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A framework for integrating BIM and IoT through open standards

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ABSTRACT

The built environment provides significant opportunities for IoT (Internet of Things) deployment, and can be singled out as one of the most important aspects for IoT related research. While the IoT deployment in the built environment is growing exponentially, there exists a gap in integrating these two in a systematic way through open standards and systems. From technological perspective, there is a need for convergence of diverse fields ranging from Building Information Systems and Building Services to Building Automation Systems, and IoT devices and finally the end user services to develop smart, user oriented applications.

This paper outlines the efforts to develop a platform that integrates the built environment data with IoT sensors in a campus wide, web based system called Otaniemi3D that provides information about energy usage, occupancy and user comfort by integrating Building Information Models and IoT devices through open messaging standards (O-MI and O-DF) and IFC models. The paper describes the design criteria, the system architecture, the workflow and a proof of concept with potential use cases that integrate IoT with the built environment. Initial results show that both the end users and other research groups can benefit from such platforms by either consuming the data in their daily life or using the data for more advance research.

1. Introduction

Recent advances in technologies such as Internet of Things (IoT), wireless sensors, data processing and analysis, and Building Information Modelling (BIM) have the potential to transform how we interact with the built environment and improve the experience for end users and service providers [1–7]. The IoT devices and sensors are increasingly being deployed in the built environment and industrial applications. The number of connected devices have already overtaken connected human beings and are estimated to be around 9 billion. The sensor nodes are being deployed in various application areas such as the industrial, transportation, health and wellbeing, building automation, automotive and retail. The number of sensor installation is increasing at an exponential rate and some estimates suggest that there will be around 50 billion connected devices by 2020 [8].

As majority of the IoT devices are deployed within the built environment, the integration of built environment information and IoT becomes a prime challenge [5,6,9,10]. The built environment represents almost all aspects of human life, from healthcare to education and industries, where the field of BIM is rapidly expanding as an information delivery and management platform. BIM models are used across the entire project lifecycle including design and construction to operations and maintenance [11,12]. With the emerging popularity of the BIM platforms, there is an opportunity to leverage this technology so that it can be used to build open platforms that synchronise with diverse information sources such as wireless sensors and building automation systems. However, there is a gap in research in integrating built environment data with IoT standards that shows tangible open systems which are built upon open standards. The need for open standards become acute due to plethora of protocols and information exchange standards being used in both the built environment and IoT domains [13]. Moreover, the IoT domain is siloed with many researchers highlighting the need for cross cutting applications built from user centric perspective. There is also a growing consensus that future "smart" applications should be more human centric and support bottom up innovation rather than being technology centric and supporting top-down decision making. This research attempts to address this gap by providing the details of a proof of concept development that a) integrates built environment and IoT data; b) provides tangible, intuitive and open user interfaces and c) is situated in the real-world rather than being lab based. One of the motivations behind this study is to support distributed, cross cutting and bottom-up innovation by supporting both consumption of data provided by the system and development of applications and further research by utilising the APIs (Application

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Programming Interfaces) provided by the platform.

The paper begins by providing a background on the key technologies followed by the design rationale that explains the main factors that influenced the design of the proof of concept and the underlying framework. A description of the system architecture follows that outlines the main components of the system. Subsequently, the proof of concept implementation, Otaniemi3D is described in detail followed by a real-life use case, discussion and conclusion.

2. Background

The field of built environment is plagued by information silos and lack of standardization that affects the information flow [3]. The industry which touches upon almost every aspect of human activity, is one of the most important at both the micro (things, spaces and buildings) and macro levels (campuses, cities, and regions) for IoT deployment [7,14]. Where context is important for almost all IoT deployments, spatial nature of the built environment provides a natural and important platform that plays an important role there [5,6,10]. As a major platform emerging to host built environment data, BIM is an important technology to consider from IoT integration perspective. This section provides a state-of-the-art review in the area of BIM-IoT integration, Open standards within both BIM and IoT domains and the IoT deployment.

2.1. BIM and IoT

BIM now extends itself to cover many technological advances the industry is witnessing and is the natural interface for IoT deployment [11]. Several researchers have started to explore the potential synergy between these two platforms. There has been research that demonstrates the usefulness of IoT in breaking traditional silos in the built environment for the entire lifecycle, from design to construction to handover [16].

Teizer et al. [17] have proposed to integrate BIM data with IoT sensors, with a focus on making available performance, environmental and localisation data of workers in an indoor work environment. The goal of the research is to create a safe job site where information integrated from several sources such as production control and BIM can be synchronised with IoT sensors (lighting, proximity, etc.) to provide real-time feedback to workers. The researchers use off-the-shelf BIM technologies along with readily available Bluetooth beacons and RFID sensors to integrate BIM and IoT information sources. Rowland [6] proposes gamification as an entry point in integrating BIM and IoT, where the author proposes to bridge the vertical silos of BIM with the horizontal silos (or information flows) of IoT along with several use cases including wayfinding, spatial and context awareness and above all persistence of data for the project lifecycle. Alongside gamification, the author also puts forward the use of Augmented Reality to interact and visualize BIM and IoT information.

On a macro scale, Isikdag [10] conceptualises the integration of BIM and IoT in order to develop a GIS based city monitoring or management application framework. The author proposes to integrate information from physical IoT sensors with “virtual sensors” that represent BIM objects and their state (which can provide contextual and spatial information) through RESTful APIs.

