INTEGRATION OF SPATIALLY ORIENTED DATA FROM IOT TO FACILITY MANAGEMENT AND BIM

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ABSTRACT:

With the increasing complexity of buildings and their facilities, integrating IoT infrastructure with digital building models has become essential. This integration allows facility managers to make informed decisions using spatially oriented sensor data, creating a digital twin of the building for more efficient resource management and problem-solving. This contribution reviews various case studies that demonstrate the potential of IoT-driven BIM models, showcasing approaches to optimize thermal comfort, HVAC performance, and building monitoring using GIS data and CFD simulations. To streamline these systems, the article introduces a proprietary classification system for IoT sensors and actors. Lastly, the paper presents a unique approach to integrating this classification system with BIM while managing spatial data, further enhancing the efficiency of facility management.

1. INTRODUCTION

Industrialized societies today are swarming with complex initiatives, activities, and multitudes of control systems of various kinds. A concert held at a theater, a new construction site next door and the work of countless server rooms in a city consist of many interwoven and intricate processes that feed into the omnipresent complexity of the world. Consequently, effective management relies heavily on accurate measurement and assessment. To navigate this landscape of data, the integration of Internet of Things (IoT) and Building Information Modeling (BIM) have emerged as a powerful solution to streamline and optimize facility management.

IoT refers to a vast network of interconnected self-configuring nodes (things) that exchange data, analyze information, and coordinate actions to improve industries' efficiency and deliver societal benefits (Botta et al., 2016; Ghiaci, Ghoushchi, 2023).

Furthermore, the Circular Economy (CE) approaches are increasingly attractive for businesses both in the European Union, where its principles are at the forefront of political vision, and in the emerging economies alike. The allure of the CE is explained by its ability to generate value by increasing resource efficiency while simultaneously decreasing adverse environmental impact. So much more appealing is the CE-IoT synergy that maximizes resource utilization—energy resources above all—and extends useful life while fostering competitiveness and innovation across various sectors (Askoxylakis, 2018; Patwa et al., 2021; Ghiaci, Ghoushchi 2023).

Consequently, IoT systems are most often regarded as a way to optimize energy production and consumption. As Sadeghi-Niaraki's study shows (Sadeghi-Niaraki, 2023), there are 8 distinguishable main categories in IoT review papers: IoT applications, the types, technologies, data, communication networking, IoT communication Protocols and development. In IoT applications the papers are generally published on infrastructure, community, consumers/users and environment. Finally, the infrastructural IoT applications review papers concentrate on the following fields of application: geomatics, utilities, transportation, industry (i.e., agriculture, manufacture) and energy sector. Generally, the most cited articles are written on the interaction between IoT systems with grid power systems as is the most cited article in the field. More often than not, the research in this area is focused on the ideas of smart grid and smart home, the latter being included in the notion of the former (Stojkoska, Trivodaliev, 2017).

However, in circular business models, two primary IoT-specific challenges exist: (1) lacking structured data management processes to guarantee top-notch data collection and analysis, and (2) the intricate process of creating software and hardware for IoT-enabled products and components that can maintain interoperability, adaptability, and upgradability as technology advances (Ingemarsdotter et al., 2020).

In facility management, the biggest leap towards overcoming these problems was a wide-spread implementation of BIM software. BIM is a collaboration tool for integrated design and construction management, using multidimensional models to enable real-time collaboration and informed decision-making among stakeholders (Lester, 2014). It is also a tremendously useful building management system. As such, it aggregates data from various sources in a structural way and serves as a ready-made software for IoT-based facility control with a use of geospatial data. Nonetheless, it can be stated that there's a palpable need of additional classification systems to work with various producers of the IoT-related equipment.

Hence, the goal of the article is twofold: to showcase the effectiveness of BIM-driven IoT systems in buildings that use

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spatial data and to present our own classification system for IoT sensors and actors that helps us keep track of them. Together they offer a viable solution to the existing challenges in CE-IoT economy.

2. CASE STUDIES

The number of publications on IoT-related topics has increased dramatically over the last 10 years, rising from under just 20 review papers per year before 2015 to more than 800 review papers per year in 2021 based on Scopus and Web of Science databases. That corresponds to a 40-fold increase. As was indicated before, in this evolutionary field of development and innovation we can consider the topic "IoT Applications", which roughly coincides with case studies of real-world applications, as the leader (Sadeghi-Niaraki, 2023). In this article we will walk through articles on the smart campus in Zaragoza, BIM-IoT-Thermal comfort model "My Comfort", a full-fledged digital twin BIM model from Norway, IoT-aided CFD simulation in a BIM model of a building in Hong-Gong, a take on combining BIM and IoT from Italy and minuscule IoT sensors "TinyNode" from Finland.

