ISUMS: Indoor Space Usage Monitoring System for Sustainable Built Environment Using LoRaWAN

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Abstract— **In this work we investigate how IoT in conjunction with the data-driven Circular Economy (CE) model can contribute towards a more sustainable Built Environment (BE). We address longstanding challenges related to the distribution of resources and the multi-sectoral impact of the buildings sector. We first discuss recent developments in policy making that underpin the recently introduced Green Deal by the European Commission and the paradigm of Circular Economy. This motivates the development of ISUMS; an Indoor Space Usage Monitoring System. The system provides the facilities and the estates management teams of commercial and office buildings with an IoT-enabled system able to provide fine grained and timely data on occupancy rates of shared building spaces. This type of data can then be used to develop new or inform existing action plans towards increasing building sustainability. The development of the system comprises a) a Pre-Analysis Plan (PAP) for a smart campus use case at the Talbot Campus of Bournemouth University; b) a proof of concept IoT end-device that can be integrated in pieces of furniture for occupancy monitoring; and c) a measurements campaign for evaluating the use of LoRaWAN in indoor environments. ISUMS expands the notions of smart buildings and buildings management beyond interconnected actuators and towards adaptive space management with dynamic changes in the use requirements.**

Keywords—Internet of Things, Circular Economy, sustainability, LoRaWAN

I. INTRODUCTION

Internet of Things (IoT) along with the recently introduced 5th generation of mobile networks (5G) and other novel technologies, like Low-Power Wide Area Networks (LPWAN), Cloud Computing, Big Data, Machine Learning, and Artificial Intelligence currently lead the "Information Age" [1] [2]. These technologies underpin the development of digital interlinked ecosystems with the ability to share information among devices with different computational, memory, and energy capabilities [3].

While their aim is to improve everyday life in many aspects, an additional concept called Circular Economy (CE) targets to take this aim a step further [4]. Data-driven CE principles, in particular, are using intelligent assets that constitute vital components of the aforementioned technologies as the main building block for the development of a system that can provide society, economy, and the environment with added value and growth while keeping resources' consumption levels at the minimum. Applications built upon a sophisticated combination of data-driven CE strategies and IoT technologies can significantly contribute in terms of efficiency and sustainability.

A holistic approach to the problem is illustrated in the light of large cities and the challenges they face regarding the Built Environment (BE). It is well known that cities are complex systems with an economic model that is based largely on the rate of growth and takes no account of the effective use and control of the asset supplies available [5]. This linear economic model combined with the ineffective use of existing interior spaces and the ever-increasing demand for buildings results in the quest for solutions such as urban sprawl and/or densification. However, these methods are static (i.e. characterised by certain lifespan) and they have long been blamed for their negative environmental, economic, and social impacts [6]. During the construction phase, around 10-15% of building materials are wasted [7]. Moreover, at the end of its lifecycle, a building is demolished or dismantled, and the materials are also either landfilled, incinerated, and only a few are recycled, or reused. However, apart from construction and product's end-of-life related wastes, the built environment is responsible for other forms of wastes resulting from inefficient energy usage and underutilisation of spaces. Consequently, the problem is that resources are invested in static solutions with multiple adverse consequences in the long term.

The alternative systemic answer to this problem is the so-called Smart Building; a building that is cognitive, flexible, climate and energy resilient, focused on performance while enabling a 24/7 working and living circular economy.

Our Contribution. We focus on commercial buildings and in particular in University Campuses. Often part of a city, University Campuses face comparable challenges on a smaller scale. Therefore, they can serve as test grounds for approaches that can further be applied to larger projects. Current approaches in estate management of Campuses means that Universities lack circular strategies and support of innovative technologies. They consume large amounts of resources and the outcome is inversely proportional to the utility they provide. Indicative examples are high levels of energy consumption and greenhouse gas emissions, underutilised open spaces and classrooms, or unsatisfied users who spend too much time finding suitable working/resting spaces.

This work aims at increasing sustainability in the built environment by providing the Corporate Real Estate Management (CREM) and the Facilities Management (FM) teams with space usage insights that will further support the formation of innovative and efficient action plans with multiple positive outcomes as defined by the Values Adding Management (VAM) concept (i.e., Intervention → Management → Added Value) proposed in [8]. Data related to occupancy rates can be fed to software applications which will further provide the building's governance, users, and the environment with the following benefits:

- Spaces can be re-designed to meet the users' needs.
- The overall user experience can be improved without interfering to the normal activities nor to the privacy of the occupants.
- Minimisation of time wasted while searching for available spaces can be achieved by providing the users of the building with instant visibility and guidance to the "free" areas.
- Optimal allocation of resources could be reached based on the needs arising from the respective use of each space.
- Cleaning and maintenance services can be significantly improved.
- Optimisation of indoor environmental quality (IEQ) and energy consumption are achievable by controlling HVAC systems according to occupancy rates.
- Reduction of the environmental footprint as a result of efficient management of energy distribution and consumption.
- Costs and produced wastes (in all possible forms) can be reduced.

We consider the concept of Shearing Layers in order to highlight the importance of details and the impact they have onto the achievement of a greater successful outcome [9]. We identify the Stuff layer as the field of action for the implementation of the IoT end devices, the Space Plan layer and the Services Layer as those to be directly affected by the FM and CREM teams which will formulate actions according to the collected data, while also elucidate how the rest of the layers can benefit from these actions.

