfied with it.

Figure 10 shows the percentage of success of our system in relation with the optimum comfort condition estimated in each location, taking into account all the aforementioned issues. From these results, we can state that this module is able to provide customized comfort services with a high level of adjustment to both occupant requirements and context features.

5.2.3. System evaluation for the energy-efficient management of the appliances.

In the succeeding text, we demonstrate the benefits of considering accurate user positioning information (including user identification) and user comfort preference during the management process of HVAC appliances, showing how energy wastage derived from overestimated or inappropriate thermal settings is avoided.

It is important to highlight that our energy efficiency system needs a long evaluation period to extract relevant figures of merit regarding energy saving. Furthermore, each simplification or adjustment in the system (different input data, rules, locations, comfort conditions, etc.) requires extensive testing and validation with respect to the environment chosen to carry out the evaluation. In addition, system validation must cover different seasons in order to analyze behaviour in different weather conditions throughout the year.

During the data collection process performed in the experiments, the subjects were asked to walk along a set of paths involving different directions and transitions among the environments considered (living room, bedroom, corridor, office, and dining room), and to work or relax in the areas designed specifically for such purposes (Figure 7). These experiments were repeated over two consecutive months (3 h per day) in different conditions of user paths and activities, and environmental conditions.

For the evaluation of energy savings, a comparison was performed between consecutive months in the winter of 2013: January, without energy management, and February, with intelligent management. It is clear that environmental conditions cannot be respected exactly. Even so, during both months, the daily routines were very similar, and the weather conditions did not suffer any abrupt change. But it is worth mentioning that the month of experimentation with the management platform in operation was cooler than the previous month, and so the energy needed for heating would presumably have been higher. We compared the energy consumption value for each day of February with that for the same day of the previous month, including in this comparison, the first three days of March to make a complete contrast for 31 days. In Figure 11, we show the mean values of the outdoor temperature of such dates. Note that the maximum difference between

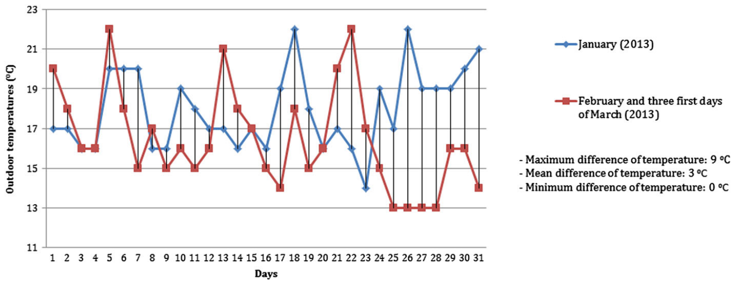

Figure 11. Outdoor temperatures during the experimental time period.

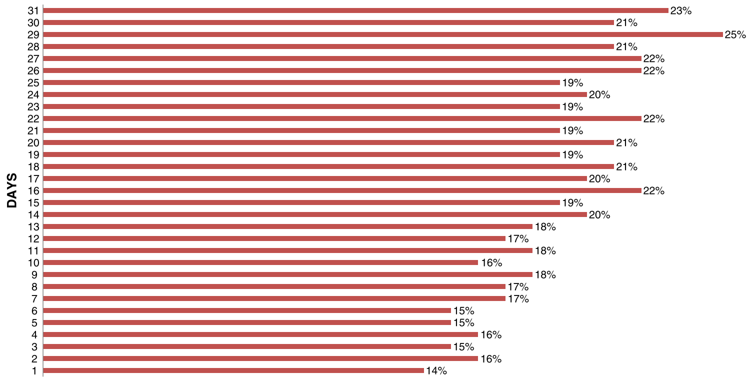

Figure 12. Percentage of energy consumption savings in heating considering user location data.

the temperatures during the selected months was 9^{o}C, which could not be considered as extreme, and the mean difference was only of 3^{o}C, so no great environmental difference occurred.

Fifteen monitored people (all postgraduate students from the Information and Communications Engineering department of the University of Murcia) were asked to carry out their normal every day tasks of working and interaction among themselves during both months. The daily energy saving values achieved during the month of operation of our energy management system compared with the previous month is shown in Figure 12. As we can see in this figure, energy savings varies between 14 and 30%. Therefore, we can state that the experimental results obtained to date already reflect energy savings in heating of about 20%, compared with the energy consumption in a previous month without any energy management and despite the fact that the expected energy consumption for heating during February was higher than for January. At present, a constant and deeper evaluation of the system is being undertaken to provide further details about the system's performance.

6. CONCLUSION AND FUTURE WORK

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, because this constitutes the cornerstone of the overall problem.

For greater energy efficiency in buildings, automated solutions are required to monitor and control the capabilities offered by a sensor and actuator network 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, which are responsible for providing comfort conditions. A building management system able to tackle energy efficiency requirements, whereas user comfort conditions are also taken into account is necessary. 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 work, we propose a platform 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 user location and identity, so that customized services can be provided to them, whereas any useless energy consumption in the building is avoided.

The applicability of our system has been demonstrated through its installation in a reference smart building. This building is automated to gather data from the building (sensors, user interaction, data bases, etc.), and all these data represent the input of the management system presented in this work. Thus, using user location data and considering target regions of occupancy for comfort and energy management in the building, we show that heating-related energy consumption can be reduced by a mean of 20% compared with the consumption in the same scenario and under very similar contextual conditions when no energy management approach is considered. 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 8% could be achieved by installing energy management systems in buildings, and this figure only takes into account thermal appliances.

At the moment, we are carrying out experiments to analyze each of the different pieces that make up our system: influence of the input data on system behaviour; the suitability of prediction for power consumption given user profiles and current settings of appliances (which results in the energy-efficient performance of the building); the capability of the system for auto-assessment and auto-adjustment to changes in the context; and finally, accuracy in terms of comfort prediction according to user preferences (considering both HVAC and lighting services). More experimental tests and evaluations are now being performed, because they are needed to provide a system able to respond to different conditions that cover different seasons, different users and different indoor contexts. Moreover, we are experimenting with mobile crowd-based sensing techniques for gathering data from occupants' devices, since this information will be able to complement the data obtained by the infrastructure-based system.