2.1 Zaragoza University Smart Campus

It is fascinating what an IoT system can accomplish without needing BIM and spatial data in standalone projects, where the placement logic of sensors is guided by the experience of building occupants. Such projects enable us to assess the effectiveness of a barebones IoT implementation and compare it to BIM- or spatial-data-driven solutions. A university campus in Spain serves as one such example.

The concept of smart campuses is a hot topic in regions where it is cold in winter and hot in summer. One such region is Aragon in the north-east of Spain. The capital of Aragon, Zaragoza, and the local university there have long been tackling issues related to HVAC systems as Garcia-Monge and his colleagues describe in their smart campus case study (Garcia-Monge et al., 2023). In fact, HVAC most often consume more energy than anything else in large buildings.

Therefore, in order to reduce energy consumption, the university management has set up an IoT system with its own software "senzoriZAR". "SensoriZAR" consists of a variety of devices (meters, electronic door locks, cameras, fire alarm system, etc.) connected to management systems that pre-process and forward data to the back-end of "sensoriZAR", and from there that data is distributed to users of the proprietary application.

Carbon dioxide (CO2), light pollution, humidity, temperature, room occupancy and air quality, among other things, are measured on the university campus. A total of 90 sensors connected using the LoRaWAN protocol (Aranet 4 Pro, Siemens QPA1004, senseCAP EU868, Dragino LHT65 and a couple of custom sensors) were used. Even though this implementation does not collect geographic data and does not use it in data processing, there were certain spatial considerations in place. When choosing the location for the sensors, the simplicity of battery replacement was preferred. NDIR sensors were used to measure the carbon dioxide content in the air, which, according to the authors, show very high measurement accuracy. The university has managed to reduce its overall electricity consumption by about 40% using a not too complicated but custom-made IoT system.

In the next sub-chapter we are going to compare "sensoriZAR" implementation with a much more complex dynamic system "My Comfort".

2.2 My Comfort Software

"My Comfort" is a proprietary software created by Kanna and her team from the Moroccan College of Geomatics and Surveying Engineering (Kanna et al., 2022) that links BIM, IoT and thermoregulatory behavior—expressed as thermal preference—of building occupants. The system in question, similar to "SensoriZAR" from the previous sub-chapter, was designed to reduce energy consumption through smart control of the HVAC system. In the case study it was tested in an office building. The result was expected to reduce energy use by 75 to 95% in the office building which is obviously much more effective than "sensoriZAR" even though both case studies took place in hot climates.

The office building was equipped with humidity-temperature sensors. This implementation is based on an ESP32 microcontroller and DHT11 humidity-temperature sensors, which are placed in close proximity to the office workers' desks at a height of about 1 m above the floor. Digital copies of the sensors were then created in the BIM similar to another case study (Valinejadshoubi et al., 2021). Consequently, their outputs are sent to the "My Comfort" software's backend. "My Comfort" utilizes a BIM model of the building to create a regular three-dimensional grid, which is divided into voxels. These voxels allow values to be stored within the grid. This allowed for two things: firstly, it served as a digital twin by extrapolating temperature and humidity values in the voxels with a sensor to voxels without one; secondly, each voxel may be supplied with a feedback from persons providing a voxel-specific thermal-comfort level.

The former benefit of the system actually encompasses the underlying hardware and software. Grieves and Vickers defined the concept of "Digital Twin" (DT), describing it as a comprehensive dataset that represents an asset from its fundamental structure to its most precise functionality (Grieves and Vickers, 2017). Modern IoT systems, BIM, machine learning or artificial intelligence — all come together to create a digital twin of the building. The use cases of such dataset are endless.

The latter benefit of the system is a rather intricate part as the office workers were allowed to quickly and easily share their thermal sensations, or personal vote (PV), through an app on their phone. The was then processed in real time with a deep-learning model to calculate the so-called predicted mean vote (PMV) which characterizes thermal sensations of majority of the building occupants and its correlation to PV. This data was simultaneously used to forecast the average building user's thermal experience and adjust HVAC systems to keep the majority of the building occupants content while constantly measuring temperature and humidity in the background.