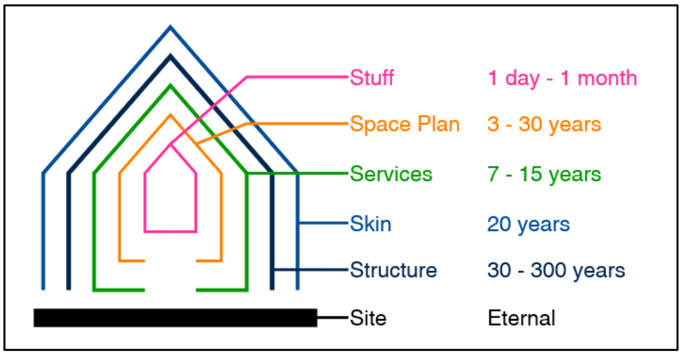

Figure 1 – Shearing layers (amended from [9])

In this context, a Pre-Analysis Plan (PAP) was developed, along with a prototype IoT end-device. The device is able to monitor occupancy and its design allows its integration to existing pieces of furniture. Following, we introduce the Indoor Space Usage Monitoring System (ISUMS) which makes use of indoor LoRaWAN deployment. The PAP and the ISUMS were developed based on a case study in the premises of Bournemouth University Talbot Campus.

II. RELATED WORK

A. *Smart buildings*

Smart buildings were among the first application areas for IoT. Their structured environment, pre-existing building automations and well-defined use cases made them ideal for trialling and evaluating newly introduced smart technologies. For instance, in [10] smart use case scenarios are implemented in a smart building (e.g. adaptation of ambient conditions to human presence and preferences) by leveraging IoT and standard Internet technologies. In [11] an IoT system for smart buildings is presented, which opportunistically augments its sensing infrastructure to include smart devices from the occupants of the building, thus introducing crowdsensing methods.

As the Built Environment is a significant component of smart cities infrastructure, the incentive for employing IoT towards achieving important gains is strong. In [12] authors define the features that smart buildings should fulfil in order to be compatible with the overall context of the smart city and a new evaluation framework of Smart Buildings Integration into a Smart City (SBISC). Their findings reveal that smart buildings have more potential to become smarter by utilizing smart cities capabilities in areas such as smart life and smart environment. This provides the motivation for developing more sophisticated building management systems by leveraging emerging ICT. In [13] authors provide a systematic review of IoT infrastructure in smart buildings.

B. *Space sharing and space usage monitoring in smart campuses*

Managing many and diverse users (students, staff, and visitors), teaching programs, and facilities is one of the most critical challenges that management teams of contemporary University Campuses face. The development of innovative infrastructures, technologies, and processes, as well as the integration of numerous application service systems, are fundamental requirements to establish a people-centric, intelligent, efficient, and sustainable teaching, learning, and living environment. A thorough presentation of the Smart Campus concept and its characteristics is given in [14].

The characteristics of space sharing can be defined by answering questions like: "*Why do we need to share interior space?", "Which spaces can be shared?", "When these spaces can be shared?", "Who will share these spaces?", "How these spaces can be shared?".* Therefore, it is possible to determine the benefits of 'sharing', and the practical considerations and challenges when using spaces in this way. A methodology regarding how this can be done is presented in [15]. The administration of an existing and fully functional University has already answered those questions as it uses lots of spaces in a flexible manner. However, the traditional techniques involved in that complex process are inadequate and fail to bring the best results. According to recent research, smart technologies have gained substantial traction in practice over the past few years by Universities across the globe [16]. In most cases, they were using Wi-Fi, infrared sensors, PC logins, video cameras, and timetables to count how the facilities are being used or to support timetable staff members and/or real estate managers. These approaches rely on the existing network infrastructure with or without additional software or hardware [17]. Although this considers being a step towards making the University Campus ‘smarter’, there are more sophisticated techniques to acquire occupancy data, analyze them and develop effective action plans that will exploit the full potentials of space-sharing; such a technique is discussed in this work.

III. CIRCULAR BUILT ENVIRONMENT

The Circular Built Environment approach is defined as a way to achieve the Sustainable Development Goals (SDGs) through business models supporting the minimisation of waste by reducing, reusing, recycling and recovering materials during the whole lifecycle of a product. SDGs are 17 global goals aiming to achieve more sustainable future for the present and future generations [18]. Challenges such as poverty, hunger and climate change are addressed, while the sustainable economic and social development, as well as the environmental protection are promoted.

According to “The Future of the European Built Environment”, by 2050, buildings will be integrating a massive volume of technological elements that will allow the connection of buildings to information management and sharing platforms. Buildings will act as a temporary storage of materials and services designed based on circular principles to provide the basis for maximum productivity, energy efficiency and well-being [19].

A. *Sustainability in the Built Environment*

The European Green Deal (EGD) was recently introduced as a roadmap towards a sustainable economy across Europe [20]. The main pillars of the proposed action plan are the transition to a clean circular economy which will result to a more efficient relationship between the industry and the finite resources, and the restoration of biodiversity in parallel with zero pollution by 2050. To meet these goals a European Climate Law [21] is also introduced for the European member states to not only politically commit but rather legally oblige to the action plan while triggering relative investments at the same time.

