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A Human-Centric & Context-Aware IoT Framework for Enhancing Energy Efficiency in Buildings of Public Use

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ABSTRACT The GreenSoul project introduces an innovative energy-efficient platform which enhances traditional public-use buildings with various technologies, such as smart adaptors, energy analyzers, an occupant aware decision support engine, mobile applications, and interactive ambient interfaces. These enhancement aims to directly improve the interactions between occupants and energy-consuming assets in their environment. The GreenSoul framework is further enriched by the deployment of lightweight edge-computing GreenSoul-ed devices, which reduce energy consumption by cooperating with other devices, smart metering equipment and, very importantly, with eco-aware users. The decision making process is supported by a socio-economic behavioral model, which provides the necessary understanding of occupant indoor behavior toward transforming energy consuming devices into active pro-sustainability agents that inform users how energy-efficiently they operate them, provide notifications as to improve that aspect, and even adapt their own functioning to reduce energy waste. These eco-wise devices, which are coined as GreenSoul-ed Things, are explained in detail throughout this paper as well as the sensor-based architecture that supports their operation. The deployment of the framework across six pilot buildings is addressed, as well as the designed experimental setting to corroborate the potential of such a collaborative approach to enhance energy efficiency in office buildings.

INDEX TERMS Energy-efficiency, Internet-of-Things, decision support systems, human factors, persuasive technology.

I. INTRODUCTION

The Energy Efficiency Directive (Directive 2012/27/EU) [1], embraced by the EU on 2012, lays the foundation of a) a reduction of greenhouse gas emissions by 20 % in comparison to 1990 levels, b) a growth in the number of renewable sources used for energy generation up to 20 % and c) an increase in energy efficiency by 20 %. Later on, on 2016, the European Commission updated these objectives by setting up a new 30 % energy efficiency target for 2030.

With the intention of outdoing the energy efficiency objectives established by the EU while fostering environmental-friendly practices in the background of smart cities, the GreenSoul (GS) project contributes to transforming the energy consumption practices of employees within buildings of public use and the operation mode of the electrical devices with which they interact, such as PCs, printers, coffee-makers, lifts, etc. This approach lays on the idea that one of the primary causes of non-essential energy consumption is the misuse of systems and devices within buildings. Considering that, energy use in buildings accounts for about 40 % of the global energy consumption in the EU [2], any improvement related to energy efficiency can prove to be critical.

Against this background, the objective of this research is to delve even further into the work presented in [3], which set out the sensor-based architecture of the GS platform, and focus on the interrelationship of its components with the network of GreenSoul-ed Things that are in charge of conveying energy awareness feedback to end-users through a set of well-defined persuasive strategies. The GS architecture follows a User Center Design (UCD) approach since the targeted actors of the proposed architecture are employees of office buildings, their socio-economic status, and their intrinsic and extrinsic motivations to reduce energy at their workplace. To validate the proposed architecture, this paper presents the experimental setting devised for six different public buildings across Europe (UK, Greece, Spain, and Austria). The main strategy to increase the pro-environmental awareness and the motivation to reduce the energy consumption of employees is based on persuasive principles coming from social sciences. Hence, the Decision Support System (DSS) that relies on a persuasion engine for taking actions (either feedback to users to make them actuate in favor of the energy efficiency or applying automation when end-users neglect the advice) is explained in detail. From the best of our knowledge, the presented architecture and its design is novel and contributes to the research community interested on how to include the needs, attitudes, and motivations of end-users in an ICT-based that gives incentives according to their different behavioral profiles. We consider that the proposed approach can be easily extrapolated to another context within the smart cities as it puts the end-users in the center regardless of the application environment.

The article is organized as follows: Section 2 reviews the related work on architectures that take into account the user needs and which are based on IoT or Edge Computing paradigms; Section 3 describes the overall approach followed to design the context-aware architecture. Next, Section 4 addresses the cornerstone to deploy and integrate sensors and actuators in the six pilot buildings as well as Section 5 provides an overview of the information flow. Section 6 is devoted to cover everything related to the GreenSoul-ed Things as novel actors of the proposed framework. Section 7 details the core of the architecture which is the Decision Support System make-up of several components such as Persuasion Engine or the Profiling module. Section 8 covers all the designed visualization interfaces for managers and employees. Section 9 expands on the deployment of strategies and the experimental setting and Section 10 covers the validation methodology of the proposed settings. Finally, Section 11 provides a brief summary of the paper and outlines the avenues of future research.

II. RELATED WORK

The attitude and behavior towards energy consumption is heavily influenced by a great number of factors, such as the personal education, age, social standards, beliefs and cultural traits, marketing and dissemination strategies, and of course the technological development. Recent research suggests that the ever changing characteristics of consumer preferences over time [4], call for actions to shift the isolated analysis of energy consumption behaviors to how society is influenced and conditioned by different consumption practices. There are also additional ways to convey feedback and await an appropriate reaction to them as analyzed in [5]–[7]. The key, however, lies in the combination of distinct methodological approaches that can achieve energy savings up to 20 % [8].

There is a significant amount of evidence that suggests that technical interventions have a lower impact when carried out in isolation and without an adequate methodology designed to encourage and foster behavioral change. The analysis of the relationship between the deployment of monitoring systems, such as Smart Meters, and the fostering of behavior analytics is therefore crucial, as pointed out by [5]. In this line, research related to behavioral change paradigms [9] focuses on recognizing the main variables that drive different energy consumption patterns, whether socio-economic, psychological or educational, and aims at establishing policy initiatives or incentives to produce a strong influence on those patterns. In the case of public buildings within smart cities, the problem lies in the fact that tenants, employees, or visitors lack the motivation and awareness in terms of energy consumption in contrast to how they may behave in their own homes. Indeed, the behavior of occupants can have as much effect on the energy consumption as the use of energy inefficient equipment [10].