Thus, to summarize, the "My Comfort" implementation was user-oriented in a sense that it used constant users' feedback to train the machine learning algorithms to control HVAC in such a way that would be both pleasant for the office workers and resource-efficient at the same time. The system relies on a proprietary REST API and a database to collect data and further send them for analysis. Altogether, "My Comfort" is a patented software designed to reduce energy consumption through intelligent control of HVAC systems by linking BIM, IoT and thermal behavior of building occupants.

However, there is more DT potential to harness in IoT-driven BIM facility management as will be shown in a upcoming case study from Norway.

2.3 I4Helse and Tvedestrand School Buildings Case Study

A combination of real-time sensor readings and occupant feedback may be integrated into the BIM environment directly for a more thorough and precise assessment of a building's performance as shown by the Hosamo's study (Hosamo et al., 2023). Recently, they have developed an intricate DT framework to streamline decision making for facility managers to maintain a comfortable environment inside the buildings. The framework helps to identify the source of possible physical discomfort in a HVAC system based on occupant feedback, to notify facility managers about upcoming equipment maintenance, and to solve space inadequacy problems (i.e., issues with lighting, noise pollution, uncomfortable temperature, air quality, space sufficiency, layout, etc.) — all that through a custom Revit extension. The DT framework was successfully tested in I4Helse university building and Tvedestrand school located in Norway. Both buildings were fitted with sensors to keep track of their performance and they had HVAC units installed consisting of rotary heat exchangers, bypass, heaters and chillers, and various valves, fans and dampers.

The data from the sensors was collected and sent directly to BIM. The user satisfaction data was evaluated at various points in the buildings and included in a probabilistic machine-learning model in Dynamo to pinpoint comfort and discomfort factors. Dynamo serves as a visual programming platform compatible with BIM applications like Autodesk Revit (Seghier et al., 2017) making it very easy to output the results straight to the BIM. Simultaneously, the BIM model collected data on factors like HVAC controls, design flaws, occupancy rates, and environmental conditions, which was then utilized in a Bayesian network (BN) model. BN model allows making probabilistic forecasts about a building's condition by observing the state of its components. The DT framework's goal was to provide a comprehensive insight into the buildings' performance, facilitating improved decision-making and building operation optimization.

Authors illustrated their work by recounting a solved HVAC issue tracing it from the initial complaint down to the discovery of a leak in a system. The occupants of one of the rooms complained about his comfort issues. This complaint was loaded into the BIM model and a list of relevant mechanical components was generated. Then the algorithm analyzed HVAC system by comparing, for example, the needed cooling load to the cooling capability of the system, which it was able to do because of the thought-through sensors' placement. Finding no fault in the interior workings of the HVAC system, the algorithm concluded that the problem's source is in the outside unit. Upon inspecting the unit the facility management team discovered the leak and fixed it without going to the location where the occupant submitted his complaint. Overall, the authors noticed a 35% reduction in the time required to resolve a HVAC issue from the moment it appeared in the Revit plugin.

By being complete, a good DT-IoT framework is pervasive and accounts for a lot of nuance in facility management. However, an IoT-driven BIM model doesn't have to help to upkeep the building. One of the less obvious use cases of such a complex model is conducting computational fluid dynamics experiments to improve HVAC, space adequacy or sensors' placement.

2.4 IoT-BIM Model Used for CFD Simulations

An interesting study from Hong-Kong (Cheng et al., 2022) investigates the optimization of temperature and CO2 sensor placement in a multi-zone indoor environment with limited field measurements. The objective was to provide a methodology for optimizing sensor placement in a typical office floor for thermal comfort and IAQ (indoor air quality) monitoring using BIM and CFD technologies. The study takes into account different seasons, MVAC (mechanical ventilation and air conditioning) system settings and occupancy scenarios when optimizing the placement of sensors. Using a genetic algorithm (GA) and machine learning, sensor placements were generated that met LEED (Leadership in Energy and Environmental Design) coverage requirements, with more than 70% of the areas with significant temperature and CO2 fluctuations located within the sensing range of the sensors.

The results of the study showed that the corridor has the highest number of sensors placed per square meter within the optimal sensor distribution for both temperature and CO2. This implies that more sensors should be placed in areas without an MVAC system installed because more significant fluctuations in temperature and CO2 are observed there. This finding is unusual because most ventilation designs and operations do not consider the corridor as a thermal zone that needs to be conditioned and monitored. However, the simulated results suggest that the corridor is an important area for sensor monitoring because it can be significantly affected by ventilation systems in adjacent areas. The data collected by the sensors installed in the corridor reflect the overall thermal comfort and IAQ levels, as corridors connect all other rooms on the floor.