The new “Circular Economy Action Plan for a cleaner and more competitive Europe”, as it is known, while focusing on climate neutrality, resource efficiency, and economical competition, delineates seven key product value chains as vital attributes for the formation of the proposed Sustainable Product Policy Framework [22]. One of them, directly reflects to the aims of this work as it targets sustainability enhancement in the Built Environment.

Furthermore, an additional measure, the “Renovation Wave” [23], has been detached from the Green Deal so that to be reinforced and act as a separate key initiative to increase energy efficiency and economic growth of the current buildings across Europe, as most of the buildings will remain operative by 2050. The Renovation Wave Action Plan [24] was released in April 2020; it is a well-structured plan with a basic requirement for its success: the collective effort from all the actors involved in the value chain.

Buildings Performance Institute Europe (BPIE) argues that buildings should be the focal point of the EGD, not only because they are responsible for high percentages of negative environmental externalities but also because any effort towards climate neutrality will be performed in a way that it will increase the overall quality of life of the people using them [25].

B. *Structural Waste in the Built Environment*

For the designers and developers of a sustainable BE to design out any form of waste of the building’s lifecycle it is important to understand the environmental impact of the different lifecycle stages. Thus, the building's lifecycle can be divided into four different stages: production stage, construction stage, use stage, and end-of-life stage. The following figure depicts the structural wastes in the BE across Europe. Although the study concerns three out of four stages, it still offers a valuable summary. What is also interesting in this study is that utilization, even if it is not a stage of the building’s lifecycle per se, has a significant impact on BE wastes.

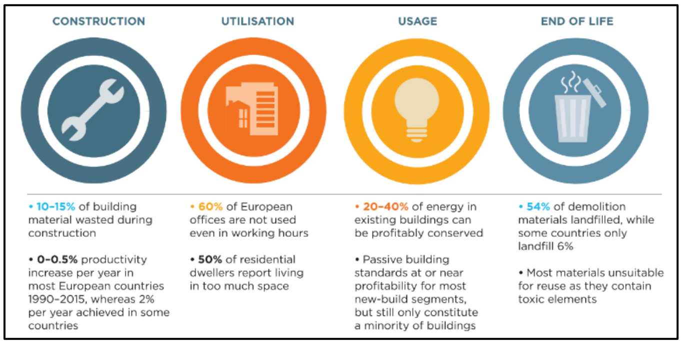

Figure 2 Structural Waste in the BE across Europe [7]

During the *production stage*, raw materials are extracted, transported, and converted into construction materials. The extraction of natural resources has a great impact on the availability of non-renewable resource and might lead to their depletion. Besides, a large amount of water and energy are related to this process. The manufacturing of construction products also requires a large amount of energy as it has been estimated that the construction materials production industry is one of the biggest energy consumers at a global level. Moreover, energy consumption leads to the release of air pollutants.

The *construction stage* is when the building takes its form. The construction stage of a building requires a considerable amount of energy, and materials while involving a high number of stakeholders.

The *use stage* is usually considered as the longest in the building lifecycle. This stage includes activities such as maintenance, and it is characterized by circular strategies such as reuse, repair and refurbish to extend the life span of the building. The use stage leads to environmental impact caused by the users and the physical characteristics of the building, i.e., energy and water use and waste generation.

The *end-of-life stage* in the context of the Circular Economy would mean that the buildings can be safely disassembled into different components, hence they can be reused, repaired, remanufactured, or recycled. In the currently established Linear Economy model, the end-of-life of buildings is the demolition process. Demolition creates huge quantities of bulk waste which might be reused, recycled, or simply landfilled. The environmental impact from this phase is related to the release of green gas emissions from machinery and transportation, as well as emissions related to landfill disposal.

Inefficient *utilisation* of buildings is a major issue and the statistics above (see Figure 2) show that it needs special treatment. It is strictly related to the "use stage" but it has the power to impact the "end-of-life" stage of existing buildings or even the whole lifecycle of new buildings, if it is not taken into account since the early stages of the building's design.

C. *Data-driven Circular Economy*

The digital revolution combined with the concept of a Circular Economy can fundamentally change the industry and the way materials and finite resources are treated. Moreover, it has been identified that success is hidden in the data collection, especially while products are in use [26]. Data can provide insights regarding the identification of the most suitable CE approach for each product and the point in its life cycle where it should be implemented. One of the key enablers of data-driven CE is the IoT paradigm which facilitates the interconnection between the physical and the cyber world as it offers sensing, computing and actuating services through independent Machine-to-Machine (M2M) and/or Machine-to-Human (M2H) communication. The beneficial contribution of IoT systems to the data-driven Circular Economy is discussed and well presented in both the CE-IoT [27] and the IDEAL CITIES [28] EU H2020 projects.