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

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Contribution of the PhD student
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An IoT Based Framework for User Centric Smart Building Services

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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.

Keywords: User-Centric; Smart Buildings; Energy Efficiency; Indoor Positioning; Context Awareness.

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1 Introduction

Recently, the number of Internet connected objects and devices has exceeded the number of humans on Earth, marking the dawn of a new era of the Internet of Things (IoT) (1). IoT represent a key enabler for smart environments, enabling the interaction between smart things and the effective integration of real world information and knowledge into the digital world. Smart things, instrumented with sensing and interaction capabilities or identification technologies, will provide the means to capture information about the real world in much more detail than ever before, which means it will be possible to influence real world entities and other actors of smart eco-systems in real time.

The initial roll out of IoT devices has been fuelled primarily by industrial and enterprise centric cases. However, their exploitation potential for smart services that address the needs of individual citizens, user communities, or society at large, is limited at this stage, and not obvious to many people. Unleashing the full potential of IoT means going beyond the enterprise centric systems and moving towards a user inclusive IoT, in which IoT devices and contributed information flows provided by people are encouraged. This will allow us to unlock a wealth of new user-centric IoT information, and a new generation of services of high value for society will be built. In this sense, the main strength of the IoT paradigm is the high impact that it will have on several aspects of everyday-life and behavior of potential users.

From the point of view of a private user, one of the most obvious effects of the IoT will be visible in the building environment, since IoT provide the means to make smart buildings a reality. A smart building provides occupants with customized services thanks to the intelligence of the contained objects, be it an office, a home, an industrial plant, or a leisure environment. Furthermore, the smart buildings field is currently undergoing a rapid transformation towards a more technology-driven sector with rising productivity. Among these sectors, that related with energy sustainability of buildings has gained global relevance, bringing with it a wide range of research and technological challenges that concern many aspects of people's lives. This is due mainly to the accelerated progress in energy and greenhouse gas (GHG) reduction. For instance, in Europe there are already initiatives for energy saving like the EU 2020 and 2050 objectives (2). This will ultimately create a solid foundation for continuous innovation in the building sector through sustainable partnerships, fostering an innovation eco-system as the foundation stone of smart cities.

Since the building environment affects the quality of life and work of all citizens, buildings must be capable of not only providing mechanisms to minimize their energy consumption (for instance, integrating their own energy sources to ensure their energy sustainability), but also of improving inhabitant experience and productivity. From this point of view, IoT represent the main enabler to achieve smart buildings able to provide user-centric indoor services while ensuring energy-efficient performance.

Following this approach, in this work we analyze the human-centric perspective of emergent IoT systems in the context of smart buildings, where users are 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. Then, we present our proposal for a kind of smart building based on the optimal integration and use of the information provided by, among others, the users themselves. Our proposal of solution is able to collect and analyze information in an effective way, and propose and/or perform specific actions for the control of building infrastructures, making it possible for the occupants to design such actions. Thus, although a large part of the IoT infrastructure integrated in our system is composed of wired and wireless sensors and actuator networks embedded in the environment, the occupants, through their interactions with the system, also play a key role. Finally, in order to demonstrate the energy saving impact of providing user-centric services in buildings, we show how, despite the relatively short time of operation of our system in a real case of smart building, energy savings of 9% at building level have already been achieved unlike when user participation was not taken into consideration in the building management system.

The structure of this paper is as follows: Section 2 describes the user-centric perspective of pervasive services offered by smart buildings. Section 3 reviews main aspects of energy efficiency concerns in buildings and presents related works from the literature that tackle this problem. Section 4 presents our proposal for an intelligent management system integrated in an automation platform based on IoT, where the goal is to provide user-centric services and ensures the energy sustainability of the building. Section 5 presents the scenario chosen to deploy the system as well as the first experimental evaluation that takes into account both energy saving issues and user perception. Finally, Section 6 offers conclusions and a description of future directions of our work.

2 User Perspective in Smart Buildings

Thanks to pervasive computing practices, the integration and development of systems based on IoT support and enhance 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 with their increasing familiarity with Information and Communication Technologies (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) rooms heating can be adapted to user preferences and to the weather; ii) room lighting can change according to the time of the day; 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.

Moreover, the smart grid has been introduced by using smart net meters with the aim of overcoming the weaknesses of conventional electrical grids. This system allows us to monitor, analyze, control and communicate within the supply chain to help improve efficiency, reduce energy consumption and cost, and maximize the transparency and reliability of the energy supply chain. A smart grid is an electricity network based on digital technology that is used to supply electricity to consumers via two-way digital communication. In this sense, we may think of energy providers that use dynamically changing energy prices to influence the overall energy consumption in a way that smoothes load peaks. An automation logic may optimize the power consumption costs throughout the day by observing when prices, which are provided by an external web service (for instance, a cloud-based service) and are set according to the current energy production and consumption, are cheap, and by considering the specific requirements of each appliance at home (battery charger, refrigerator, ovens). Following this approach, currently there are some works addressing these issues, such as: i) *Energy@home* aimed at enhancing the energy efficiency of an entire house system (3); and ii) *Flexible Alternating Current Transmission System (FACTS)* solutions within the context of grid automation transmission (4).

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 provide users with increased awareness (mainly concerning the energy they consume), and permit them to be an input of the underlying processes of the system.

Nevertheless, the success of user-centric services depends primarily on people participating and sharing the information flows generated by smart objects around them and in their possession (for instance, their smart phones). Enabling such participation and sharing requires a number of technical challenges to be resolved, such as lowering the technological barrier of user participation by making solutions simple, easy to use and affordable.

More importantly, however, willingness on the part of people to participate in these systems is required. This willingness is predominantly dependant on the perception of people: the perceived trust and confidence in IoT and the perceived value that the IoT generate for them. In other words, the greater the trust of users in the IoT, the greater their confidence in the system and the more willing they will be to participate. Thus, at first glance, it is necessary to understand the willingness of people to have intelligent systems at their service, since, although these systems are intelligent, they are under the complete control of users. User trust in intelligent systems lets to smart systems provide people with efficient services centered in their needs. For instance, as regards to the fact that users do not have any awareness of the energy wastage associated with their energy consumption behavior, this is due partly because most of the people do not know actually, what the optimum comfort conditions are according to environmental features and their needs. It is clear that, although each person has his/her own comfort preferences, and these preferences are strongly conditioned by subjective concerns, there is a minimal and a maximum set of comfort conditions recognized as common to everyone to ensure the quality of life (7). 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 if the goals of this type of systems are to be achieved.