The proposed methodology in the study considers CFD results at the floor, nose and ceiling level, including all areas that occupants typically visit. The study also discovered that the number of sensors proposed by the standards is insufficient for IAQ monitoring, with at least 20 sensors needed to capture significant fluctuations. The generated sensor deployment with 20 sensors captures at least 75% of significant changes in temperature and CO2 concentration on the floor.

Without the IoT-driven BIM model, the CFD simulation would not have been possible in the first place. This further strengthens the notion that BIM is a universally beneficial tool for buildings. However, the model should not limit itself to data from sensors, as incorporating external data could arguably enhance the existing IoT system.

2.5 IoT-BIM Model with External Data Usage

A case study of smart energy management was carried out in Italy (Bottaccioli et al., 2017), focusing on the combination of Building Information Models (BIM), Geographical Information Systems (GIS), weather forecasting, and IoT data to simulate energy consumption in a primary school. The aim was to reduce energy waste and CO2 emissions, moving towards a more sustainable use. The research centered on blending two categories of information: communicating and processing physical and environmental data enabled by IoT devices and communication protocols, as well as the creation of digital repositories of buildings and neighborhoods facilitated by BIM. This integration allowed for the visualization of building energy consumption information in real-time and the evaluation of building energy performance through energy modeling and simulation, using field data and actual weather conditions.

The study implemented sensors in similar rooms within the building and at the shadiest point outside, enabling data transfer to the BIM. Such a software architecture can be utilized to create better energy models, detect undesirable or inefficient energy behavior, and evaluate building performance (Bottaccioli et al., 2017).

However, not all IoT systems should equally demanding as mentioned case studies. One of the advantages of Internet of Things in general is its ability to adapt to every scale.

2.6 TinyNodes Sensors

A case study conducted in Finland (Maatta et al., 2017) demonstrated the use of small TinyNodes sensors placed in an apartment and HVAC system to measure indoor air quality.

The study proposed a solution to overcome the problems related to indoor air quality and building construction caused by HVAC systems operating with default settings and without installed automation. The solution relies on a wireless indoor environmental monitoring system and IoT sensors control concepts developed at VTT (a well-known Finnish university) combined with advanced IoT technology and a cloud-based computing system. The TinyNodes are as big as a coin, making it possible to use it both outside and inside HVAC systems. The IoT solution provides not only control, but also monitoring and maintenance-related information for the building's equipment. The study concludes that the proposed solution is an effective and innovative way to optimise indoor air quality, and has been tested and verified inside VTT's test environment and with some customers (Maatta et al., 2017).

3. INTEGRATION OF IOT INTO BIM AND FACILITY MANAGEMENT

Having a BIM model helps to structure data management and to maintain some degree of interoperability and scalability. However, while designing one, a good classification system for IoT sensors and actors might come in handy. In this chapter, we will describe a proprietary classification system tailored specifically to the needs integration of IoT data into facility management systems.

3.1 Proprietary classification system

A good classification system should help an IoT engineer to distil the important characteristics of a device in stock of a company into a coded expression that would relay its functionality in a concise and straightforward manner. This classification should be agnostic to secondary information (e.g., the manufacturer, the price, the amount in stock, etc.) and focus on essential parameters (e.g., measured values, working temperatures, accuracy, etc.). As a result, an IoT specialist can design an IoT system for a building without having to deal with non-essential details that are then outsourced to a procurement department.

In the proprietary classification system each sensor gets assigned an alphabetic identifier. The identifier is gradually assembled out of short-hands for categories. As the categories are hierarchal, the identifier has a strict succession of symbols. The first overarching criteria and simultaneously the first letter in the alphabetic identifier is whether a device is a sensor ("S"), a detector with binary output ("B"), a hub ("H") or a miscellaneous accessory ("D"). After that the classification branches out (Figure 1).