From the literature review it emerges that the BIM and IoT integration research is in nascent stages where most proposals are at a conceptual stage. Except for Teizer et al. [17], none of the other research has developed/demonstrated any real-world applications or proof of concepts. It should also be noted that the aspect of open data and open communication standards has not been addressed sufficiently within the domain of BIM and IoT integration.

2.1.1. Open standards, BIM and automation

The fields of BIM and IoT are mired by proprietary file formats and closed ecosystems where information is still not shared openly amongst stakeholders [3,13]. BIM still remains a tool for the experts, and the information that can be used to improve the quality of life of the inhabitants hardly ever reaches them [6]. Within the subdomain of building management systems, which at the moment is the “low hanging fruit” from IoT deployment perspective since it already hosts majority of sensor deployments, there exist plethora of protocols and standards such as Zigbee, KNX, BACnet, LONWorks, DACI, Mobus, oBIX, OPC, etc) [3]. Achieving integration and developing user interfaces that improve the quality of life of its inhabitants remains one of the biggest challenges for IoT deployment in the built environment.

2.1.2. Visualization of spatial information in real-time

The quest for 3D BIM real-time visualization arises from the communication needs between various actors in engineering, construction and architectural businesses. A 3D visualization offers a natural representation that is useful in a range of applications along the design and construction processes. As a mediator of various data sources, an integration phase is required, typically collating CAD, BIM and GIS data sources to a multipurpose platform [18]. However, as the related data sets are typically very complex, real-time visualization thereof has become a severe challenge, easily exceeding the capacity of the computer [19]. The hopes often lie in future hardware; unfortunately, even the latest hardware always seems to become overloaded [20]. Hence, designers are forced to split the model to smaller parts. Despite this, commonly used software tools for BIM visualization would still either fail to load the 3D data or be unable to render it in real-time, unless the model is further remodelled and simplified [21]. For a mobile case, the situation becomes considerably worse due to the lack of resources [22]. The software engineering approach of the building walkthrough case has also been suited for large scale mobile urban visualization. In this case, it was shown that an improvement of two orders of magnitude can be reached without sacrificing model detail, achieving interactive rendering rates for otherwise too complex a model [23]. This kind of approach has not yet been applied to the BIM case.

2.2. IoT standards

As a rapidly growing area, IoT has become a technological focus for academia, industry, and even government organizations [8,24]. The IoT envisions a world of heterogeneous objects uniquely identifiable and accessible through the Internet [25–27], the whole forming a dynamic global network infrastructure with self-configuring capabilities. Nonetheless, IoT is entering a new phase with an increased focus on how to avoid the continual emergence of vertical silos, which hamper developers to produce disruptive and added value services across multiple platforms and sectors (data is “siloed” in a unique system, cloud, domain, and stays there). This vision of interoperability requires the mastery of protocols and standards to leverage system interoperability due to the large number of products, platforms, and competing applications that coexist in the IoT [16,28,29]. In lack of standardized solutions, it is likely that a proliferation of architectures and identification schemes will develop side by side, each one dedicated to a particular or separate use, which will lead to the fragmentation of the IoT [27,30]. At the time of writing, there are more than 250 reported IoT platforms available on the market [31].

2.3. IoT deployment

Most IoT deployments remain expert driven and cater to specialised use cases. Also, majority of sensors due to their inherent nature are hidden away from human interaction, which in turn make them an area reserved for top-down innovation. The IoT domain in general and its deployment areas such as Smart Cities have come under criticism for being top driven and self-congratulatory [32]. There is a growing concern that the entire area is driven by corporates, where greater societal needs and benefits are neglected. While the hype has certainly been created, there has been too few examples of real-wold, bottom-up innovation [33,34].

Researchers have realised the potential of campuses as rich test bed for IoT deployment. This is as campuses, University, School or Organisational, are a highly dynamic environment and provide excellent opportunities for active participation of researchers and students to develop innovative solutions and use cases for a developing technological area such as IoT [35–37]. However, such opportunities are also somewhat restricted due to point wise implementation of proprietary technologies that do not provide open interfaces [38]. Also, researchers have criticised that previous smart campus deployments have mainly been conducted in a lab based environment that provide limited potential to engage with real life users [4].

3. Otaniemi3D –core framework

At the outset, a three way challenge is addressed by this research, i) the integration of built environment data and IoT sensors; ii) ensuring that open standards are used in deployment and integration of both IoT and BIM standards; iii) developing application areas to demonstrate the potential of this integration through real-world applications. This section provides a framework to tackle this challenge and describes: (1) the design rationale, (2) system architecture and (3) the technical details of the core components, i.e. IoT devices, Standardized Web-API and BIM Service Frontend.

3.1. Design rationale

The main aim of this research is to connect spaces/buildings with the data they generate through IoT devices with people living/working in those spaces as shown in Fig. 1. Humans have significant cognitive abilities to understand and interpret visual and spatial (either 2D or 3D) information as compared with textual representations of spatial information. This knowledge can be useful when analysing data: for example a temperature sensor positioned close to a window might be the reason why the recorded value is an outlier in the considered data set.

In addition, there are important usability considerations behind this research. Plain data, in a database or flat files is hard to understand (what it is about, which sensor, from where it comes from etc.), as it often lacks the necessary documentation and context to be properly used. Leveraging again on the strong human understanding of 3D spaces, and the contextual information extracted from the built environment, IoT interfaces should be able to provide a rich and intuitive interfaces to end users.

There is a set of more concrete objectives, which represent the foundation of this research, i) develop an end-to-end open source, secure IoT stack, from devices' firmware to web services; ii) provide programmatic data access using the standardized Web-API; iii) connect IoT data with the context and spaces in which it has been generated, and iv) develop interfaces including Virtual Reality to provide context aware information to various stakeholders.