However, light can be glimpsed at the end of the IoT tunnel. There are already two billion people around the world using the Internet, and there is scientific evidence that people are not only passively affected by technology, but also actively contribute to shaping its use and influence (5) (6). It could be stated that the current use of Internet is not already only an option, but also represents the greatest source of new alternatives for facing up to a multitude of different daily life's aspects, being almost indispensable for many people already.

To summarize, Figure 1 shows a schema of the different aspects described in this section regarding the user-centric perspective of smart buildings.

3 Addressing Energy Efficiency in Buildings

For a building to be considered energy-efficient it must be able to minimize conventional energy consumption (i.e. non-renewable energy) with the goal of saving energy and using it rationally. Optimizing energy efficiency in buildings is an integrated task that covers the whole lifecycle of the building, and during the different phases it is necessary to continuously adapt the operation of its subsystems to optimize energy performance indexes. However, this process is a complex problem full of variables and constraints (8).

At electronic device level, currently, there are different devices on the market that contribute to energy efficiency (E2) in functional features (e.g. energy harvesting devices)

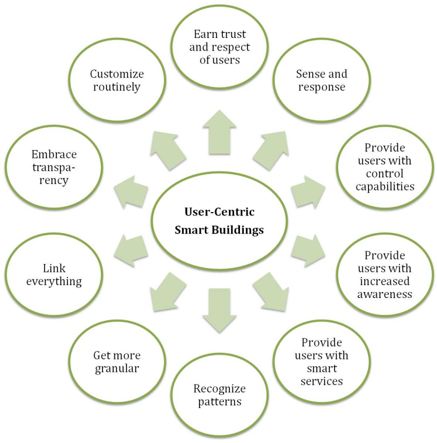


Figure 1 Features of smart buildings from a user-centric perspective

and conceptual aspects(e.g. smart metering devices). Therefore, the construction of E2 buildings (E2B) is already possible.

On the other hand, devices can be embedded to address more complex problems of comfort and energy efficiency in a building as a whole, taking into account the users and indoor environmental conditions. Therefore, new models, methods and tools are required to integrate and manage the large amount of information that becomes available on the status of the building and its users' needs. Some works have already looked at this; for example, the *eDiana project* (9) proposes models, methods and tools developed at building level, which can serve as know-how and as an initial step for developing energy-efficient buildings.

Nevertheless, most of the previous works addressing the problem of energy efficiency of buildings present partial solutions regarding monitoring, data collection from sensors and control actions. In this sense, in (10) an examination of the main issues in adaptive building management systems is carried out, and, as the authors state, few works deal with this problem completely.

According to (11), achieving energy efficiency in buildings requires solutions in the following fields:

1. *Automation systems*. Automation systems in smart buildings take inputs from the sensors installed in corridors and rooms (presence, light, temperature, humidity, etc.), and use these data to control certain subsystems such as heating, ventilation and air conditioning, 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.

2. *Monitoring and consumption feedback*. As is already said in Section 2, monitoring building status and providing users with energy consumption feedback is necessary for energy saving and should be used as a learning tool.

3. *Economic strategies*. Finally, an intelligent management system must provide proper adaptation countermeasures for both automated devices and users, with the aim of satisfying the most important comfort and energy efficiency requirements. On the one hand, a suitable comfort level involves guaranteeing the thermal, air quality and illuminance requirements of occupants, while, on the other hand, energy savings need to be addressed by establishing a tradeoff between comfort measures, the energy resources required and the cost associated with the solution proposed.

As regards the first field mentioned, i.e. building automation systems, many scientific works in the literature address this concern. For instance, a relevant example is the proposal given in (12), where the authors describe an automation system for smart homes over a sensor network. However, the proposed system lacks automation flexibility, since each node of the network only offers limited I/O capabilities through digital lines, i.e. there is not a local friendly interface for users in the house, and, what is most important, the integration of energy efficiency capabilities is weak. The work presented in (13) is also based on a sensor network to cope with the building automation problem, but this time the messages of the routing protocol include monitoring information of the building. Nevertheless, although there has been much investment in smart building technologies, the research area of using real-time information and providing indoor services with a user-centric perspective is not yet fully exploited (10). Therefore, static and dynamic information, as well as energy saving and user comfort objectives, must be considered together for the successful design and operation of an intelligent system addressing the problem posed in this paper.

On the other hand, the number of works addressing energy building management systems using automation platforms is more limited. In (8) for example, a reference implementation of an energy consumption framework is given to analyze the efficiency of a ventilation unit. In (14) 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 found in (15), but with the main difference that it is less focused on efficiency indexes, and more on a cheaper and practical solution to cope with a pilot deployment to collect the feedback from users and perform the actions necessary to improve the system behavior. Thereby, among the works proposed, none is able to exploit completely every IoT capability offered.

Regarding to commercial solutions in the market for efficient management of buildings' infrastructures, there are proposals such as those given by the manufacturer *Johnson Controls*[1], which provides products, services and solutions that let increase the energy efficiency and reduces the operation costs of its clients' buildings. Other known manufacturer is *Siemens*[2], this offers a technical infrastructure for building automation and energy efficiency as market-specific solutions in buildings and public places. The main differences between these commercial solutions and our system proposal for automation and energy efficiency in smart buildings, are its features related with its open and transparent character, as well as its capability of gathering data from a large amount of heterogeneous sources.

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. In this paper, we present our own smart system proposal, which is a flexible solution to collect and analyze information, and propose concrete actions which could be applied in the management of any controllable infrastructure. We propose a platform based on the optimal integration and use of gathered information which is provided by, among others, the users themselves, who have total control of the system and whose desires and/or orders are learned intelligently by the system. We present this real and interoperable experience for the case of smart building automation, which is able to address, among other things, the problem of energy efficiency in buildings, the comfort services of occupants, environmental monitoring and security issues, by means of a flexible IoT approach which gathers data from a plethora of different sources and controls a wide range of automated parts of the building.