The GS architecture that we present in this paper follows the Edge Computing paradigm [11] and features similar aspects related to the users as the GS framework does [12], [13]. The work carried on by Vega-Barbas *et al.* [12] is actually relevant to the GS architecture as it also accounted for the feasibility of building an interaction model based on the characteristics of the different types of users. Other existing works included the human perspective in the designing phase of the ICT, however these are all related to pervasive health and telemedicine [14]–[16]. Whereas these health-care architectures are of potential interest for our research, the interaction provided to the user is always prescriptive if not mandatory for end-users (e.g. pills intake, doing specific activities in a correct order or following guidelines according to a health calendar). Our approach is more oriented to learn from everyday human practices through the interaction that employees and building tenants do with their surrounding electrical appliances and devices of private and collective use. A piece of research on that direction empowered citizens with mechanisms to participate as prosumers in future smart cities [17]. The work presented here resembles some of the proposals of Jara *et al.* [17], but instead of only motivating people to participate (in our case, do actions to reduce energy consumption) the GS architecture enables a team-based relationship between augmented devices, the so called Internet of Things (IoT), and end-users to cope with energy inefficiency in the workplace as if they were allies in favor of the environment. Finally, the work pursued by García *et al.* [18] is worth mentioning, as it follows a similar rationale for attaining the GreenSoul's objectives of reducing energy consumption in public buildings.

Their paper presents a serious game based on the social computing paradigm that integrates advanced technologies through the framework "(Context-Aware Framework for Collaborative Learning Applications (CAFCLA)", including wireless sensor networks and real-time locating systems. Their proposed system continuously monitors the use of lighting, the use of HVAC systems, the electrical energy consumption at the site of each user, the temperature and luminosity of the environment, and the location of users through a Wireless Sensor Network. Thus, all data are obtained in real time according to the activity inside the space, its temperature, if the use of lighting is being efficient, if users turn off or suspend their devices when they leave their job, and whether users use an lift or the stairs to reach the monitoring place. All of these data facilitate checking energy efficiency targets and consequently rewarding the users with virtual coins or penalize them otherwise. The main conceptual difference between their proposal and the one presented in this paper lays on the persuasion mechanisms to convince users towards energy sustainable behavior; where García *et al.* mainly rely on serious games to engage the participants, the GreenSoul approach aims at enhancing every day consuming devices to make them become the main actors to increase users' awareness and foster eco-behavior change through persuasive strategies.

III. GREENSOUL ARCHITECTURE

A three-layer scheme following the physical building deployment (Figure 1) was designed for the GS architecture, namely: 1) the Device Layer; 2) the Building Layer, and 3) the Front-end Layer. This Section provides a brief description of each layer, along with their software and hardware components, the communication interfaces, the protocols and databases selected, and finally the various inter-dependencies among the devised GS components.

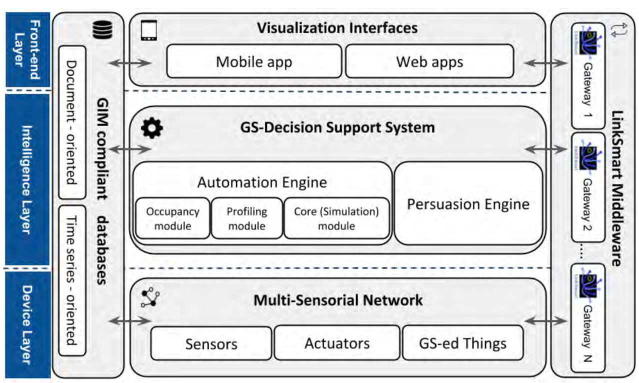

FIGURE 1. **GreenSoul reference architecture.**

The *Device Layer*, bottom part of the architecture, features the set of sensors that are considered relevant for data extraction and analysis (e.g. presence sensors in some parts of the building); actuators that can be remotely controlled to assure that energy efficiency is achieved (e.g. open/close the windows automatically) whether already installed or to be installed within the building, and adaptors, which are new electronic devices connected to home or office appliances, of personal (e.g. monitors, PCs, etc.) or collective use (e.g. printers, coffee-makers, outlets or power strips, etc.). The purpose of such adaptors is to optimize efficient usage of the mentioned appliances.

The *Building Layer* is responsible for giving value and meaning to the information retrieved. It consists of the GS-Decision Support System (GS-DSS) component, responsible for processing data and generating final operational recommendations.

Finally, the *Front-end Layer* features the components of the Visualization Interfaces that provide users access to web-based dashboards and mobile applications. These interfaces allow the GS platform to capture, store and manage energy-consumption data per device and user in a manner that can then be analyzed and displayed for educational and informative purposes.

The GS architecture benefits from flexibility in terms of (i) enabling remote intelligent management of diverse remote devices (energy-meters and persuasive-ambient devices); (ii) applying persuasion techniques through GS-ed devices and mobile apps to eco-educate users both individually and at user-group level; and (iii) providing device and environment decision-intelligence at local and global level in order to enhance the eco-friendliness profile of a given installation, where several common use devices are used by a group of users.

To better understand the functionality of the GS-architecture, next we delve deeper into its core components.

IV. MULTI-SENSORIAL NETWORK

For a building energy management system (BEMS) to be fully operational, it is imperative to have real-time robust information flow from a variety of heterogeneous sensors deployed within the building presenting current building operation (e.g. energy consumption, environmental conditions, occupancy, etc.) [18]. Through the GreenSoul project, six different building topologies have been integrated. These cover a wide range of infrastructures installed such as (1) complete building KNX installations; (2) newly acquired and installed wireless technologies (e.g. Wi-Fi, ZigBee, EnOcean); (3) complete monitoring and control of building energy-related aspects; or (4) limited installations with only specific smart meters applied. Furthermore, the topologies are not only related to ICT but to the size of the buildings. Thus, from small areas with few occupants (e.g. W.E.I.Z. pilot in Austria - 12 occupants) to large establishments with significant numbers in terms of offices and employees (e.g. Institute of Cartography of Andalusia, Spain - 200 occupants). Hence, a highly heterogeneous layout has been addressed, requiring an interoperable, secure and robust design and interfacing for the data flow required for each pilot case for all sensors and devices in the energy-related information exchange.

In order to have a complete understanding of such information, as well as to be able to feed the Decision Support System (Section VII) with all the information needed for more efficient and intelligent decision making, a variety of sensors and devices are included in the overall GS Multi-Sensorial Network. At this point, it should be noted, that an evaluation of existing infrastructure in each pilot revealed equipment that was feasible to be integrated to the GS framework. Thus, some of the technologies utilized were sensors and actuators already available with minor modifications for integration purposes.

A. ENVIRONMENTAL CONDITIONS

Starting with environmental information, wired or wireless sensors have been deployed to strategical locations within the building's areas (thermal and lighting zones), measuring mainly temperature, humidity, and luminance. This information is essential in order to be able to evaluate thermal [19] and lighting comfort [20], which are two of the main factors that determine occupant comfort in indoor building environments and are examined by the GS-DSS.