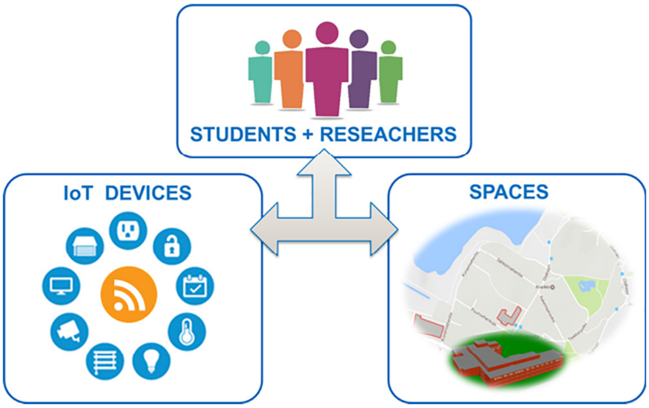


Fig. 1. SmartCampus project aim.

3.2. System architecture

Fig. 2 depicts the conceptual system architecture of Otaniemi3D, an open, campus wide platform that integrates Building Information using IFC with wireless sensor nodes through Open APIs. In synthesis, the developed system can be broken down in 3 main components:

IoT Devices: Their primary function is to sense and act upon the environment in which they have been installed.

Backend Server: A collection of loosely coupled services communicating with each other following the SOA (Service Oriented Architecture) design style. The grey boxes in Fig. 2 (IoT Service and BIM Service) are already implemented, while the green boxes represent the planned services to be integrated in the future. The data and functionalities of each component are exposed to multiple Frontends, Apps, WebApps via the standardized interface O-MI and O-DF (Open Messaging Interface and Open Data Format). This layer deals with the interpretation of the built environment data through standard formats such as IFC (Industry Foundation Classes) either through directly stored local data or through data stored in servers and accessed through APIs.

Front end(s): The primary function of the frontends is to manage the interaction with the target users of the system (students and researchers). In practice the front end can be implemented as websites, WebApps or smartphone apps. They consume data from the backend, transforming into a human friendly form. In addition some of these frontends are used to collect user inputs and data and feeding back to the backend system. So far only one front end has been developed, which will be described in the following section. However, one of the main goals of the entire smart campus project is to spark the development of a multitude of apps, leveraging on the competencies and interests of various research groups. In the vision, providing programmatic open-access to data is paramount for realizing the true potential of this type of systems.

3.3. Standardized Web-API

One of the objectives of the Smart Campus backend is to harmonize publishing and consumption of data though a standardized Web-API. The selected standards for achieving this goal are the Open Messaging Interface (O-MI) (Open Group IoT Standard) and the Open Data Format (O-DF) (Open Group IoT Standard) published by the Open Group (TOG), IoT work group in 2014. The TOG-IoT work group has an ambitious vision: “Whereas the Web uses the HTTP protocol for transmitting HTML formatted information which are rendered in the browser for human consumption, the IoT will use O-MI for transmitting O-DF payloads which will be mainly consumed by information systems.”

A detailed explanation of these standards is outside the scope of this paper, nevertheless Fig. 3 depicts the core operation supported by O-MI and its transported payload. The key characteristics of these standards are:

1. Transport agnostic: O-MI runs on top of existing transport level protocol. In general HTTP and WebSockets are the preferred protocols.
2. Publication and discovery of data sources and semantic metadata: The data and methods available provided by a given node can be discovered using the ReadAll operation. In addition O-DF tags can be semantically enriched using RDFa and LinkedData vocabularies.
3. Payload agnostic: Even though the preferred payload is O-DF (XML formatted), within specific O-DF tags any payload could be transported (CSV, HTML, proprietary file formats), or even binary file