IV. ISUMS : PRE-ANALYSIS PLAN (PAP)

As explained in [29], a PAP is a research protocol, written and registered prior to a study, with the aim of raising the credibility and reliability of its results, and improving the statistical conclusion validity. This section includes a set of PAP elements/sections as they are suggested by this protocol. In addition, Wagner and O'Brien [30] also refer in their book with the title "Exploring Occupant Behavior in Buildings: Methods and challenges" to the PAP as best practise in research design. However, they identify that it is often not done in building occupancy research and they conclude the PAP part of their work by stating that "a research to be useful must not only produce findings, but also quantify the uncertainty in those findings to show they lie within the acceptable margins of error for that purpose"; while also saying that, "accepting that things cannot be measured perfectly, mapping the theoretical model, choosing an appropriate research design, and selecting and applying appropriate methods all help in reducing uncertainty". Hence, our intent here is to highlight the importance of conducting PAP in cases where occupants' behaviour in buildings is being monitored.

A. *Overview of the study*

Sensing devices will detect the presence of occupants in a shared space inside the University campus, namely the "Staff Centre". This is an open multifunctional area for the staff members of BU and covers an area of approximately 300m^2. It is divided, in a semi-structural way, into 4 subareas where the users can perform several activities (see Figures 6). In particular, one subarea comprises work-stations, another one is used for informal meetings, a third one is used for casual meetings (e.g. enjoying tea or coffee with a colleague), and the last subarea is the dining area. The available spaces are non-bookable but used on a walk-in basis. Each one of these subareas is characterized by different parameters that need to be considered at the early stages of the design and implementation processes of ISUMS. These parameters are associated with the practical and methodological challenges of the ISUMS implementation, which are discussed in Section IV.C.

Figure 3 Staff Centre room (a)

Figure 4 Staff Centre room (b)

Figure 5 Staff Centre room (c)

B. *Definition of testing assumptions*

Assumption 1: Each user has a defined set of activity intentions/requirements (e.g., a user is looking for a table of 2 to have a semi-formal meeting). By using the mobile app, they should be able to identify the appropriate available seats in the corresponding area.

Assumption 2: Value Adding Management by the FM and CREM teams according to occupancy rates and behavioral patterns. Here, the interventions and the associated KPIs defined by van der Voordt and Jensen [8] should be used as guidelines.

Variables to be used:

a) Presence: The IoT device that is integrated in the piece of furniture is able to monitor in real time if the seat is occupied or not.

b) Activity: As shown in Figures 3-5, the space has been designed and equipped with specific furniture and appliances to serve the respective needs or services. Hence, the following types of activities are assigned to subareas accordingly; leisure, working/studying using PCs, meeting, and dinning (see Figure 6).

c) Location: Each sensing device is unique and is attached to a specific seat that is part of a set (e.g., left seat of a double sofa that is 1 of 2 sofas assigned to a specific table; in other words, a specific seat in a table of 4 people). If the tables and chairs are mapped and assigned to devices in a unique way, then it is possible to identify the exact location of each device. For that reason, the following mapping pattern depicted in Figure 6 is developed.

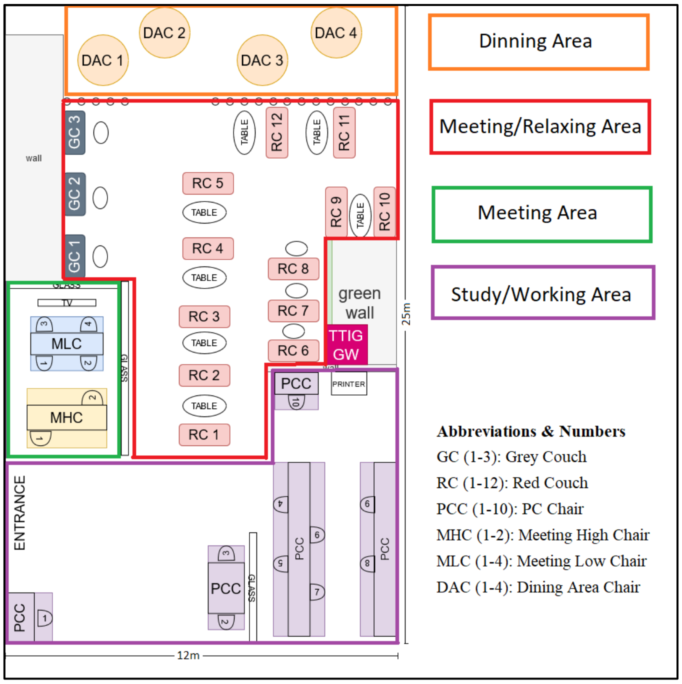

Figure 6 Staff Centre room demo site. The 4 subareas and their relevant activities.

Abbreviations and numbers are assigned to all IoT devices according to the physical characteristics of the furniture each device is attached to or the functionality of the subarea the furniture belong to.

C. *Practical and Methodological Challenges*

The main practical and methodological implications are related to the placement and distribution of the nodes and sensors.

The polymorphism of the physical environment (i.e., the building's structure and furniture) necessitate *custom interventions*, which may result to the need for additional resources (e.g., special technical personnel, equipment, tools, extra working hours, etc.). It also allows *intentional/unintentional obstruction* to take place, which may further result to wrong sensor readings or packet loss of data during wireless transmissions. Moreover, it may *negatively affect the accessibility and maintenance* of the IoT devices.