4 A User-Centric Comfort and Energy Building Management System

In this section we first present the base platform of our smart building proposal, and subsequently describe the energy building management system charged with providing user-centric indoor services.

4.1 Holistic IoT Platform for Smart Buildings

The automation platform integrated in our proposal of smart building is based on the *CityExplorer* system (formerly called *Domosec*), whose main components were presented in details in (16). This automation platform is divided into an indoor part and all the connections with external elements for remote access, technical tele-assistance, security and energy efficiency/comfort provisioning services.

The architecture of this platform is modelled in layers which are generic enough to cover the requirements of different smart environments, such as intelligent transport systems, security, health assistance or, as is the case analyzed in this paper, smart buildings, promoting high-level interoperability at the communication, information and services layers. The layers of such architecture are depicted in Figure 2, and are detailed below.

4.1.1 Technologies Layer

Looking at the lower part of Figure 2, 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 framework. 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 BMS (Building Management System) proposed in this work (i.e. considering the CityExplorer platform), it gathers information from sensors and actuators deployed in the building. Furthermore, this platform is responsible for monitoring environmental parameters, collecting tracking data about occupants, detecting anomalies (such as fire and flooding among others), and is able to take actions dealing with key efficiency requirements, such as saving power or water consumption. These actions can be made directly by the system (due to the intelligent management system presented below), or can be taken and communicated by occupants involved in the system.

The main components of CityExplorer are the network of Home Automation Modules (HAM) and the SCADA (Supervisory Control And Data Acquisition). Each HAM module is an embedded system based on a CPU of 32bits 4MB connected to all the appliances, sensors and actuators of the different spaces of the building. These devices centralize the intelligence of each space, controlling the configuration of the installed devices. Additionally, the SCADA offers management and monitoring capabilities through a connection with each HAM. Thus, all the sensed data about environment and occupants are first available in

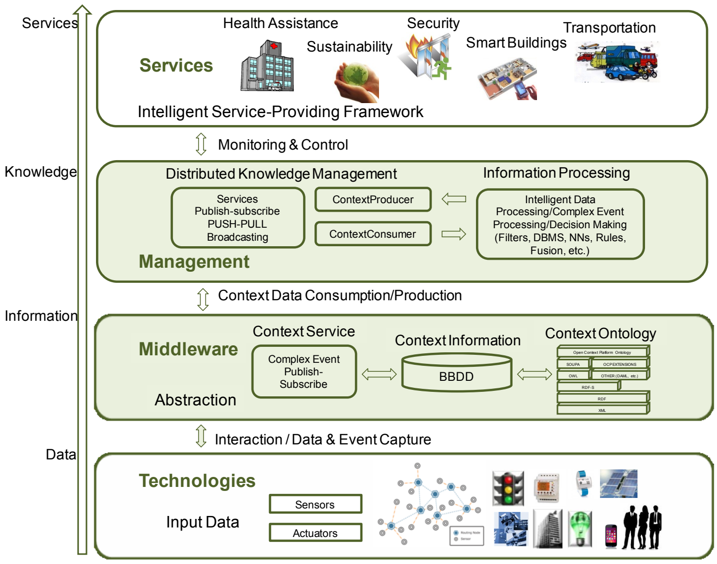


Figure 2 Layers of the base architecture of our building automation platform

the HAMs and then reported to the SCADA, which maintains a global view of the whole building 's infrastructure. And finally, for taking intelligent decisions in terms of energy efficiency and optimum comfort conditions, our system integrates a module in charge with the associated data processing that is fully described in 4.1.3.

Each HAM unit of CityExplorer supports several communication protocols in order to connect with many devices. By complementing the direct digital and analog I/O through common wiring, ZigBee (or 6LowPAN) and Bluetooth connections are available to support direct IP access to sensors and actuators through the SCADA as proxy, and following an IoT approach. A CAN (Controller Area Network) bus can be used to extend the operation range or provide a more evenly distributed wiring solution. X-10 connections over the power line are also available for low-cost domotic installations, whereas the KNX-EIB controller offers a powerful solution for connecting with more sophisticated appliances. Finally, Serial-485 devices can be connected, and the Modbus protocol can be used too.

On the other hand, a Local Area Network (LAN) infrastructure is used to connect all IP-based elements with the HAMs, whereas a changeable communication technology can be used to connect the in-building network with Internet. Optical fiber, common ADSL, ISDN, 3G or cable-modem connections could be enough to offer remote monitoring/management and a basic security system. Although our system permits integration with smart electric grid systems, this system is not currently considered as part of our proposal since no electricity suppliers are able to offer such services in the geographic context of our system (i.e. in Spain). Furthermore, the SCADA offers web access in a multi-user way and is totally independent of the operative system of the machine through which users can access CityExplorer (i.e. Windows, MacOSX or Linux).

4.1.2 Middleware Layer

Given the heterogeneity of data sources and the necessity of seamless integration of devices and networks covered by the technology layer of our architecture, a middleware mediator 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 the middleware layer. We use the OCP platform (Open Context Platform) developed by the University of Murcia and further described in (17). OCP is a middleware able to develop context-aware applications. It is based on the producer-consumer paradigm, and is responsible for the management of the information flows provided by the different data sources. Such sources could be sensors, data bases, Web pages, user feedback, etc.

Data sources can be consulted through several coordination mechanisms, for instance through publisher/subscriber methods. Hence, the producer (in our case CityExplorer) collects information from the automated devices and sensors, and adds such information to OCP. Meanwhile, one or more consumers interested in some specific context parameters are notified about the changes performed in these data. The context information is collected in an ontology containing the knowledge model of the target application domain (the smart buildings context in our study case), while a service to manage this information using OCP is used by consumers and producers of the context.

The ontology implemented to represent the knowledge of the smart buildings context clearly follows a user centric approach, which takes into account all the information that characterizes the situations and conditions of our system's entities, such as: time of day, weather forecast, feedback provided by users, energy consumption levels of appliances, characterization of users (identity, role, preferences, activity, location, etc.), devices (type, location, power consumption, control capabilities, parameters sensed, etc.) and building (floors, rooms, corridors, etc.). Thus, the system adaptation and personalization is based on the reasoning over this ontology by means of properly defined logic and production rules (SWRL (18) and Jena (19) rules respectively), which eases the modelling process.