B. OCCUPANCY

In terms of occupancy extraction, various different approaches were explored leading to the selection of two main solutions: wireless people counters in each entrance/exit and wireless or wired passive infrared motion sensors for motion detection. Based on the selected technology, the granularity and accuracy of the occupancy information provided differs. As such, different algorithmic approaches have been adopted to extract occupancy information. Based on them, different decision making has been implemented to better support the results produced by the GS-DSS.

C. BUILDING DEVICES

Beside GS-ed Things (Section VI), basic building and office equipment have been integrated into the GS framework, covering lighting, HVAC, home and office appliances. Wireless or Wired actuators (on/off relays, dimmers, plugs, fan coil controllers, etc.) were selected in order to provide monitoring and control access to the building's infrastructure. In cases were such extensions were not feasible (i.e. control capabilities from the system were not supported), devices' overall status and consumption were measured by smart analyzers installed directly in line with the devices' circuits. To further explore the capabilities of the GS framework in regard to high energy consuming equipment, some new electronic devices have been developed to enhance the functionality of the multi-sensorial network described above. These devices, that are provided either as adaptors (GS-adaptors) or embedded components to newly defined intelligent devices (GS-ed Things), adopt the Edge Computing approach and their purpose is to optimize the utilization of the integrated appliances, as described in detail in Section VI.

V. INTEROPERABLE AND ROBUST INFORMATION FLOW

Dedicated Device Managers (software) were implemented and assigned to sensors or sensor groups based on topology, communication protocol as well as other restrictions that occurred during integration and deployment (such as serial or parallel read/write requests). These Managers collect and pre-process raw data from the sensors/actuators and transform them in GS Information Model (GIM) compliant event messages (either in XML or JSON format). These event messages are published to the GS Middleware from where they are accessible to every GS component subscribed to it.

In order to cope with information provided from heterogeneous sensors, actuators and software systems installed, a well-known Internet of Things (IoT) Middleware called LinkSmart [21] has been employed to support interoperability (right side of Figure 1). LinkSmart provides the necessary tools for integrating seamlessly GS-ed devices, commercial sensors/actuators infrastructure with GS components. The Device and Event managers provide an easier access to the three-layer architecture, especially for the lower Device Layer regardless of the technology used, and a publish/subscribe service, that enables event-based communication, i.e. enabling publishing and distribution to those components which have subscribed to receive them, respectively. Figure 3 summarizes the operation of LinkSmart through its Device Gateway (DGW) for integrating legacy and new devices from different vendors, protocols or communication channels into the GS architecture.

VI. GREENSOUL-ED DEVICES

The concept of GS-ed devices, also known as GS-ed Things, covers a group of electrical devices of shared use, specifically chosen due to their high energy consumption (coffee-makers, lifts, printers, desk's power strips, lighting and HVAC systems), and enhanced with built-in adaptors that enable the adoption of Edge/Fog Computing approaches [22] by providing not only local intelligence and remote actuation mechanisms, but also persuasive interfaces for user interaction and energy-awareness engagement.

Composed of several Open Source Hardware and software components, the objective of the GS-ed Things is twofold: (a) on the one hand, they provide feedback to the end-users through both physical and ambient cues with the purpose of influencing a more energy efficient interaction with the smart devices and systems in the environment; (b) on the other hand, they enable remote control for sustainable energy-modes when the user ignores their eco-advice. For enabling these two features, sensors, actuators, and a microcontroller are embedded into the GS-ed Things. In addition, these devices are capable of exposing their resources and connecting seamlessly to the LinkSmart middleware through REST-HTTP or MQTT. Figure 2 shows the exchange of information at network and application level between the GS-ed Things and their virtual agents hosted in a Raspberry Pi that features an instance of the LinkSmart middleware. As can be observed in such communication diagram,

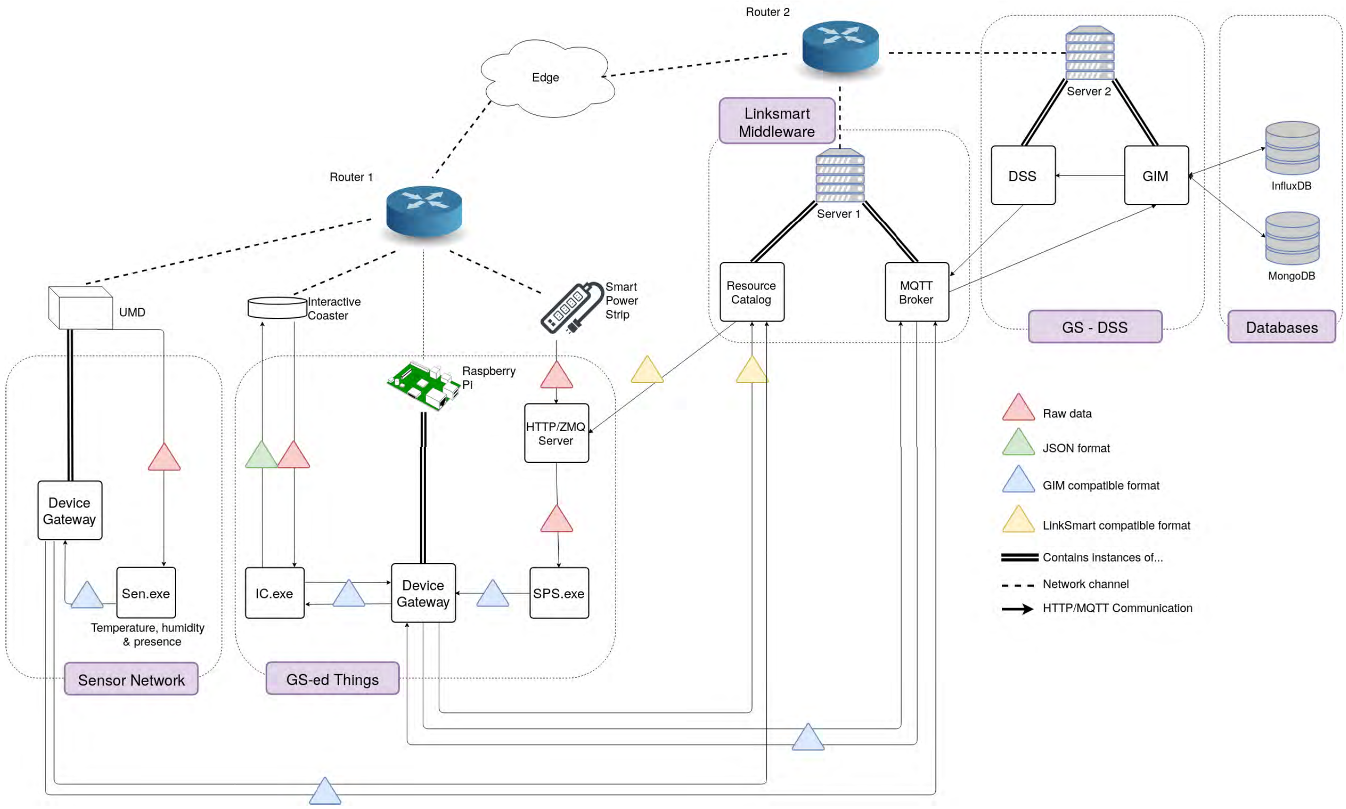

FIGURE 2. Sensor and GreenSoul-ed Things architecture. The diagram shows the communication channels at network and application layer between the IC, the SP and the UMD (electrical circuit analyzer) and the servers with deployed instances of Linksmart middleware and the DSS.