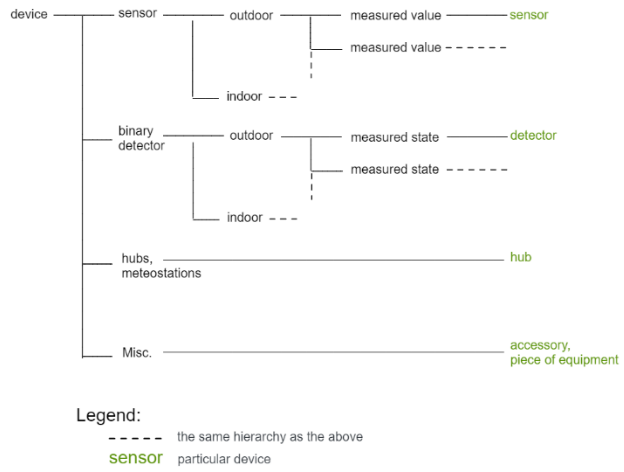

Figure 1. Sensor categorization schema.

Sensors and detectors could be used indoors as well as outdoors ("In" and "Ex" in alphabetic identifier accordingly) based on their working conditions. The last step of the classification is a list of all values or states a sensor can measure in brackets.

For example, an NDIR module for CO2 ("CO2"), temperature ("T") and relative humidity ("RH") measurements would be assigned the following identifier: S-In-[T-V-CO2]. A Sonoff Zigbee PIR - SNZB-03 motion detector ("MD") is abstracted to B-Ex-[MD]. Both of those sensors might be substituted for their analogue without hindering the project.

In conclusion, the proprietary classification system for integration of IoT data into facility management systems effectively simplifies IoT sensor and actor representation in BIM-driven case studies. By focusing on essential parameters in a hierarchical structure, IoT engineers can design building systems efficiently. The system's adaptability to various devices and its flexibility for substituting sensors with similar functionality make it a valuable tool for both IoT specialists and procurement departments, streamlining communication and decision-making in IoT-driven BIM projects.

An important feature of proprietary classification systems must be correspondence to a generic standardised classification system used in BIM processes and a converter between the two classification systems. A generic standardised classification system for BIM processes by its nature does not achieve the detail of a proprietary classification system and for specialised specific purposes may not be sufficient and therefore the use of a proprietary classification system is desirable. However, for the transfer of data within BIM processes, the proprietary classification must be linked to the generic classification so that all data is clear and legible when transferred, which is one of the main objectives of implementing BIM processes.

One of the classification systems used for BIM processes is, for example, the Construction Classification International (CCI) classification system, developed especially for the consistent transfer of general object data in BIM processes. The classification system itself has five facets and each object can be classified according to each facet. The facets include building entities, built spaces, functional systems, technical systems, components. Some of the phases are hierarchical and multi-level. The classification code consists of several letters from which the hierarchy classification can be derived.

For example, the IoT sensors can be classified in the fifth facet – Components. There is a classification code for "Multi-sensor" with [BUA] code. This sensor is usable for microcontrollers where multiple sensors are placed. But, this classification does not give any information about which sensors are there places and what the sensor can be used for. From [BUA] code, it is possible to read that it belongs to the classification branch [B??] – sensing object and [BU?] – multi-quantity sensing object. In the CCI classification system, there are also classification codes for distinct sensors, e.g. [BTA] – temperature sensing object with scalar output. This object belong to the hierarchical category [B??] – sensing object and [BT?] – temperature sensing object. The CCI classification system is usable for classification of the objects in BIM model to distinct and classify object from other construction or technical object in BIM model but is not sufficient for abstract designing the IoT sensor. Then, the proprietary classification is necessary to use.

3.2 Integration to facility management

Nowadays, it is important to implement the data from IoT to facility management software to complete the complexity of building data in order to create an online digital twin of the building. For efficient property management, it is no longer desirable to keep IoT sensor data separate from other building management data, as all data is interdependent in building management processes. Since building management is a participant in BIM processes, the continuity is thus made to BIM processes as well.

The integration of IoT sensors data will then help administrators make faster and more efficient decisions, for example when regulating heating or cooling (temperature sensor, heater, boiler), when monitoring the working environment in buildings and compliance with hygiene regulations (monitoring of CO2 in the air, monitoring of volatile substances, temperature and humidity) and will help increase security in buildings (door and window sensors, control of lights, movement). A very important element is also the acquisition of current data from measuring devices such as electricity meters, gas meters, colorimeters or water meters. The data from the IoT sensors at these measuring stations can be directly linked to the already maintained data in the building management software.