4.1.3 Management Layer

The management layer is responsible for processing the information extracted from the middleware 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.

In this layer, two phases can be distinguished:

1. The first one acts as context consumer of the middleware. In this phase, both SWRL and Jena rules are applied to reason over the ontology model of the middleware layer. Then, intelligent data processing techniques are implemented over the data generated.
2. The second phase acts as context producer, where complex event and decision making processes are applied to support the service layer with useful knowledge. During this second phase, new context information can be generated, which is provided to the middleware for its registration in the ontology, acting as context producer.

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 the management layer. In this context, and following a user-centric perspective, intelligent decisions are made through behavior-based techniques to determine appropriate control actions, such as appliances and lights, power energy management, air conditioning adjustment, etc.

4.1.4 Services Layer

Finally, the specific features for service provisioning, which are abstracted from the final service implementation, can be found in the upper layer (Figure 2). Our approach offers a framework with transparent access to the underlying functionalities to facilitate the development of different types of final application.

In order to provide a local human-machine interface (HMI), which should be considered trustworthy by users and lets them interact easily with the system, several control panels have been distributed through the building to manage automated spaces. This comprises an embedded solution with an HMI adapted to the controlled devices and able to provide any monitored data in a transparent way. Bearing users in mind, the HMI of the control panels of CityExplorer manages to reduce the risk of injury, fatigue, error and discomfort, as well as improves productivity and the quality of the interactions.

Taking into account the above mentioned services cited in the smart buildings context, we now describe the details of our management system to address energy efficiency in buildings, taking into consideration user feedback and needs. This system is intended to be integrated in the back office part of the CityExplorer solution, using the SCADA as data source and gateway to control appliances and machines, and which empowers users to interact with the system to indicate their desires, strategies of control, comfort preferences, etc.

4.2 User-Centric Energy Building Management System

Our proposal for intelligent management system has the capability, among others, to adapt the behavior 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 follows:

- 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 comfort conditions control 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.
- Windows 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 on the management of lights and HVAC subsystems since they represent the highest energy consumption impact at building level. For instance, HVAC represents 76% of energy consumption in buildings in European Countries (28). User interactions have a direct effect on the whole system performance, because the occupants can take the control of their own environment at any time. Thus, the combined control of the system requires optimal operation of every subsystem (lighting, HVAC, etc.), under the assumption that each operates normally in order to avoid conflicts arising between users' preferences and the simultaneous operations of such subsystems.

Given the different concerns that need to be addressed in our system, a multivariate problem exists with no a unique solution. In our approach, we break the overall system into different and simple subsystems, giving rise to a multi-agent system composed of multiple interacting intelligent agents within a context (22). This type of system can be used to solve problems that are difficult or impossible to solve by an individual agent or in a monolithic system.

Figure 3 shows a schema of the different subsystems comprising the intelligent management system integrated in each HAM of the CityExplorer platform, where the outputs of the system (i.e. the optimum settings for the heating/cooling subsystems and electric lighting) are forwarded to the actuators deployed in the building.

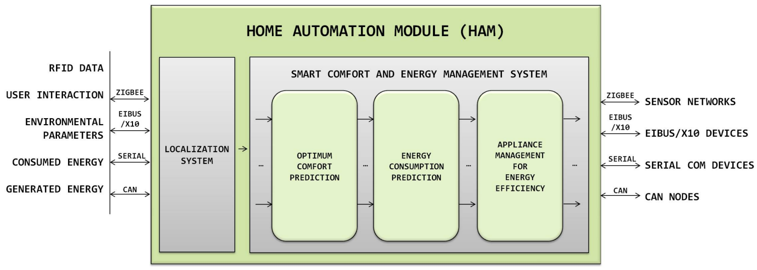


Figure 3 Schema of the modules composing the management system in charge of the building comfort and energy efficiency

As we can see in this figure, the first task to solve is related with user identification and localization. Information about the number and location of occupants, and even about their activity levels, is needed because, depending on this, the comfort requirements will differ, and the appliances responsible for providing occupants with such comfort services can be identified individually. Therefore, overuse or wastage associated with inappropriate service supplies are avoided, achieving a high granularity level of control (specifically, at device level). User identities are important to provide occupants with customized services according to their preferences. For these reasons, we implemented a mechanism which provides identification and localization data of occupants by using RFID (Radio-Frequency Identification) and IR (Infra-Red) sensors deployed in the building (23).

The second problem to solve is related with the issues of comfort and energy efficiency in the management of the building. Here, the main goal is to get the electrical equipment in charge of comfort provide the occupants with the optimum comfort conditions according to their preferences, while bearing in mind energy consumption aspects of the building. For this problem we need to develop an intelligent mechanism in charge of controlling the entire operation of the building.

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% (30). In fact, there are studios stating that this type of energy usage feedback is the most successful approach where users are involved in saving energy in buildings (31). Therefore, it is important to note that energy usage feedback in our system needs to be provided to users frequently and over a long time, offering an appliance-specific breakdown, and presented in a clear and appealing way using computerized and interactive tools. With this in mind, we provide our intelligent system with deep user-centric principles, applying a cyclic learning/adjustment process that satisfies the user requirements of design, data gathering, implementation, deployment and behavior assessment.

Consequently, our management system is gradually provided with innovative persuasive 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 minimal comfort conditions of occupants while energy efficiency aspects are considered. For this purpose, we take into account the comfort models proposed in (21), which predict the comfort response of building occupants considering features such as location type, user activity and date. Besides, 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. And on the other hand, the system tries to satisfy the preferences of the highest number of occupants. For addressing all these concerns, we apply optimization techniques based on Genetic Algorithms (32). Therefore, after the identification and localization of occupants inside the building (which is performed by our localization system integrated in CityExplorer), different comfort profiles for each user are generated with default settings 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 HAM associated to their location, or through the SCADA-web access of CityExplorer. Our management system is able to update the corresponding user profiles as long as these values are within the comfort intervals defined according a minimal level of comfort in light of the features of the building context (21). On the other hand, when occupants are distributed in such way that the same appliance is providing comfort service 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, besides to CityExplorer lets users explore monitored data by navigating through the different automated areas or rooms of the building, 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 CityExplorer, and without needing to program by code any controller. 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 CityExplorer where some rules were defined by users is shown in Figure 4.