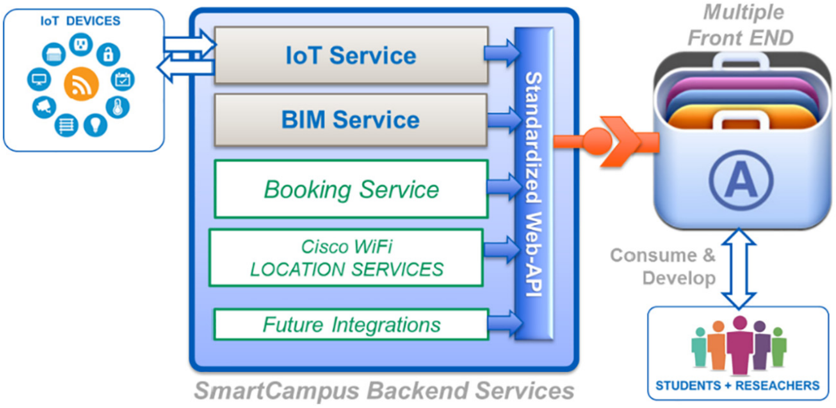


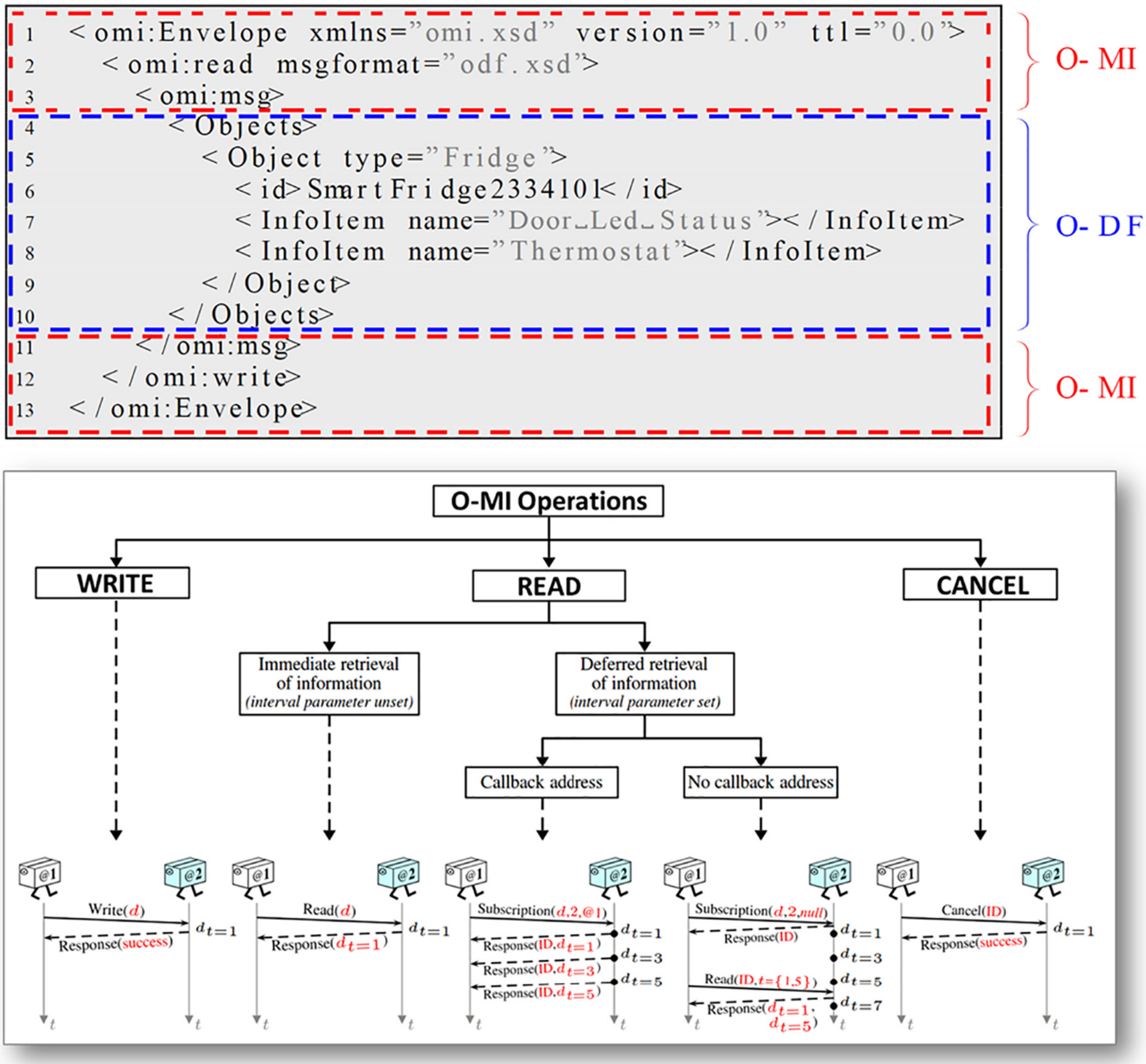
Fig. 2. Conceptual system architecture.

formats converted using Base64 binary-to-text encoding.

4. Support for Subscription: The possibility to create ad hoc, time limited information flows by specifying for how long (TTL) and at which sampling rate (INTERVAL) the data should be received, is the cornerstone of O-MI and what makes it particularly suited for IoT applications.

3.4. IoT devices and service

The IoT Service has been implemented using the open source



```
<omi:Envelope xmlns="omi.xsd" version="1.0" ttl="0.0">
  <omi:read msgformat="odf.xsd">
    <omi:msg>
      <Objects>
        <Object type="Fridge">
          <id>SmartFridge2334101</id>
          <InfoItem name="Door_Led_Status"></InfoItem>
          <InfoItem name="Thermostat"></InfoItem>
        </Object>
      </Objects>
    </omi:msg>
  </omi:write>
</omi:Envelope>
```

Fig. 3. Top: O-MI and O-DF payload. Bottom: O-MI main operation.

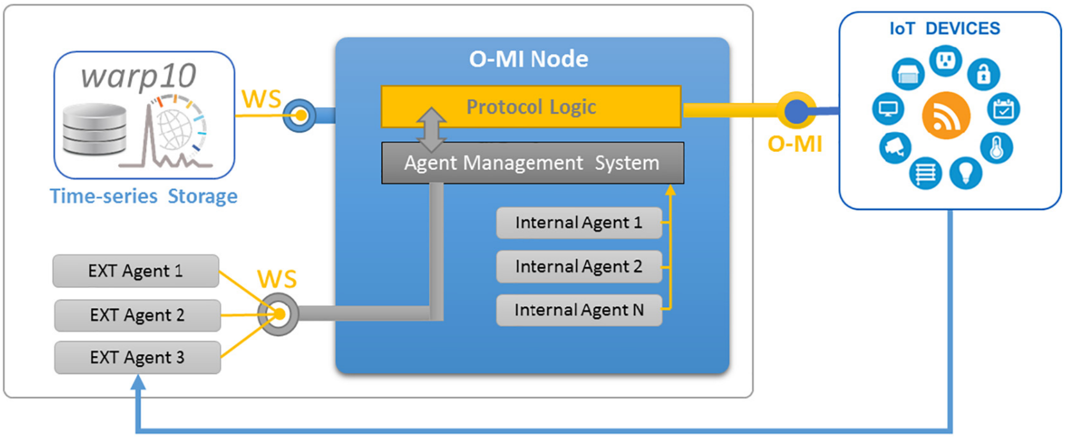


Fig. 4. IoT service main components (WS stands for WebSocket).

reference implementation of the O-MI and O-DF standards, developed at Aalto University (available online at https://github.com/AaltoAsia/O-MI). This particular implementation is an agent based system: Agents are simple programs, which in this instance are in charge of encapsulating the complexity of the lower level communication with IoT devices and the interaction with other services of the SmartCampus backend.