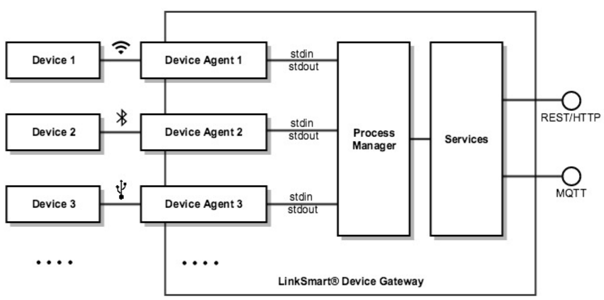

FIGURE 3. The DGW provides an implementation of the Device Connector offering a simple integration of various IoT devices in LinkSmart. Implementing the Device Connector functionality, it and acts as a gateway between the low-level hardware access protocol and a TCP/IP network exposing services as REST-HTTP or MQTT protocols.

the intelligence and computation is very close to the GS-ed Things. Thus, instead of allocating virtual agents in distant servers, these are running in closer gateways (i.e. Raspberry Pis). The presented solution aims at reducing the complexity of the network, data traffic and enhancing the security of the data which are characteristics of the Edge Computing paradigm. Nevertheless, the core of the decision-making of the operation of the GS-ed Things is computed by the DSS and transmitted to the devices through MQTT as can be observed in Figure 2.

To facilitate the comprehension of the novel concept, the following section puts the focus on a specific device that has been transformed into a GS-ed Thing, a power strip for personal use.

A. POWER STRIP TRANSFORMED INTO A GS-ED THING

The device seeks to optimize the energy consumption in office desktops due to misuse of laptops or PCs, monitors, chargers or personal fans and lights (i.e. leaving them switched on without apparent reason, when employees are absent of their place). For that endeavor, we sought to devise mechanisms to provide visual and ambient cues to individuals whilst office employees are working in their desktops.

The GS-Adaptor consists of a device that augments the power strip with sensing technology towards gathering energy data at the desktop level and linking to it an external interface to prompt ambient interactions to end-users according to the energy being drawn by the power strip. These twin-devices aim at educating and warning users about the energy consumption of surrounding electrical devices. The physical twin can be observed in Figure 4. The former device, called

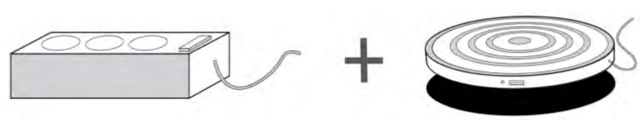

FIGURE 4. An sketch of the SPS and the IC which together make-up a GreenSoul-ed Thing.

the Smart Power Strip (from now on, SPS), is a device ready to measure the power consumption of the three plugs that it features where electrical appliances can be connected to. The latter is a physical device that displays information related to the own energy consumption being drawn by the users. It has been coined as Interactive Coaster (from now on, IC). This device provides persuasive 'just-in-time' cues that inform the user about its energy consumption and performance.

1) SPS

As the majority of the functional requirements were not addressed by off-the-shelf smart power strips, we decided to devise and develop our own device. Therefore, the SPS is a power strip enabled with Wi-Fi connectivity that monitors the energy consumption of each of the three outlets that it features. Furthermore, it is able to communicate the individual measured power consumption to LinkSmart through HTTP (See Figure 2). Three relays are embedded in the device to allow remote operation over the outlets when the DSS takes the decision of switching them off. The reason why these GS-ed devices were custom implemented rather than using commercial smart meters is that the sampling rate of our power strips can be remotely controlled to improve the system responsiveness, and they can be switched between polling or event-driven mode to reduce the wireless channel usage, thereby saving more energy. Moreover, they can dynamically connect to other augmented devices, such as the IC, improving the configuration setup to provide more desirable and flexible services as well as meaningful interaction.

2) IC

The shape of the coaster is based on concentric circles. These bring about the ecological metaphor of tree's trunk rings for providing to the user a sense of connection with nature. The selection of wood as the material for making some parts of the case of the coaster goes in the same direction (See Figure 5 (a)). The desired User Experience provides a mimic of a tree evoking ecological feelings that aim to sustain the pro-environmental behavior change. In the digital design, we substituted the tree trunk rings by light strings that will be colored depending on the message that the system wants to

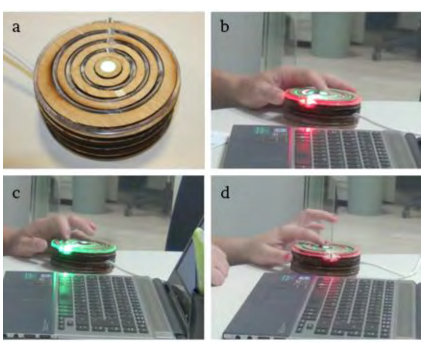

FIGURE 5. A picture of the IC (a) and screenshots from the video recorded at the user testing session (b, c, d).

```
{
  "color": [255, 255, 255],
  "brightness": 10,
  "effect": 0|1|2,
  "duration": 500,
  "interval": 2000
}
```

Listing 1. JSON sample to remotely operate the IC.

convey to the user, e.g. alerts, connectivity, performance, etc. The button in the middle of the device has been conceived as the main mean of interaction with the coaster. As the persuasive devices intention is to make users aware of their energy consumption, we provided different modes of use according to the different user profiles. On the one hand, when the user presses the button he/she will receive a message through ambient lights. On the other hand, the IC is able to actuate by its own providing alerts and ambient just-in-time visual cues to make users aware of certain actions that are opposite to energy efficiency.