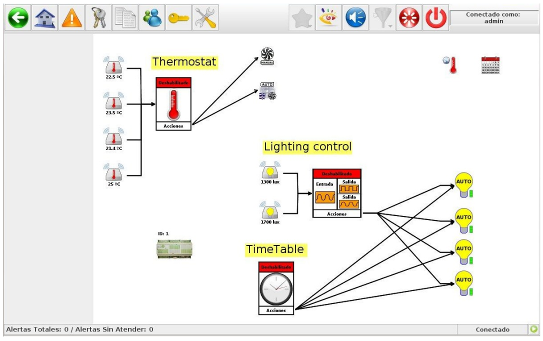


Figure 4 Example of rules defined through the CityExplorer's editor

Furthermore, our system can detect inappropriate settings indicated by users according to both their comfort requirements and associated energy consumption. Therefore, 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, CityExplorer 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, included in our management system, contribute to user behavior changes and increase their awareness over time, or detect unnecessary stand-by consumption of the controllable subsystems of the building.

After the whole commented, we can split the overall problem described above into three simpler subproblems (see Figure 3) related with (i) the estimation of optimum comfort conditions in each location of the building; (ii) the estimation of energy consumption involved in such comfort conditions; and (iii) optimization of the setting of those comfort devices involved in the target locations in such a way that they ensure the energy efficiency of the building. The energy performance model of our building management system is based on the *CEN Standard EN 15251* (20), which specifies the design criteria to be used for dimensioning the energy system in buildings, establishing and defining the main input parameters for estimating building energy requirements and evaluating the indoor environment conditions.

Regarding the computational techniques suitable for solving this type of problems, Neural Networks (NNs), Fuzzy Logic Systems (FLSs) and Genetic Algorithms (GAs) are the most commonly applied by researchers and developers (24; 25). Since, a key issue in the design of our user-centric intelligent system is that it must be understandable to the end users, and be able to show the reasons for the actions automatically proposed, we decided to use fuzzy logic techniques to solve the problems mentioned in Figure 3. Fuzzy techniques offer a framework for representing imprecise and uncertain knowledge in a similar way to that in which people make their own decisions (26). Thus, it is possible to identify anomalies and configuration errors of the system, and then users can understand the reasons for such suggested actions, using this as a learning tool.

Fuzzy systems provide mechanisms to approximate reasoning which allows vague and incomplete information to be dealt with. In addition, fuzzy controllers exhibit robustness with regard to noise and variations in system parameters. However, these systems have a well known problem concerning to the determination of their design parameters, i.e. their rule sets and membership functions, and so they need to incorporate learning mechanisms in order to auto-adjust during their operational life. On the other hand, our system must consider user feedback received through user interaction with the system. Therefore, and as an extension, machine learning algorithms can be used as a solution for learning the parameters of fuzzy systems and to adapt the system to the dynamic conditions and changes of the environment and users over the time (27).

Therefore, 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 CityExplorer. A combination of techniques based on behavior-centered mechanisms and computational intelligence (26) are implemented to solve the comfort and energy management of smart buildings.

Thus, and finally, besides to use SWRL and Jena rules as we mentioned previously (which are applied over the semantic model representing the context of our problem to infer relationships and new knowledge), we apply fuzzy logic rules over the whole available knowledge to take decisions related with the control of the key automated appliances involved during the considered operation time of the system for optimizing their energy consumption. Such target knowledge compound the final inputs of the management system showed in Figure 3, which are firstly segmented through a fuzzy clustering technique for generating the fuzzy model identification (33).

5 Deployment and Assessment

5.1 System Deployment

The reference building where our smart system is deployed is the Technology Transfer Centre of the University of Murcia (29), where CityExplorer is already installed and working. Figure 5 depicts one of the floors of this reference building, where a set of laboratories is present on the lower part of the map. This screenshot has been obtained from our SCADA-web, which also offers the possibility of consulting any monitored data from the heterogeneous sensor network deployed in the building.

Every room of the building is automated through an HAM unit. Therefore, we hereby consider a management granularity at device level in every automated area of our reference building, i.e. in rooms, corridors and shared areas like entrance, stairs, etc. However, since occupants spend most of their daily time inside rooms, we focus on the room space to carry out the experiments and the system assessment.

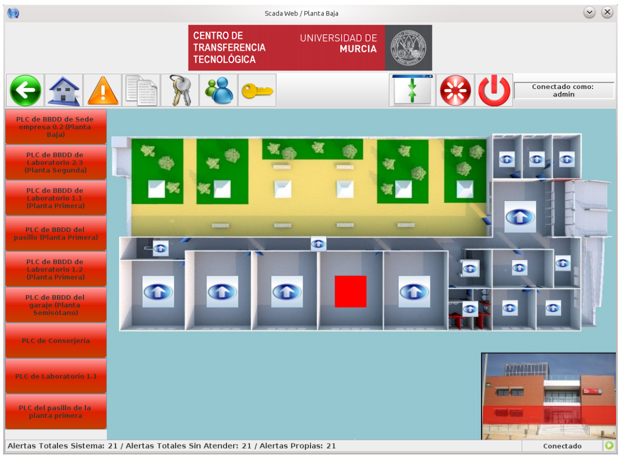


Figure 5 SCADA-web view of the ground floor of the reference smart building

As regards the monitoring and control capabilities at room level, data involved in energy and comfort services provided in each room comprise the input data of the intelligent system integrated in the HAM installed in the target scenario. On the other hand, separate automation functions for managing lighting and HVAC devices distributed in each room are also provided by the HAM unit installed there. Therefore, at room level, it is possible to minimize energy consumption according to the actions suggested by the management system allocated there, which also takes into account user interactions with the system using the control panel of the room or the SCADA-web access.