The data collected from the devices can be stored in a variety of databases. Currently, the O-MI and O-DF reference implementation supports all the major RDBMS (Relational Database Management Systems, such as SQL Server, Oracle, MySQL, Postgresql, SQLite etc.) providing a JDBC (Java Database Connectivity) driver. In addition, noSQL solutions improving scalability and overall read/write performance, such as Warp10 (an open source GeoTime Series database), is also supported (Fig. 4).

3.5. BIM service and front end

This service is essentially used to manage the relationship between spaces/buildings (described using IFC) and IoT data, in particular the translation of static IFC files into interactive web documents. Fig. 5 describes the overall workflow and some important considerations regarding how the BIM model must be built. The translation toolchain adopted, required some custom programming for retaining the association between the IfcSensorType and the final output web formats. The process described is very similar to the one adopted by BIMServer (http://bimserver.org/). The integration with the BIMServer is part of ongoing work and will be available in future integration of the SmartCampus backend.

It is important to highlight that the outputs produced by IfcOpenShell and InstantReality/AOPT is acceptable if the main purpose is simply to visualize the model. During model translation some features (e.g. IfcSensorType and IfcSpaces) are lost or wrongly aggregated. Retaining the association of these features between the original IFC file and the final web formats is crucial to enable interactivity with the 2D/3D models in the browser. A dedicated script (written in Python) has been developed to fix the output of this translation tools. Unfortunately, this utility is not yet error free and in some cases the final web formats needed some manual rework. Improving the described toolchain for achieving fully automated translation is an ongoing work.

4. Otaniemi3D proof of concept

The proof of concept has been called Otaniemi3D, where Otaniemi is the name of the Aalto University Campus and 3D stands for the

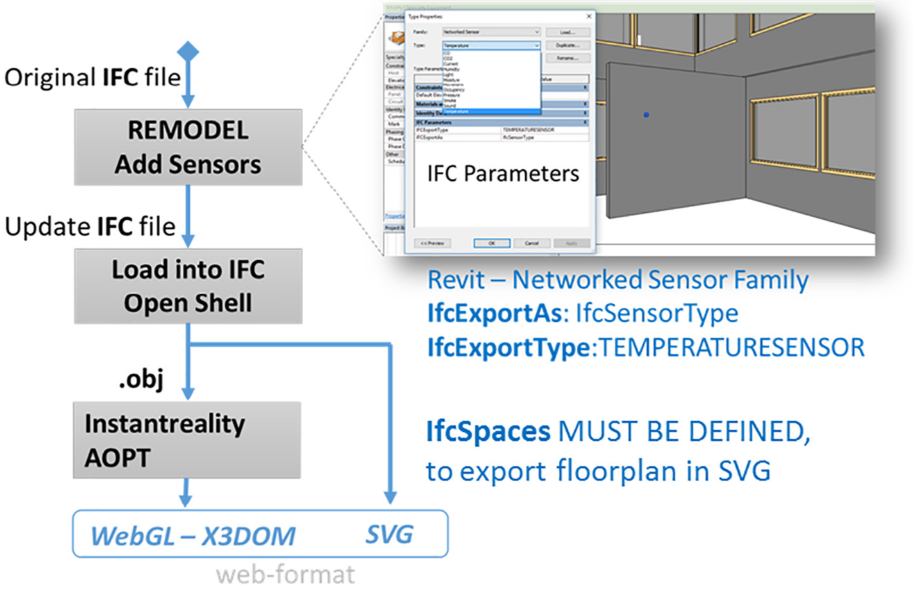


Fig. 5. IFC to WebGL and SVG translation toolchain.