Aesthetics-related concerns arise when altering the current state of the physical environment (i.e., furniture, space) while attaching the IoT devices to it.

Inefficient positioning of the devices is also related to the Hawthorne effect, according to which, people are changing their behavior when they know that they are being monitored [30]. This may happen in case the end users can have continual visual contact with the sensors and the devices.

Operational dependencies that exist between different departments of the organization might also affect the deployment of the IoT devices (e.g., inefficient collaboration between IT services and Estates Departments).

D. *Ethical Considerations*

Technological developments, in general, are often confronted with obstacles that result not only in practical but also in ethical implications. Especially for digital surveillance of workplaces and open access or shared areas inside an organization, guarantees are needed that the technologies are cyber-secure and do not violate any data privacy regulations and legislation. Moreover, decisions must be made on the use of anonymized and personal data (if any). When it comes to data gathering, processing, and storage the acquisition of consent is of paramount importance. The methodological approach also needs to be vetted by the legal department of the organization so that all actions adhere to relevant laws and regulations (e.g., Human Rights Act, Lawful Business Practice, Interception of communication, and GDPR).

E. *Details of the Study*

The geographic region: In this work we consider one shared space in the Talbot Campus; namely the "Staff Center".

Research population: According to the room's capacity and the daily volume of use, approximately 200 people per day.

Sampling frame: People who are using the facilities of BU (i.e., staff members, students, and visitors)

Inclusion/exclusion criteria (with clear justification): All occupants are included as they are the subject of the research. Samples that are excluded from the study are items that may be placed on a seat (e.g., bag, laptop, helmet, etc.). These items are irrelevant to both aforementioned assumptions.

Unit of analysis: The Unit of analysis here is a Social artefact. i.e., Individuals' presence in buildings.

Attrition criteria as applied to individual participants: Attrition bias is not applicable as users are participating passively (normal behavior).

Early termination criteria for the study: Not applicable as the study is designed for continuous research purposes.

Expected timeline of the study, including a detailed description of when the intervention and data collection will take place: Regarding the first assumption, there is no specific timeline as there will be constant collection of data that will be processed in real-time to provide the campus users with continuous and real-time guidance. With regards to the second assumption, the timeline of the study should follow the academic calendar timeframe and its intervals. During teaching periods (the most active periods) of every year it is necessary to ensure uninterrupted, successful, and secure collection of valid data, while during breaks the data should be readily available and processed in order for the FM and CREM teams to apply the relevant action plans.

F. *Intervention Technical Details*

The technical details of the intervention with regards to the physical environment where the IoT devices will be deployed is common for both assumptions. Further analysis of the technical details on the device's hardware and the IoT network to be used are presented in section V. Technical details regarding data processing and visualization (e.g., via Big Data Analytics or Machine Learning methods) will be addressed in future work.

G. *Data Collection Methods and Procedures*

Data will be collected via IoT devices that will be able to monitor the occupancy of a seat via pressure sensors and that will be integrated accordingly in pieces of furniture. The devices will transmit their data wirelessly over the deployed IoT network at regular intervals or if a triggering event is detected. The IoT network will relay the data to a back-end to be stored and analyzed.

H. *Formulation of metrics to be used*

The use of the monitored space will be evaluated in the short term via the occupancy rate which is defined by the *occupied seats* over the *total seats available. Occupancy rate* (T_s)*, Total occupied seats* (T_s)*, Total seats available* (T_a)

$$O_r = \frac{T_s}{T_a} * 100 \qquad (1)$$

In the long term, appropriate statistical metrics will be used such as average, minimum, and maximum values of occupied and free seats over time, and occupancy rates for specific periods, (e.g., per day, week, month or year) and for each room, subarea and activity. More elaborate metrics will be identified by using Machine Learning (ML) methods following the VAM aims and objectives defined by the FM and CREM teams. While continually improving the occupancy assessment, the FM and CREM teams will be able to gradually improve the sustainability profile of the corresponding space.

V. ISUMS: TECHNICAL SOLUTION -DESCRIPTION

A. *ISUMS Architecture*

Figure 7 depicts the architecture of ISUMS. The network makes use of LoRaWAN and includes nodes and gateways deployed in a star-of-stars topology ensuring a secure and reliable bi-directional communication between the Nodes and the Network Server.

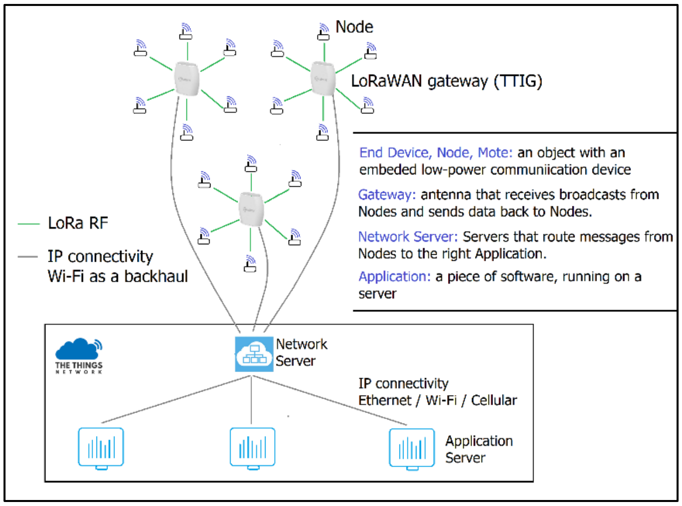

Figure 7 ISUMS Architecture

Messages are wirelessly broadcasted by the nodes (uplink) and then enter the sleep mode to save energy. Following, one or more gateways pick up the messages and forward their payload to the core network. Gateways are more powerful devices, compared to nodes, but typically they have no built-in intelligence. On the other hand, the LoRaWAN® Network Server (LNS) is the focal point of the LoRaWAN network as it is responsible for message consolidation, routing, network control, and Network and Gateway supervision [31]