Looking at Figure 5, we have taken the second laboratory starting from the left as the reference testbed for carrying out the experiments. In this test lab we have allocated different room spaces where sensors are distributed. Figure 6 provides an overview of such deployments as well as the contexts of an office, a dining room, a living room, a corridor and a bedroom.

As mentioned in the previous section, we focus on managing intelligently the lighting and HVAC equipment installed in the building. Therefore, taking into account the lights and HVAC appliance distribution in this testbed, we can distinguish different target regions where user location problems must be solved to provide occupants with customized comfort conditions according to both their preferences and needs. For such regional divisions, it is also necessary to consider features such as user activities expected to be carried out and the associated lighting and thermal requirements. These target regions are highlighted in different colours in Figure 6.

The lighting and HVAC appliances installed in these scenarios must be managed according to information from the user allocated in each target region and the environmental parameters sensed in the room (lighting, temperature, ventilation and humidity in this study case). All the information sensed is gathered in real-time and is available through CityExplorer. On the other hand, the intelligent system controls the different settings for the appliances which provide service to occupants. Figure 7 shows some examples of the

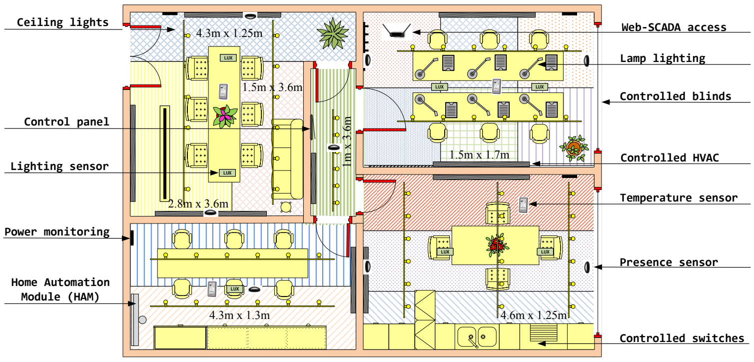


Figure 6 Different contexts in a test lab of our reference smart building

automation actions defined through the SCADA-web integrated in CityExplorer to control HVAC and lighting appliances for saving energy in a specific area of the target scenario. Specifically, the control actions showed in Figure 7(a) are based on regulating the operation power of the HVAC appliances when outdoor temperature is higher than 27.9^o with the aim to achieve indoor temperatures between 20.9^o and 25.3^o, and in Figure 7(b) are based on regulating the lighting appliances when outdoor lighting level is lower than 654lux. to achieve indoor lighting level higher than 584lux.

By considering contexts with different needs and features, the system can learn and adjust its behavior in a sufficiently generic way to ensure a suitable response to different situations. Below, we describe the experiments carried out in the considered test lab, and show the results and their analysis.

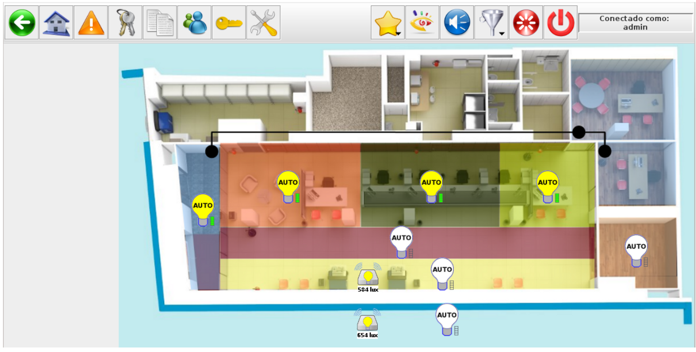
5.2 System Assessment

For the experiments described here, fifteen people took part in the focus group studies which help us extract user-preferences and pinpoint design concerns. Understanding user contexts, such as motivation for saving energy and the constraints for implementing energy saving behavior, enables better understanding of user preferences and how the energy monitoring system can work with users to achieve the best possible behavioral changes.

During the data collection process performed in the experiment, the subjects were asked to walk freely along the different scenarios considered (see Figure 6), and to work or relax in the different areas designed specifically for such goals. This experiment was repeated during 3 hours per day considering different conditions of user movements and activities, environmental conditions, preferences, etc.

At the time of writing, the system has just completed the first 62 days of measurement, so this time is the baseline period used to assess the impact of including users in the loop of our system. During the first 31 days of the experiment, users lacked any feedback about their energy consumption as well as any control capability over the setting of comfort and energy levels, but during the last 31 days of the experiment, users were empowered and were included as a holistic component of the system. During this second phase of the system

(a) SCADA-web view showing some HVAC automation actions



(b) SCADA-web view showing some lighting automation actions

Figure 7 Examples of the rules implemented over the automated appliances of one of the target rooms of our scenario

operation, the system displayed real time energy usage in kW, cost of energy usage, energy saving tips, energy usage history (hourly, daily, monthly), etc. through both SCADA-web and the control panel installed in the target scenario. Also, during this last phase, users could define their own strategies to control any appliance or monitor any specific parameters sensed by the system.

Despite the relatively short time of evaluation (one month), an early analysis shows that the system has already had a positive impact on user behaviors, which can be translated into energy saving terms. Figure 8 shows the energy savings achieved during the second month of operation of our energy management system in contrast to the first experimental month. It can be seen how we achieved a saving of up to 12% of the energy involved, and the medium value of 9% for the experimental month. Furthermore, the results reflect how the increased savings become more stable with time, specifically from the 17th day of the system operation. The reason of this saving increasing is because our system is able to learn and adjust itself to any feedback indicated by users regarding their comfort associated profile, and to recognize patterns of user behavior.