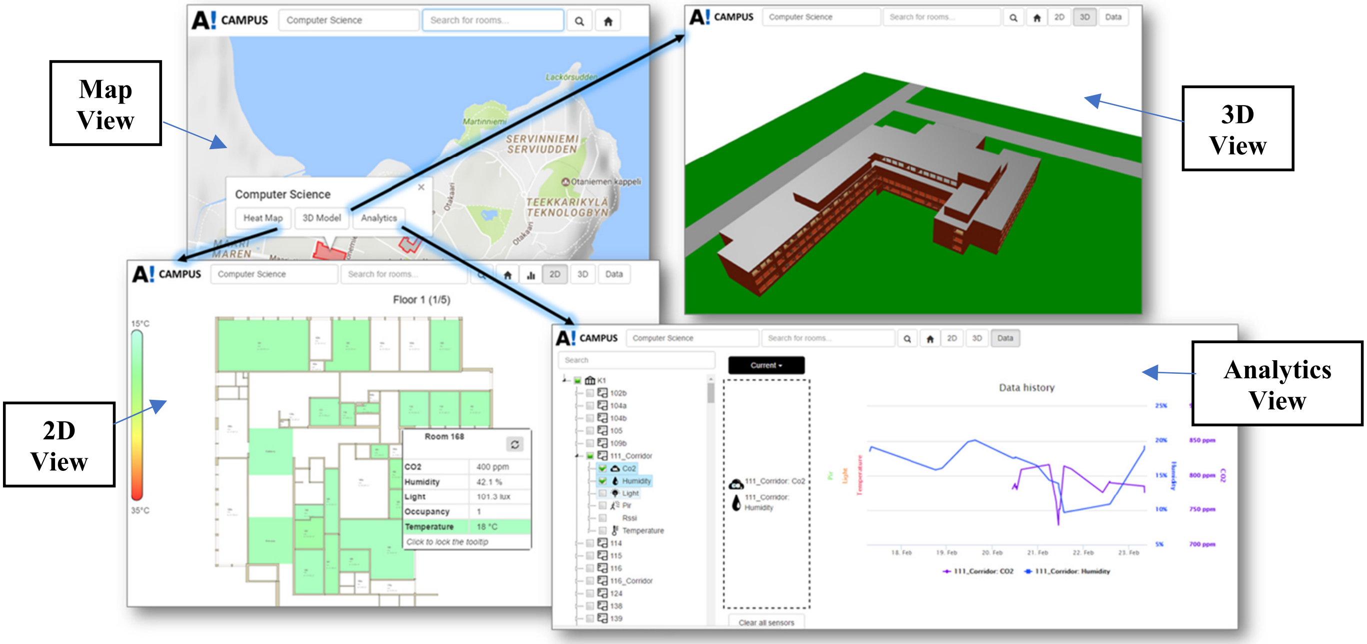


Fig. 6. Otaniemi3D frontends.

dimension in which the BIM and IoT data is presented. Fig. 6 depicts the main pages of the frontend of the system, the core components are:

(1D) Data Analytics Page.

(2D) Floor Plan and heatmaps page.

(3D) 3D Model and precise sensor location.

The next section will explain the functionalities and interactivity implemented in these views.

4.1.1. 1D view. Live and historical sensor data

This view simply presents the sensor data in a traditional graph form. Fig. 7 depicts the functionalities implemented. The tree on the left side of the image is a user-friendly rendering of the XML retrieved from the O-MI Service running in the backend. To plot sensor readings, it is possible to drag and drop the items in the tree (e.g. CO_2, Humidity, Temperature, etc. sensors organized according to room in which they have been installed) into the dotted line box. The sensor time series will be automatically plotted with an associated colour and scale. In this way it is easier to compare it with trends from other sensors, spotting possible correlations. In addition, it is also possible to select the time frame of the plot (Current (Last 20 readings), Last Week, Last Month, Last Year and a custom time range).

4.1.2. 2D view. Floorplan heatmaps

This view leverages the same functionalities implemented for the 1D-View, but instead of plotting single data points, it calculates an average for the selected time period generating a heatmap which is overlaid on the building floorplan.

This view tries to tap into the innate human cognitive abilities to

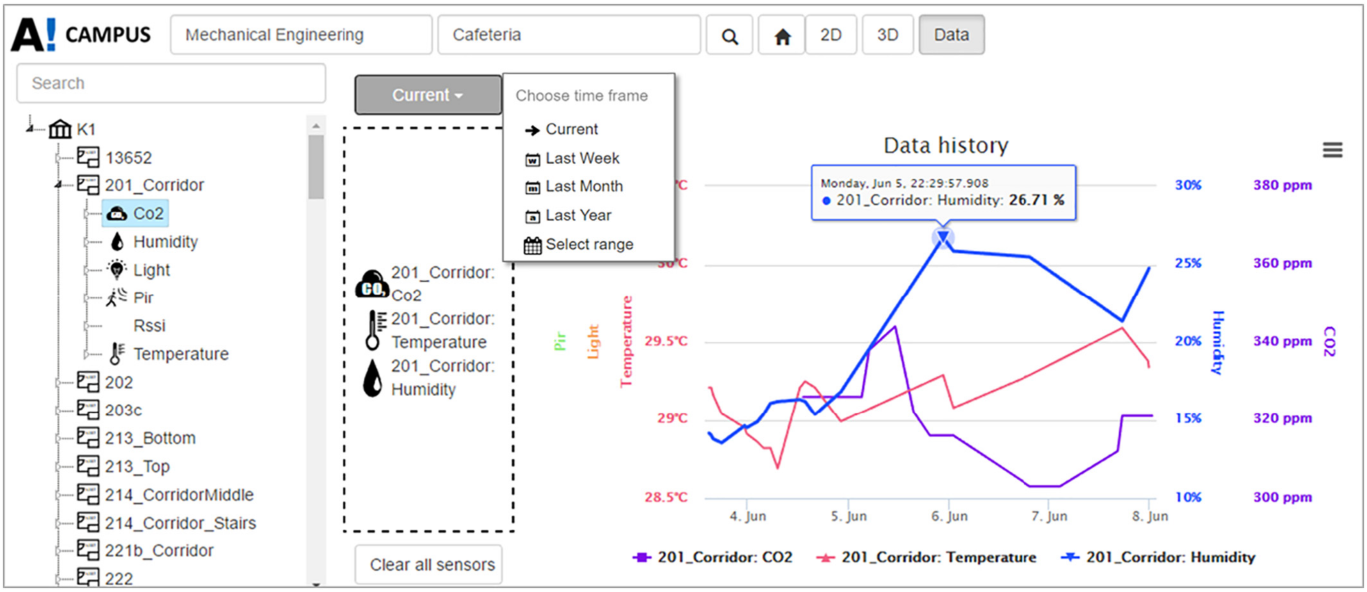


Fig. 7. 1D view live and historical sensor data.