B. *LoRaWAN Network Devices*

LoRaWAN is an LPWAN and as such it is primarily targeted towards outdoor applications requiring long distance IoT communication. As such, it is commonly not the technology of choice for applications comprising indoor environments. However, in use cases such as a smart University campus, the management teams will seek to minimize the number of different technologies and type of ICT infrastructure they will be working with; e.g. for achieving economies of scale in procurements or for developing technical know-how in certain areas. In this context, LoRaWAN was selected as the underlying IoT technology for ISUMS.

The main challenge posed by deploying LoRaWAN indoors was related to poor signal penetration through walls. While considering the results of the pre-analysis plan and the parameters listed above, few options were considered regarding the available LoRaWAN gateways on the market that would fit the purposes of ISUMS. All of them were products specially designed for indoor IoT applications. However, the handheld sized TTIG covers all the prerequisites; it comes at very low price (around £80.00), it is easy to install and configure, and covers all technical requirements. Furthermore, it is supported by The Things Network (TTN), which is used for the backend of the ISUMS's architecture, and guaranties high levels of interoperability between non-IP (LoRaWAN) and IP connections (Wi-Fi).

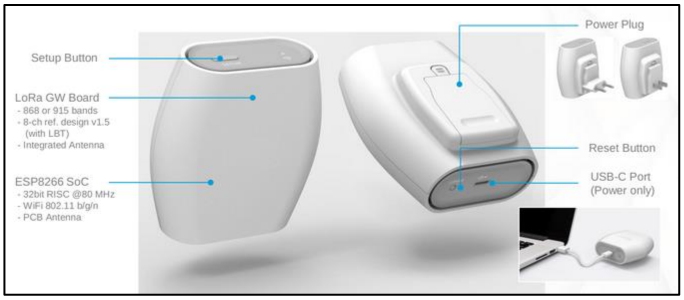

Figure 8 The Things Indoor Gateway (TTIG)

The SparkFun SAMD21 Pro RF is a single-board Microcontroller Unit (MCU) and serves as the core hardware component of the IoT end node. It comes at a relatively small size, supporting all the required technical capabilities and by simply closing the jumpers placed on the underside of the board it can broadcast in the LoRaWAN modulation scheme (863-870MHz in Europe). The board costs around £23.00 per unit.

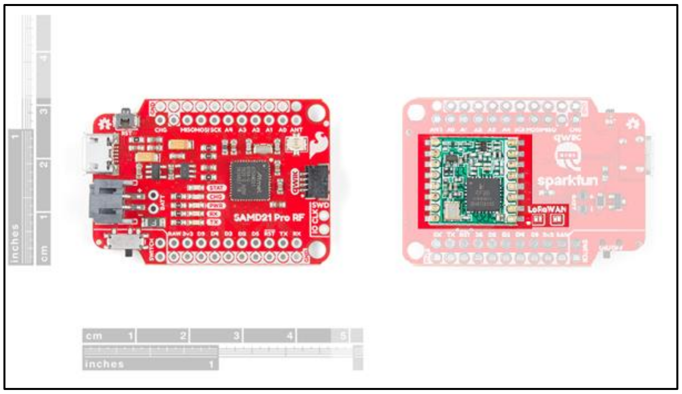

Figure 9 SparkFun Pro RF – LoRa, 915 MHz (SAMD21)

The sensing module for monitoring the occupancy of pieces of furniture is a Force Sensitive Resistor sensor. The FSR module would require to be integrated directly under the surface of the seating area, thus making its deployment somewhat copious. However, as the sensor would remain out of the sight of the end users, the installation would be robust and the monitoring process would be accurate, made this option more attractive than other options, such as the common PIR sensor.

Force Sensitive Resistors (FSR) are robust Polymer Thick Film (PTF) devices that exhibit a decrease in resistance when force is applied to the surface of the sensor. Since this sensor will act as a switch (no interest in weight measurements or posture analysis), if installed on each seat it would identify if a person were sitting on it or not accurately. This sensor also allows the identification of the time and duration of an occupied seat. The FSR 406 - square sensor comes with a force sensing range of 100g-10kg and it costs £8.60 per unit.