The IC features a Wi-Fi interface and a microcontroller to operate the lights when necessary. As it is explained in next section, the DSS (right side of Figure 2) decide what rings should be illuminated, the color, the effect and the duration of it. A sample of the JSON data received by the IC to modify its behavior is shown next.

VII. DECISION SUPPORT SYSTEM

A. DSS AUTOMATION ENGINE

The DSS Automation Engine implements the set of algorithms needed to support the optimal control of the building assets (i.e. HVAC, Lighting, GS devices, Office Appliances) whilst keeping an acceptable level of comfort. In short, the DSS aims to evaluate:

- The need of corrective action to be performed upon building assets towards energy efficiency
- The action specifications (if it represents an open/close command or a specific set-point)

The functionality of the Automation Engine is depicted in Figure 6. The building is divided into lighting (which include one or more light units) and thermal zones (including one or more HVAC units) based on topology and usage. GreenSoul devices and workstation appliances such as printers and monitors are considered as a different category. The main goal of the Automation Engine is to evaluate the operational system states which increase energy efficiency while minimizing comfort loss for the building occupants. For this purpose, the optimal operational state of each building asset is computed. Such process runs continuously, at specific time intervals, specified by the Building Manager. Also, each specific asset can be checked at different time intervals, based on the granularity required.

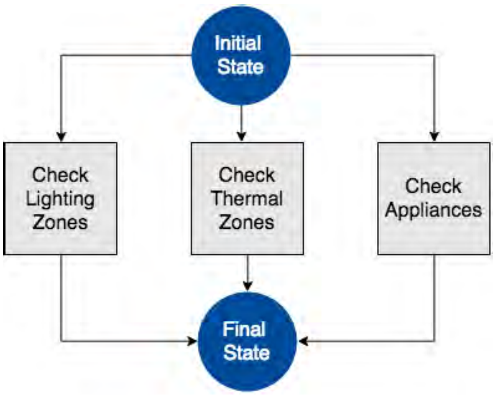

FIGURE 6. **Automation engine flow of operations.**

Figure 7 describes the main DSS algorithm in more detail. Initially, current occupancy status (or human presence) inside the building spaces is retrieved through the occupancy extraction module [23]. The occupancy extraction mechanism is a completely automated procedure which utilizes the data provided by the installed occupancy detection infrastructure (sensors). If the building zone is empty, the system sends a recommendation action to end-users in other closer and populated zones to switch off the lights (by publishing this information to Linksmart). The same process is followed for the HVAC units, but only after predicting the human presence state [24] during the next minutes. Also, the system sends an off-state signal to GS appliances, only after it has checked whether these are "locked" for a particular time horizon; this means that a device status may be altered within a specific time interval, configured by the Building Manager. If the zone is not empty, the current context is further checked in terms of occupants lighting/thermal comfort. Specifically, lighting and thermal comfort is modeled through a discomfort probability distribution, based on the corresponding environmental conditions retrieved from the multi-sensorial network. This function is continuously re-calibrated in a self-learning process, by respecting changes in users' comfort preferences (changes in operational set points of devices, such as HVACs). If comfort is within acceptable levels (and energy optimization is right), the system does not impose any recommendation action. Otherwise, it resides on a simulation mechanism to calculate the best possible combination of devices and their state for maximizing energy efficiency, while sustaining acceptable comfort conditions for the building occupants.

1) CORE (SIMULATION) MODULE

The Core Module aims to evaluate several states and combinations of the system assets while satisfying the comfort thresholds per each zone. The process to select the optimal combination of active assets to achieve the needed comfort is deterministic: A series of iterations is performed for each combination of not-locked units (e.g. lighting units) in the examined zone, thus simulating various system states; combinations of available lights are considered and the respective lighting conditions are evaluated. Indicatively, in order to achieve visual comfort, the idea is to firstly define the desired overall luminance level in the lighting zone in order to reach optimal users' comfort, based on a function of occupants' lighting comfort vs luminance. Then, considering each artificial lighting unit's operational state (on/off/dimming value), the corresponding increase/decrease in its luminance status can be calculated. Thus, the system correlates the overall luminance/thermal conditions inside the zone, reported through the Middleware, with the luminance coming from artificial lights and thermal set-points from HVAC units. With this information, it calculates the corresponding luminance/temperature setpoints and future on/off states which should be derived for each light/HVAC asset or appliance and finally sends them to the Persuasion Engine.

2) PROFILING

The reviewed literature on human behavior and ICT emphasizes the importance of the user diversity when approaching different strategies for promoting sustainable behavior change [25], [26]. Hence, defining user profiles related to sustainability is a pivotal factor to select different persuasive strategies addressed to the different user types. The characterization of the user that we embraced in this work is related to the behavioral and attitudinal profiles proposed by Lockton *et al.* [25]. According to its profiling, GS users are classified as 'Pinballs', 'Shortcuts' and 'Thoughtfulness' as it provides a simple yet consistent way of thinking on people in their relationship with the sustainability issues (in our case, energy efficiency).

- The "pinball" class refers to a simplified, linear approach of impulsive thinking: The user reacts to inputs in an unpremeditated manner, without thinking deeply and rationally about the effect of their decisions. This instinctive-based action would eventually be repetitive when the same stimulants are applied.
- The "shortcut" class refers to a user who makes rational choices, but taking shortcuts to achieve their purpose: in the case of energy efficiency, the user understands that their attitude affects energy consumption, but do not further analyze the energy-efficiency problem. They choose the less complicated way to reach this target.
- The "thoughtful" class, as its name implies, refers to users that have the deepest understanding of how their decisions affect their (e.g. energy efficiency) goals. Hence, they can thoroughly understand and take different actions per different problem set.