4640

CO2	1016 ppm
Humidity	33.63 %
Light	0.05 lux
Occupancy	23
Rssi	0
Temperature	25.48 °C

Fig. 8. (2D view) floorplan heatmaps.

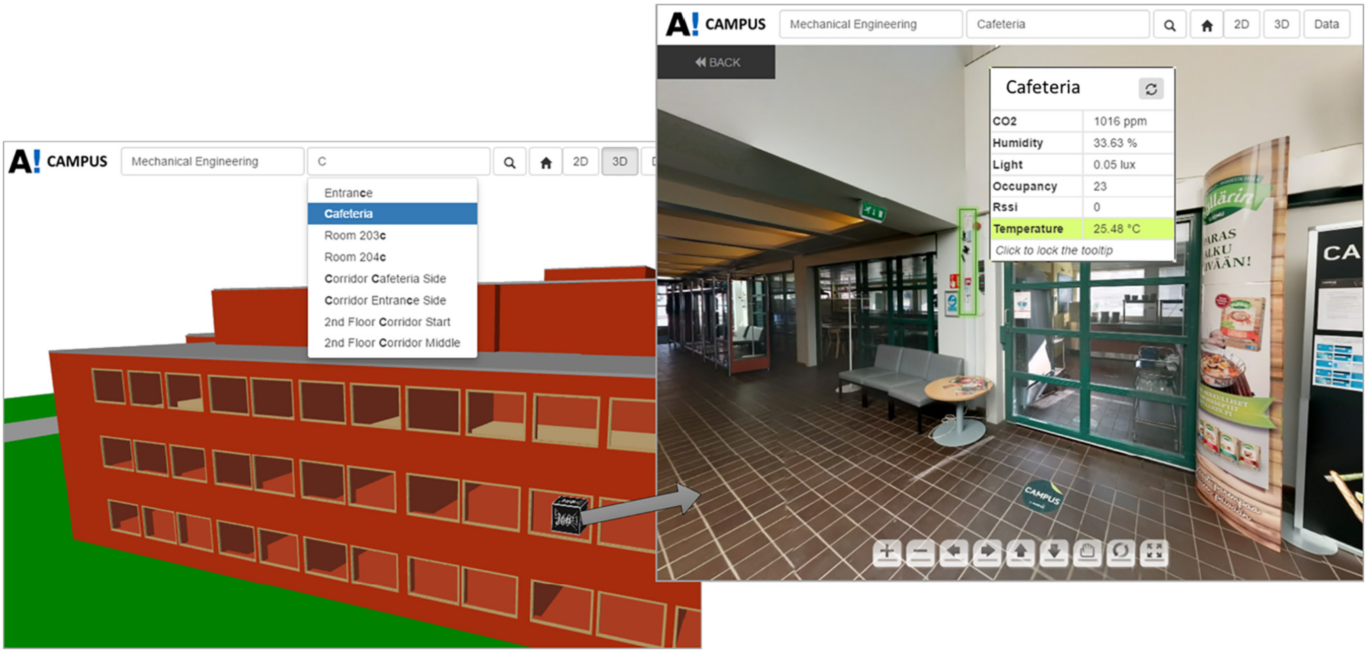
understand/interpret spaces and visual information. For example, if a certain area of the floorplan has a colder colour, the user might deduce the possible location of a heating system problem (Fig. 8).

4.1.3. *3D view. Locating sensors 3D model and 360 panoramic images*

The 3D View is still in an experimental phase. Besides the traditional 3D interaction pattern (Zoom, Pan, Tilt), it is also possible to enter a room number in the search bar activating a custom viewpoint/camera centred in the middle of the selected room (see Fig. 9). Once in the middle of the room, it is possible to click a "360° Box" which opens an interactive 360° picture of the room. In this picture, it is possible to spot and click on the installed sensor box to retrieve the current readings. The same interactivity is also possible from the 3D model.

5. Supported use cases

With an open framework, the authors envisage that a variety of use cases can be developed to demonstrate the capability of the system. Being a campus based system, there is an ongoing effort to encourage other research teams and students to develop compatible applications



Cafeteria

CO2	1016 ppm
Humidity	33.63 %
Light	0.05 lux
Occupancy	23
Rssi	0
Temperature	25.48 °C

Fig. 9. 3D view - locating sensors 3D model and 360 panoramic images.

by using the open APIs provided by the Otaniemi3D platform. The following describes a use case where a campus wide room booking and management system has been customised to work with the Otaniemi3D APIs.

5.1. *Aalto spaces mobile application*

The integration between the Aalto Space app and HVAC controls through O-MI and O-DF standards was part of the RealGO research & development project at Aalto University. The project is carried out in co-operation between Aalto Real Estate Business Unit, Aalto HVAC Team, Aalto Computer Science, Aalto CRE (Campus and Real Estate) and Aalto IT. The project is funded by STEK ry, STUL ry, Foundation for Quality of Construction Products and Aalto University. As a part of the RealGO project, integration of building control systems with IoT sensors and room booking system was carried out. Aalto Space is a mobile app for Android and iOS devices (available in respective App stores), which can be used to find and book study and group work facilities and meeting rooms within the campus. Using the map included in the app, students can also navigate to facilities not included in the booking system. It also includes an emergency messaging feature that allows the communications department of Aalto University to send notifications in case of emergency on campus. While the Aalto Space app was developed separately to the Otaniemi3D project, the developers of the ReadyGO project saw an opportunity to integrate the app with air conditioning and ventilation control along with the Aalto's campus booking facility using the open standards developed through Otaniemi3D research.