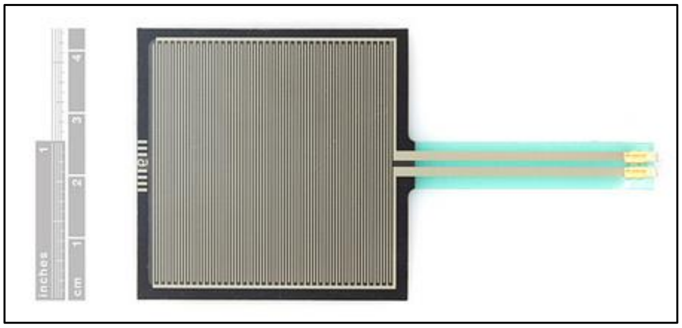

Figure 10 FSR 406 - Square

Complementary components of the end device include a plastic container, a solderable mini-Breadboard, headers, acrylic sheet 3mm, Amphenol FCI Clincher Connectors and Heat Shrink Tubing HSP2. The total cost for a complete IoT end-node is roughly £65,00 per unit.

Figure 11 depicts all the hardware components of a single ISUMS end device, including the plastic casing, battery and antenna.

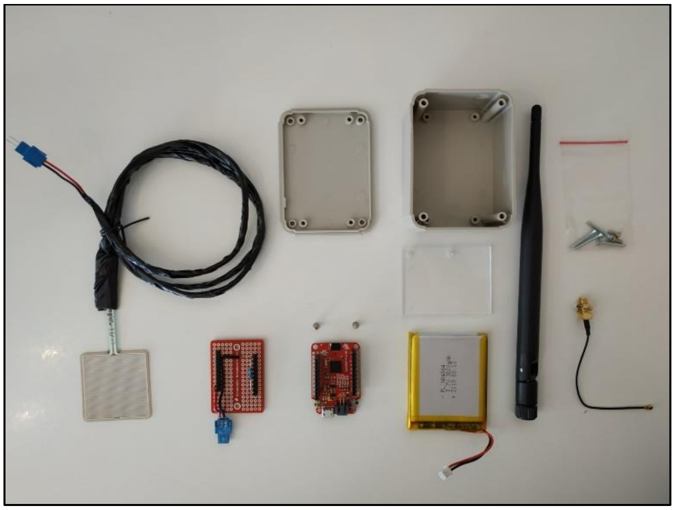

Figure 11 ISUMS end node's hardware components

The Arduino Integrated Development Environment (IDE) was used for device programming. To establish communication between the computer and the microcontroller, and to allow the code to compile, the respective drivers and libraries were installed to Arduino IDE following the SparkFun SAMD21 Pro RF hookup guide [32]. As per the instructions given by SparkFun in the Hookup Guide along with some additional information found in the MCCI LoRaWAN LMIC library [33], the TTIG gateway and the prototype end-device were registered to the "The Things Network" (TTN).

VI. ISUMS EVALUATION

For testing purposes, a seat pad is used where the prototype IoT end node is installed. For the actual implementation in the Staff Centre room, industrial designers should develop tailor-crafted solutions for each of the different furniture (e.g., chairs with wooden seat, office chairs, sofas, etc.).

Figure 12 The prototype ISUMS end node installed on an office armchair.

The Staff Centre room was divided into subsections according to their functionalities (see sections 4.2.1 and 4.2.2) which led to a node mapping pattern (i.e. GC[1-3], RC[1-12], MHC[1-2], MLC[1-4], PCC[1-10], DAC[1-4]) that reflects the individual sitting positions (Fig. 6). Thirty-five (35) sitting positions were mapped and tested for LoRaWAN connectivity, thus covering more than 90% of the currently available individual seats.

TABLE I. DATA RATES FOR EU433, EU868, AS923, CN780

Data Rate	Configuration	Bits/s (bandwidth)	Max payload
DR0	SF12/125Khz	250	59
DR1	SF11/125Khz	440	59
DR2	SF10/125Khz	980	59
DR3	SF9/125Khz	1760	123
DR4	SF8/125Khz	3125	230
DR5	SF7/125Khz	5470	230
DR6	SF7/250Khz	11000	230
DR7	FSK:50kbps	50000	230

The trade-off here is between data rate and the communication range, the further the distance, the higher the signal attenuation and higher the power consumption. Moreover, low data rate (DR0) means longer transmission times (SF12) which directly relates to less efficient packet exchange between nodes and gateways.

As distance is one of the main factors affecting connectivity, the gateway (TTIG) was strategically placed roughly in the middle of the room (see Figure 6 by the green wall). With a data rate of “SF7BW125” that keeps the power consumption and airtime low, the RSSI (Received Signal Strength Indication) and the SNR (Signal-to-noise) ratio were captured for every attempt of communication. As can be seen from the diagram in Figure 13, the RSSI values fluctuated around -40 (dBm). The same was true for the values of the SNR ratio with an average of 9.24 dB (see Figure 14). According to the analysis given in Table 2, these values indicate very good signal reception across the whole room.

Note that during deployment, vertical antenna polarization between nodes and gateway was guaranteed. Also, additional tests were performed on the same floor (ground floor) outside the Staff Centre room. Findings indicate that signal reception is still at acceptable levels in a radius of approximately 30-40 meters in open areas (i.e., reception hall), whereas in areas where more than one walls and other physical obstacles are present (e.g., study rooms, offices, etc.) the signal attenuates faster, and communication is lost. Finally, note that significant RSSI variations were observed within the network area, even for neighboring subregions (e.g., positions RC1 and RC6 in Fig. 6 and 13). This may be due to the indoor environment characterized by several sources of signal reflection (e.g., flat surfaces).