B. PERSUASION ENGINE

The Persuasion Engine's (PE) main aim is to evaluate the best fitting persuasion triplet (action, user profile, persuasion technique), considering the pool of persuasion strategies defined in the GS project and the users that reside into the examined space. Specifically, at first optimal control actions are obtained by the Building Automation module. These actions

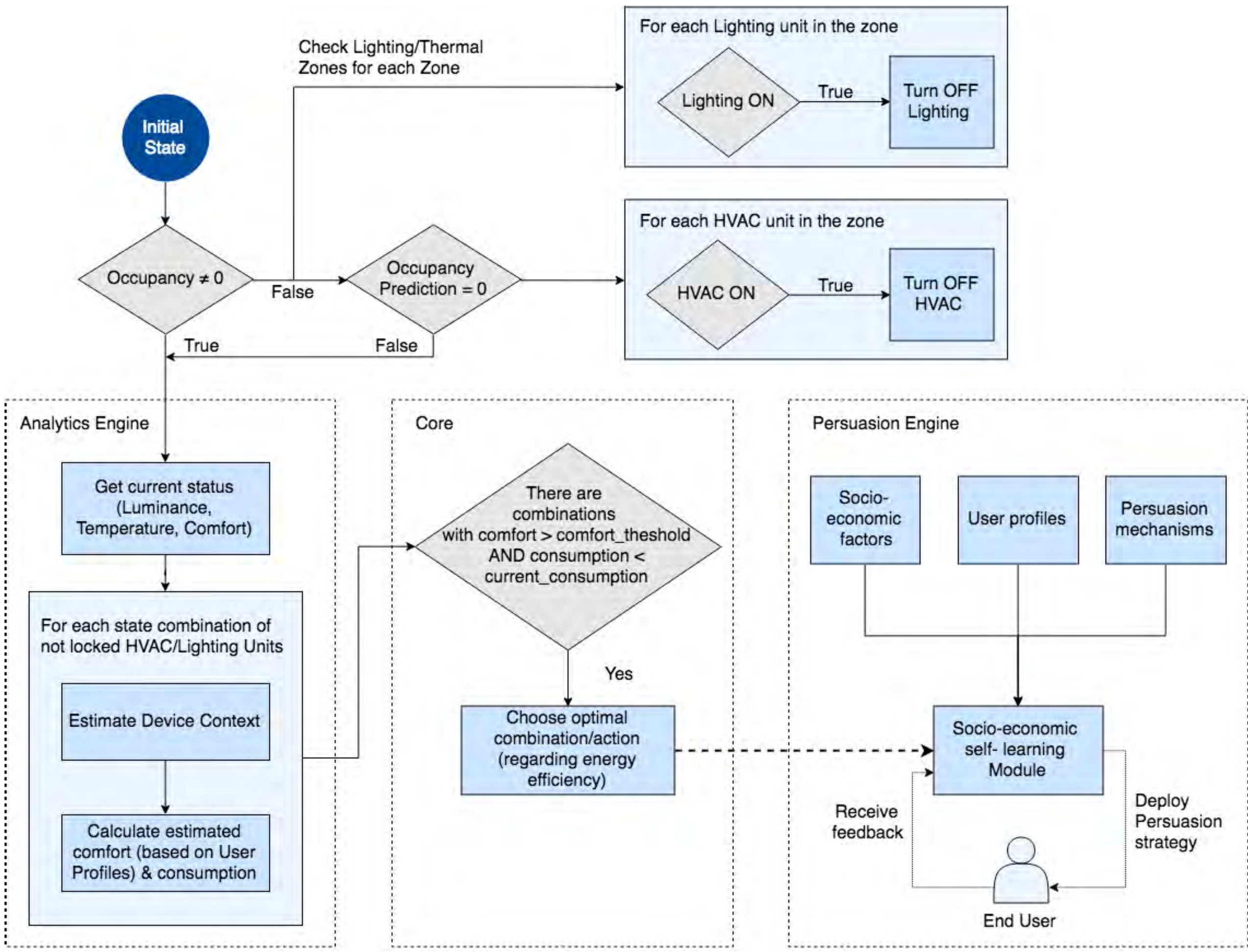

FIGURE 7. **Flow diagram for each visual/thermal zone.**

(recommendations) are "tagged" with specific information on the device and zone to which they refer to. Then, adopting a novel, socio-economic self-learning mechanism the PE:

- Aggregates users per primary (i.e. offices) and secondary spaces (e.g. corridor) and classifies them according to various socio-economic factors and behavioral attitudes (age, preferences, extrinsic and intrinsic motivations, etc.)
- Performs an initial association of persuasion techniques -retrieved from the GIM database- with user profiles ('Pinballs', 'Shortcuts' and 'Thoughtfulness'), and assigns a related weighted factor per such duets.
- Publishes the evaluated triplet of user-device-technique to the Middleware, in order to target end-users through the GS mobile application.
- Detects if the recommended action is successfully followed by the user, updating the success rate of each occupant and re-adapting the weighting factor mentioned previously, thus re-evaluating the selected strategy to be used in the next persuasive iteration.

Summarizing, in contrary to similar attempts, GS PE poses several benefits:

- Messages are validated in terms of their effectiveness, through a user-feedback adaptive mechanism, advancing from the typical generic message in one-size-fits-all approaches. Thus, the system selects both the user and the strategy that is better fitted for each case.
- Socio-economic and demographic reasons that affect the users' sensitivity to each recommendation message are also considered and through the inherited weighted factor.

C. DSS DASHBOARD

The DSS Dashboard serves as the DSS application interface. It specifically implements the information discussed in the previous sections, considering the recommended actions' statistics (number of actions, success rate), devices' status information (on/off, set-point). Also, it presents the total savings' information achieved since the initiation of the DSS service, based on the data obtained from the energy meters. Indicatively, an instance of the Dashboard, can be seen in Figure 8, where the DSS has requested to turn-off the lights and appliances inside an office space, after retrieving zero occupancy state from the sensors.

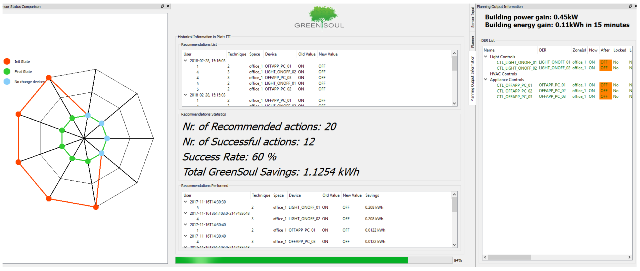

FIGURE 8. Capture from the DSS dashboard.