3.3 Spatial orientation

There is a significant importance of spatial orientation of the IoT sensor data. Every sensor is physically placed somewhere in the building. Using geodetic techniques, it is possible to determine the exact location of the sensor in building coordinate system and implement the position of the sensor to the 2D or 3D geometry of the facility or building. Spatial orientation and implantation of sensors to the drawing of the building offer much efficient presentation of the IoT data for the facility managers or users of the facility management systems. The presentation of the data in 2D and 3D models offer much faster understanding of the information when compared to the text and numerical data sheets. When an event is detected by a sensor (e.g. movement in an area of the building), the user immediately see where the movement is happening. The data can be visualized differently by different geometrical shapes (points, polygons, lines) and the value can be represented by colour, size, note, animation, etc. The spatial orientation of data from IoT sensor also offer interpolation of data between the sensors. The data are distinct but by an interpolation, the user can see the probability of values in selected areas between and observe important spatial link.

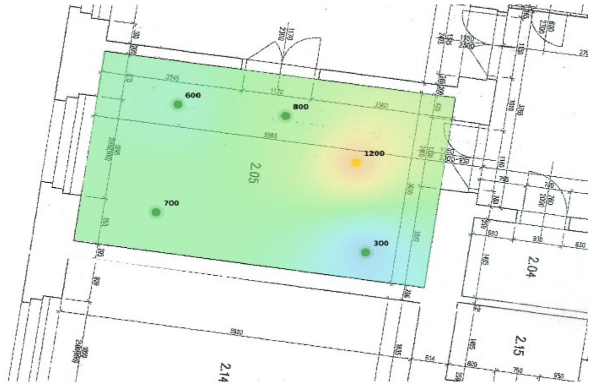

Figure 2. IDW interpolation of IoT sensor data within a selected room.

The need of integration facility management processes, BIM processes and their standardizations and IoT spatially oriented data was reflected by a project "BIM – FACILITY MANAGEMENT II - Development of modular IoT blocks for the digital twin of the building". In this project, was developed a software which fulfil all the mentioned requirements.

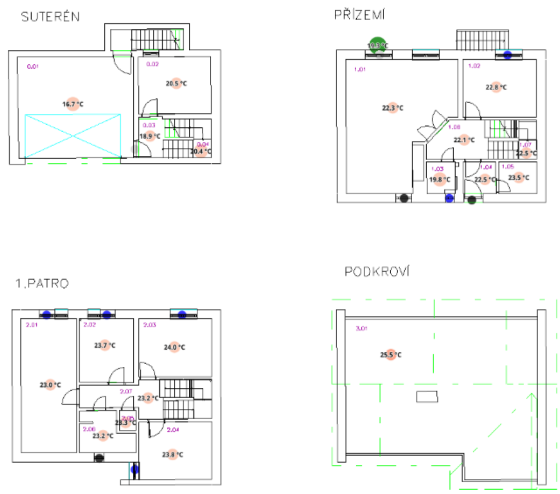

Figure 3. Software for facility management and BIM and spatially oriented IoT sensor data.

4. CONCLUSIONS

In the first part of the contribution, we have explored various case studies from around the world to demonstrate the synergy between IoT and BIM, enabling adaptable, scalable, and effective building-related data management and utilization. We examined how an IoT system combined with proper non-BIM software can achieve notable reductions in a smart campus's energy consumption. We also discussed the added value of BIM when incorporating occupants' thermal behaviour, which can nearly double the savings with the "My Comfort" approach. We looked at how the DT-BIM model streamlines facility management in Norway, the application of the model for CFD studies in Hong Kong, the enhancement of IoT control over HVAC systems with external GIS data in Italy, and the realization of an IoT system as small as a 2-euro coin. These case studies demonstrate how a well-tuned BIM model can contribute to reaching Circular Economy (CE) goals by effectively utilizing spatial data in buildings. However, to design such a system, engineers should focus on the most critical aspects without getting distracted by irrelevant details (e.g., a sensor's manufacturer or a specific model). IoT-oriented companies should implement a classification system that abstracts away most details that may hinder the achievement of objectives. This system should be universally applicable to a wide range of projects and versatile enough to accommodate changes in manufacturers without requiring significant alterations. In the second part of the contribution, proprietary classification is presents. The proprietary classification is needed for abstract design of the IoT systems inside or outside of the building. Every proprietary classification should be linked to the general standardized classification. In this case, the proprietary classification is linked to CCI classification which is generally used for all the structural and technical objects in BIM models. Spatially orientation of IoT sensor data brings for the facility managers many benefits. The data from IoT are much more understandable, it is possible to visualize them in 2D and 3D geometry, and then the users have more efficient control over the facility management processes. The spatial orientation of the IoT sensors also offers a possibility to interpolate data and get also an information about the selected surrounding.

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