TABLE II. SIGNAL QUALITY EVALUATION

RSSI (dBm)	SNR (dB)	Conclusion
-120	-10	Very weak signal reception. The RSSI is almost at its minimum and the SNR is very low. It is likely that the packet loss rate is high. Installing extra gateways is advised.
-110	-5	Weak signal reception. The RSSI is relatively good but the SNR is low. When ADR is enabled, the SF will increase.
-110	5	Average signal reception. Both RSSI and SNR are good. The distance from the gateway is about average.
-100	-7	Average signal reception. Both the SNR and the RSSI are very low. The device is in the vicinity of the gateway.
-100	7	Strong signal reception. The end device is close to the gateway
-90	5	Strong signal reception. With an RSSI higher than -100 dBm and the device is likely in a range of tens of meters from the gateway.
-40	10	Very strong signal reception. The device is probably only a few meters away from the gateway.

As a conclusion, the TTIG gateway provides full coverage and robust communication covering the area of interest (i.e., the Staff Centre room), whereas additional gateways must be placed to strategic points to expand the coverage area to additional spaces.

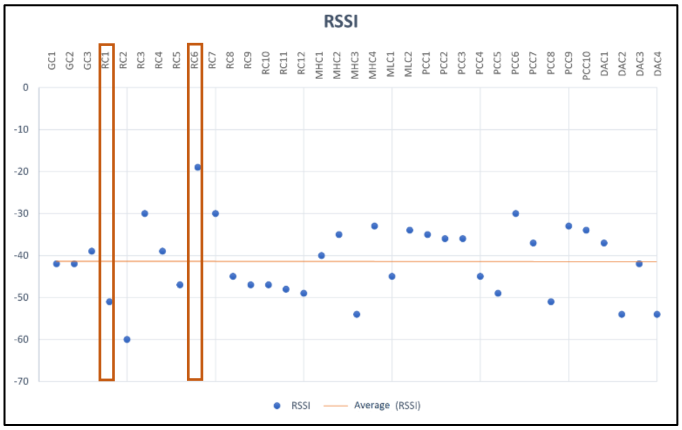

Figure 13 Network coverage measurements (RSSI)

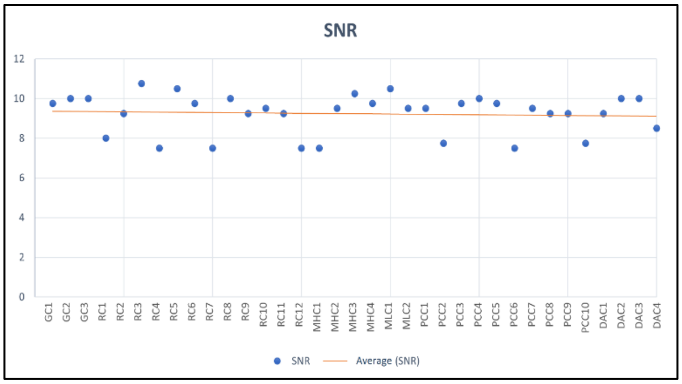

Figure 14 Network coverage measurements (SNR)

VII. FUTURE WORK AND RECOMMENDATIONS

Future work includes end-device adjustments and improvements (e.g., optimization of energy consumption, hardware protection using cryptographic chips and firmware read-out protection), development and deployment of 40-50 similar end-devices, migration from the TTN stack V2 to V3, the development of back-end data processing & analytics technologies, and the development of the software applications that will make use of the acquired data according to the use case assumptions presented in this work. Throughout these processes, the collaboration between the hardware/software developers and the FM and CREM teams of the respective organization that utilizes the ISUMS is of paramount importance. Also, the following recommendations for additional software applications that can take advantage of the same data ISUMS is collecting, promote the idea of applying CE principles on data usage.

Additional application areas are motivated by the Covid-19 pandemic and its after math. For instance, ISUMS could be employed to monitor whether the Built Environment facilitates adherence to social distancing guidelines. Additionally, end users could be informed accordingly on the occupancy of the space in real-time; e.g. if available seats are at a "safe distance" from each other. This enables a dynamic space management plan where instead of investing resources on removing seats to crate space in between, the social distancing rule is applied on-the-fly (i.e., depending on the use). Another application area comprises the integration of ISUMS to a smart Fire Alarm & Emergency Evacuation System in a way that this information in conjunction with all the other related parameters like access to emergency exits, distance from emergency exits, distance from the incident, and so forth, can increase efficiency and effectiveness of this system.

VIII. CONCLUSION

This work lies on the intersection of Circular Economy and IoT to support CREM and FM teams on developing decision-making and action plans towards sustainability enhancement in the Built Environment. Current trends, found in the literature, have been highlighted and thoroughly discussed, while end user behavior monitoring inside buildings has been identified as the primary step towards increasing building sustainability. In this context, we introduced ISUMS including an analysis and practical evaluation of LoRaWAN in indoor environments; the development of a Pre-Analysis Plan for a pilot case study in the Bournemouth University Talbot Campus; the development of a prototype IoT end-node to be used as a proof-of-concept; and finally, future work guidance pointing to the extension of ISUMS.

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