VIII. VISUALIZATION INTERFACES

To grant end-users with an enriched graphical representation of energy-related information, the GS Front-end Layer provides both individual and group-based visualization techniques through multiple user interfaces, that also acts as a distribution channel for the persuasion messages from the GS framework. Access to these interfaces is available by various devices, such as smartphones, tablets, PCs, etc., supporting a cross-platform approach that enables a wider reach in terms of end-user engagement. Given the nature of the end-user authorization and authentication capabilities, information from all three layers is accessible through a user-friendly portal that is able to analyze and display in various ways such information, for either educational and/or informative purposes. To that end, the majority of monitor technologies is supported, covering devices that are being used daily by the majority of buildings where the GS framework is deployed. The main interfaces utilized are presented below:

A. GREENSOUL WEB-BASED IOT PLATFORM

A fully flexible and customizable web-based IoT platform (Figure 9) has been created for the needs of the GreenSoul project. The platform is fully integrated with both GIM compliant databases and the LinkSmart middleware in order to have real-time access to both static and dynamic information. With a user-friendly dashboard that's equipped with a variety of widgets and tools, it is possible to alter the building information without extensive knowledge over the different protocols, types of devices, etc., offering a dashboard that exploits the interoperable GS framework to its fullest capacity. Furthermore, various graphical representations have been included in order to support optimal visualization of both individual and collective treatments (see Section IX). With a robust and secure authorization and authentication mechanism, the IoT platform in hand provides access to two different types of users: facility managers and end-users. Full monitoring and control access for all spaces, devices, users, strategies, and notifications is provided to the first group, whereas specific monitoring information is only rendered available for the later. A visitor or an end-user can have access to information that has to do with only spaces that are directly influenced by his/her actions. Finally, a notification system is also supported, presenting to end-users the required anonymized information (e.g. which device the action refers to) in the right context (e.g. which office) in order to present actions to be performed by the end-users, that would lead to a more energy efficient management of the building's assets.

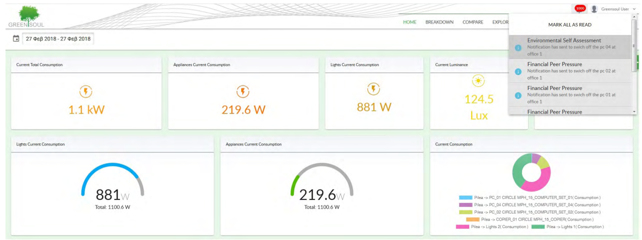

FIGURE 9. Web-based user interface.

B. GREENSOUL MOBILE APPLICATION

In order to provide more personalized notification to building's end-users, a mobile application has been created. Some of the most interesting screens are shown in Figure 10. From the one hand, this application is directly linked to the GIM databases in order to have access to the building's occupants and the available persuasion strategies. When a new user is registered through the mobile application, if the user exists in the GIM user database he/she is matched to the new mobile account. If not, then a new instance is also created in the GIM database with the new user information applied. On the other hand, a client is running in the background of the mobile application, subscribed to the LinkSmart Middleware for retrieving already published real-time information.

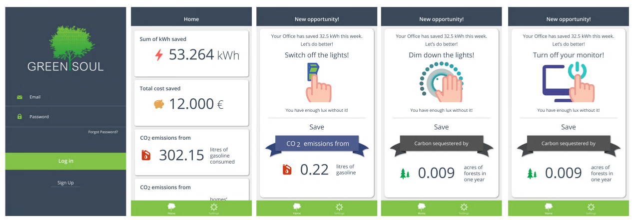

FIGURE 10. Mobile application user interface.

After logging in, the user has access to energy-related information regarding the overall building (Home screen) in quantitative Baseline KPIs that are easy to understand and compare (e.g. energy, cost, CO2, etc.). Following, if a new event has been published to LinkSmart and refers to the specific User, a pop-up notification is created and presented to the mobile screen. The "Opportunity" pop-up is supported by the graphical representation of the device, the type of action required or performed and the persuasion strategy context selected by the DSS (Opportunity Screen). In the same context, other types of events can be also forwarded to end-users (e.g. Individual treatments such as Reminders).

IX. ON-SITE DEPLOYMENT

The GS framework will be deployed and tested on six (6) heterogeneous non-controllable environments, summarized in Table 1, with the aim of monitoring and raising the energy-related awareness of the end-users. This will be achieved by

TABLE 1. Pilot Scenarios for the GreenSoul framework.

	Pilot	Occupants	Country
S	Institute of Cartography of Andalusia	∼200	Seville, Spain
D	IT of the University of Deusto	∼90	Bilbao, Spain
M	Pilea-Hortiatis Municipality Hall	∼30	Thessaloniki, Greece
E	Haywards Heath	∼20	Sussex, UK
A	Allia Ltd	∼300	Cambridge, UK
W	Energy & Innovation Centre	∼10	Weiz, Austria

yielding them with a "greener" guidance through adequate messages and incentives, enriched with effective persuasion mechanisms specially adapted to their profile. The final goal is to influence a change in the behavior of people sharing public spaces.

The devices within a typical workplace can be used at three separate levels: a) individual (power strips on workstations), b) group or work-team (printers, scanners, and coffee-makers), and c) building-level (lifts, lighting system, and HVAC system). Whereas the GS project reckons that the energy saved by the deployed devices will not attain reductions in the pilot buildings beyond 5%-10%; we hypothesize that the awareness caused by these individual devices at the workers' space will spark spill-over impacts to other shared devices and appliances at work setting (see Figure 11). Thus, the intentions and attitudes to behave in a more conscious way with the environment start with the individual awareness.

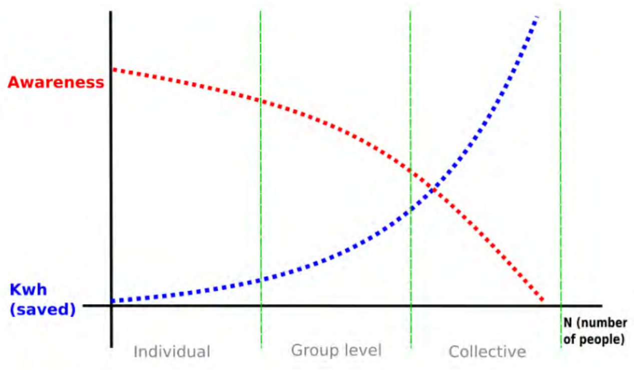

FIGURE 11. Relationship between the impact of Individual vs. Collective Treatments according to the level of personal eco-awareness and the potential energy savings.

In the energy efficiency context of the GS project, the difference between individual and collective strategies towards increasing awareness becomes palpable. If we analyze Figure 11, we can see that individual strategies have a significant isolated impact on individual awareness. However, the impact on the overall energy consumption may not be noticeable, meaning that we would need to influence a great number of users to reach the desired goal of reduction in energy consumption. This is not feasible due to the fact that the application of an individual strategy implies the physical deployment of hardware for each monitored person, resulting in elevated costs. On the contrary, collective strategies reach a greater number of users and in turn, have an immediate positive impact on the desired goal. However, the direct impact on personal awareness becomes diluted.