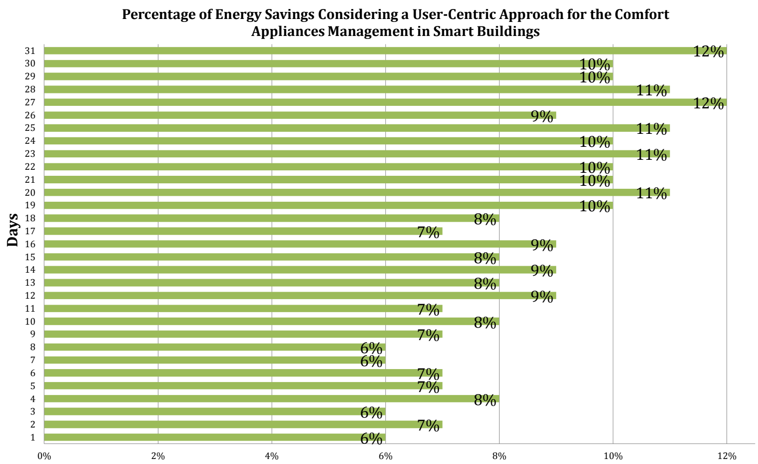


Figure 8 Percentage of energy consumption savings in comfort services considering a user-centric building management

It is clear that the environmental conditions and user behavior during both time periods were not exactly the same, and so there is a degree of uncertainty concerning the results obtained. But during both periods considered, the occupants' daily routines were very similar and the weather conditions did not suffer any abrupt change.

On the other hand, to understand the background of energy behavior 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 a posterior 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 on the energy building management area where large-scale deployments need to be accompanied by a body of study on user behavior, motivation and preferences. The same was printed out by (31).

The survey responses to the questionnaires enabled us to understand the users' belief in the system and any constraints they felt concerning energy saving behavior in buildings. The following list shows the key user enquiries together with the overall user perception of each aspect:

1. Their motivation for saving energy: financial savings (70%), environmental concerns (30%).

2. Constraints that hinder their energy saving behavior in their own homes:

- Financial constraints as regards the acquisition of energy efficient appliances and devices to control energy consumption: overall 69.2% claimed they would install energy monitoring if the cost of solutions were low/medium, while the rest (20.8%) expressed favourable attitudes to acquiring them independently of their price.
- Limitation of flexible home infrastructures: overall 97% stated their home appliances only provide them with turning on/off control capabilities, while the rest (3%) had more complete regulating capabilities over their appliances.
- Lack of information on the energy efficiency of their household and appliances: overall 91.1% said that they did not know their own home's energy performance different from the traditional electricity bills, while the rest (8.9%) had deployed and working energy meters in their homes.

3. Their opinion about the usability and usefulness of the intelligent building management system proposed here:
   - Worries about being monitored (both themselves and their environment): only overall 32.3% showed worries about this issue.
   - Worries about being connected continuously to the Internet: only 7% claimed they were worried.
   - Need for wireless and minimalistic infrastructures: 98% expressed such needs.
   - Need for information confidentiality and validity: 99% agreed with this.
   - Need for user interface to be children and youth friendly: 34% expressed such desires.
   - Interest in energy saving tips and more detailed facts on energy consumption of appliances: 100% of participants showed interest.
   - Interest and trust levels in depth information and remote access to real-time data: 100% of participants showed interest.
   - Encouraging behavior changes: 87% of participants were encouraged to change their behavior.
   - Encouraging information sharing with both the system and other people as learning tool: 75% agreed with sharing their personal information related to the energy consumption of their homes.

After analyzing these issues we transformed this information into knowledge about user requirements for the subsequent adjustment of our system. On the other hand, it is important to highlight that our building management system needs a long evaluation period to extract relevant figures, since each simplification or adjustment in the system (different input data, rules, locations, comfort conditions, etc.) requires extensive testing and validation processes with respect to the environment chosen to carry out the evaluation.

Finally, system validation must be extended to cover different seasons in order to analyze the system behavior according to different weather conditions during the year. Once our system is validated under different constraints and contexts, we intend to apply techniques for automatic pattern recognition and thus provide our system with more accurate responses to cover the requirements of different contexts. Despite all these considerations, we can safely state that the use of our user-centric energy management system has already achieved energy savings at building level.

6 Conclusion and Future Works

The proliferation of ICT solutions (IoT among them) represents new opportunities for the development of intelligent services to achieve more efficient and sustainable environments. In this sense, persuasive energy monitoring technology has the potential to encourage sustainable energy lifestyles within buildings. Nevertheless, to effect positive ecological behavior changes, a more user-driven approach is needed, whereby design needs are accompanied by analysis on user behavior and motivations. Large sample sizes are needed to understand user preferences and habits related to the indoor services that they require.

In this way, building management systems able to satisfy energy efficiency requirements and user comfort conditions are considered necessary. However, to date, studies have tended to bring users into the loop after the design is completed, rather than including them in the system design process.

In this work, we propose a platform, which is powered by IoT capabilities and forms part of a novel context-and location-aware system, that deals with the issues of data collection, intelligent processing for saving energy according to user comfort preferences, and actuation features to modify the operation of relevant indoor devices. An essential part of our intelligent management system is users involvement, through their interactions and their associated data (identity, location and activity), so that customized services can be provided.

The applicability of our system has been demonstrated through an instantiation in a reference smart building - a real automated building set up to gather sensor data for monitoring input data of our management system, and with the ability to trace occupants by means of an IoT approach to access information sources. The first experimentations using our system demonstrate that users undergo immediate behavior changes related with how they realize what their comfort needs are and how to properly use their appliances. This reflects user trust in the system responses which they use as an active learning tool. Mean energy savings of about 9% have already been achieved during the month that the system has been in operation following a user-centric approach.

Further experiments are being carried out to analyze each of the different pieces that make up our system and which can be summarized as follows: impact of each input data in the system performance, the suitability of the prediction concerning power consumption in light of dynamic user profiles and the settings of appliances (which results in an energy-efficient behavior of the building), the ability of the system for auto-assessment and auto-adjustment to changes in the context, and finally, the accuracy in terms of comfort prediction according to user preferences. Finally, we are experimenting with mobile crowd-based sensing techniques for gathering data from occupants' personal devices, since such information will be able to complement the data obtained by the infrastructure-based system.

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List of Figures

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

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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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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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[48] Nenad Gligoric, Srdjan Krco, Ignacio Elicegui, Carmen López, Luis Sánchez, Michele Nati, Rob van Kranenburg, M. Victoria Moreno, and Davide Carboni. Sociotal: Creating a citizen-centric Internet of Things. In *Information Science and Technology, The Fourth IEEE International Conference on*, pages 280–287. Society for Information Systems and Computer Networks, 2014.

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