GS aims at finding an equilibrium between individual and collective strategies, that is, the number of people becoming aware and how much aware they become, and the amount of energy efficiency reached. In order to achieve this, each of the pilots will first apply a set of individual strategies to a group of selected people, followed by a particular collective strategy.

The individual strategies envisioned for the pilots are detailed next. It is important to stress that *all* of these individual treatments will be applied in *all* the pilots.

1) **Individual treatments**
   - **Individualized reminders (PI)**. General purpose prompts with fixed sentences about sustainable actions will be written on post-its. These will serve as reminders about energy efficiency. Each person will be provided with a personal prompt along with an SPS that will monitor the consumption of the devices connected to it over time.
   - **GreenSoul Things (GST)**. Each person will be provided with an SPS and an Interactive Coaster (IC). The SPS will measure the consumption of the devices connected to each of its outlets and the IC will graphically notify through ambient light to end-users about their energy consumption behavior. The frequency and type of notifications produced by the IC will depend on the persons profile.
   - **Decision Support System - individual (DSSI)**. Graphical information is presented through the mobile app providing tips or suggestions to the user, such as turning off the lights or switching off the monitor, etc. If the user ignores them, the system will act accordingly, by modifying the intensity of the lights or changing the parameters of the HVAC. Unlike the two previous treatments, this treatment uses automation.
   - **All combined (ALL)**. All the previous persuasion techniques working altogether.

   The collective strategies envisioned for the pilots are detailed next. Each pilot will only apply a specific collective strategy, but the distribution will be pairwise.
2) **Collective treatments**
   - **Awareness campaigns (AC)**. Information related to the energy consumption per circuit is going to be provided to the managers of the buildings. Fixed sentences targeting the collective are provided in key positions (Signage). This strategy will be deployed at pilots **S** and **D**.
   - **Gamification (GA)**. Information targeting the collective will be sent through the mobile application. This information will compare the global consumption with the groups' own consumption in previous periods and/or the consumption of

other groups. This strategy will be deployed at pilots **E** and **A**.
- **Decision Support System - collective (DSSC)**. Graphical information is presented through the app providing tips/orders to the user in order to operate shared equipment. If the user ignores it, the system will act accordingly (automation). This strategy will be deployed at pilots **M** and **W**.

With this definition and distribution, we are comparing purely persuasive strategies (GST and GA) against automation strategies (DSSI and DSSC). In this way, we can test which approach works better than the other or if a higher goal can be reached by a hybrid approach, combining both. PI and CA, on their part, are used as control methods to certify whether the automation and persuasion strategies are capable of achieving far more significant results than the base strategies.

X. VALIDATION OF THE RESULTS

To assess the collective treatments a ''differences in difference'' (DiD) experimental design is planned. DiD is a statistical technique used in social sciences that attempts to study the differential effect of a treatment on a 'treatment group' versus a 'control group' in an experiment. In this sense, all pilots are going to be monitored before and after the treatments are deployed, and the differences between these measures will be assessed. It is highly likely that the experimental conditions are going to change between these two phases. In fact, the most obvious change will be the season where the measures have been taken. To remove this effect, a baseline model will be built. This model will capture the behavior of the pilot in a ''business as usual'' scenario and later on will be used to forecast the performance of the building during the pilot phase. It is known that the most important factors that affect the energy consumption of a building are its use and the weather. To control these variables, the system will retrieve the number of hours opened and the number of users inside the building and also several weather variables inside and outside the building (like the internal and external temperature, humidity, radiation, etc.). These variables will be used to fit a multivariable linear regression model to describe the energy consumption of all the pilots' sites.

The number of pilots and measurements are going to follow an unreplicated complete block design. Namely, the number of measurements per treatment is going to be the same and it is not expected to have any missing value. In these cases, the Friedman test [27] is the most powerful statistical test. Nevertheless, this test would only assess the existence of differences among the different treatments but not the specific ones that different. To this end, a post hoc analysis should be made that correct the family-wise error rate α. Several alternatives exist like the Bonferroni correction [28] or the Nemenyi test [29].

On the other hand, to assess the individual treatment a ''randomized control trial'' experimental design is planned. In this sense, a treatment (including the control treatment) will be assigned randomly to all the users that will participate in the pilots. As it is assumed that the potential external variables that could introduce variations are going to affect all the treatments equally, the measurements could be compared directly.

Unlike the collective treatment case, in this case, we expect to be in an incomplete block dissing, not only because the number of users in every treatment is going to be different but also due to the fact that some users are going to leave the experiment. In these cases, the Kruskal-Wallis [27] test is the most powerful statistical test. As the Friedman test, this test would only assess the existence of differences among the different treatments but not the specific ones that different. As before, a post hoc analysis should be made that correct the family-wise error rate α. The same alternative as in the Friedman case can be used.

XI. CONCLUSIONS AND FUTURE WORK

This work presents a human-centric and context-aware innovative ICT architecture that follows the Edge Computing paradigm, with the aim of fostering energy efficiency in buildings of public use. The architecture proposed consists of three layers that resemble their physical location: the Device layer, the Building layer, and the Front-end layer. The conceived and developed GS-ed devices along with the GS Decision Support System represent a cornerstone in resilient and autonomous data utilization for behavioral-based energy change. The GS framework will be deployed on 6 different pilots to assess in what degree the application of several different individual and collective strategies make an influence on the personal awareness towards energy efficiency, and as a result, achieve the goal of reducing the overall energy consumption.

Immediate work implies the assessment of the different individual and collective treatments in a longitudinal study where different measurements have to be taken to isolate seasonal variables. Besides, the adoption of the GS-ed Things and the adherence to persuasive incentives to act in favor of the environment within the workplace have to be validated according to the Energy Efficiency Directive. Thus, testing if this collaborative approach among people, devices, and building can surpass the envisaged 20% of enhancement of energy efficiency.

Secondly, the transfer of the acquired knowledge to private buildings and residential houses would be considered in next iterations over this project. Please note that, in both cases, the persuasion mechanisms to be used have to be adapted as the users' profiles are completely different. Nevertheless, we expect that the overall methodology here described would still be valid.

Finally, we envisage creating a more decentralized architecture where the computation of data and intelligence features will be allocated into the GreenSoul-ed Things. This objective is in line with some advances that the authors are doing on incorporating simplistic Artificial Neural

Networks (ANNs) and simple probabilistic models in low-power micro-controller units (MCUs) to get rid of intermediate devices for performing the forecasting algorithms.

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