5.1.1. *Functional description*

Fig. 10 shows a floor selection view (after selecting the building, there are currently 6 buildings available in the app) in the Aalto Spaces app where the user can select the floor to book a room. Fig. 11 shows rooms on the selected floor and their availability alongside the room number, capacity, a picture of the room showing the facilities and ratings by users. Once a room is selected the app provides the options to book the space for either 30, 60 or 90 min as shown in Fig. 12.

The newly developed features have the possibility to control air conditioning and ventilation from the room reservation in the Aalto Space app. It controls the building automation system of Fidelix (a commercial building automation provider based in Finland) and radiator thermostats of Fourdeg. O-MI and O-DF are used to standardize large parts of the interfaces. To achieve that, the control signal goes through several parts: Aalto Space app, app middleware, O-MI Node, O-MI device agent (part of the Otaniemi3D framework), and building automation control servers.

Through the newly developed features, users can control the temperature by either choosing the colder or warmer functions or setting it on Auto. Similarly, the ventilation can be boosted if the users feel discomfort as shown in Fig. 13. In future, the app will show the current temperature of the given room alongside CO_2 levels. Following the booking, the users can rate the indoor conditions/comfort level of the room. These ratings are then visible to future users as shown in Fig. 14.

5.1.2. *Technical implementation*

Aalto Space app was modified to include controls to boost ventilation and change set point temperature after a reservation is made. If the user selects any non-default settings, an O-MI write request is sent. It contains information specifying the target room, the selected settings and duration. The request is sent to the app middleware server.

The app middleware server was used instead of direct messaging to the O-MI Node as it provides a simple security model for the app communication and allows easier modifications to connections to external services. In this case the middleware server acts as a proxy and forwards the request to the O-MI Node. The node is running on-site as part of Smartcampus server and handles also many other IoT devices. When the O-MI Node receives the write request it passes it to O-MI device agent.

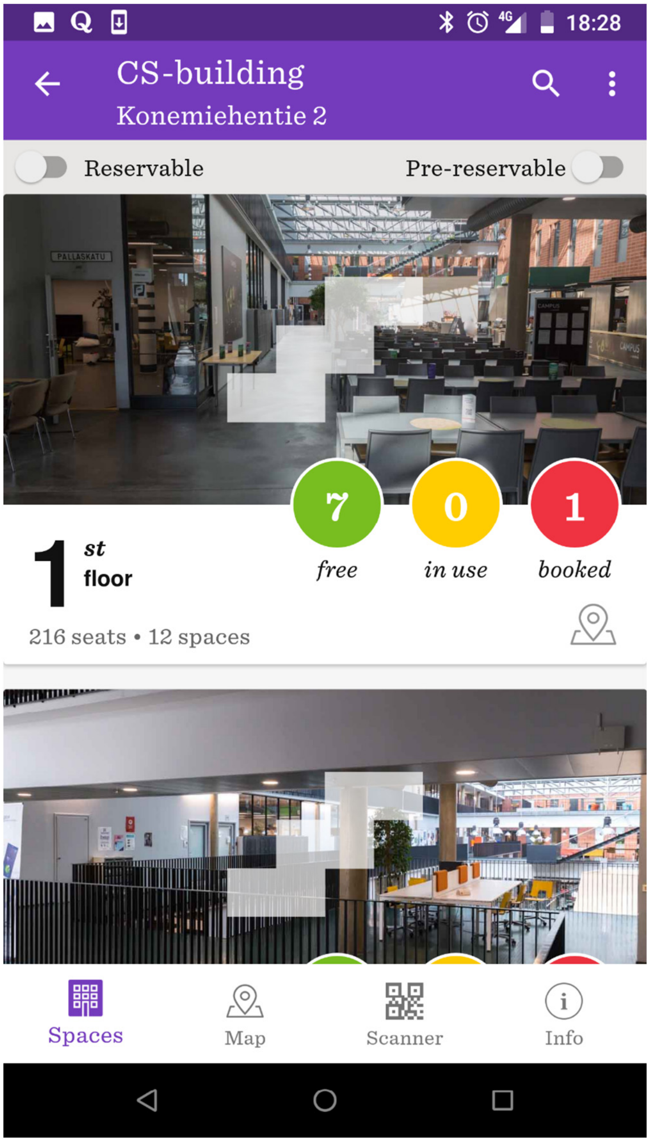


Fig. 10. Aalto Space floor selection.

The device agent is a wrapper which converts O-DF/O-MI messages to proprietary vendor specific interfaces. It also schedules the reset for default air conditioning settings and publishes the existence of the devices to the O-MI Node. In this case, it publishes virtual devices for the control signals, because the same signals are used to control two physical devices of different vendors. Two proprietary protocols were implemented, building automation was using SOAP and the thermostats had HTTP REST interface.

The building automation server was located on-site, but behind an industrial level VPN. The VPN was only meant to be used for remote maintenance, so it was decided that the building automation server is connected to the Smartcampus server via a secured Virtual LAN (VLAN). It was possible only because both servers were located on site and there were already network infrastructure for building-automation-dedicated VLAN.

5.1.3. *Benefits of Aalto Space integration*

Issues such as space utilisation, user comfort, energy usage monitoring and energy saving and a reduced carbon footprint are quite critical for all major campuses across the world. This is even more

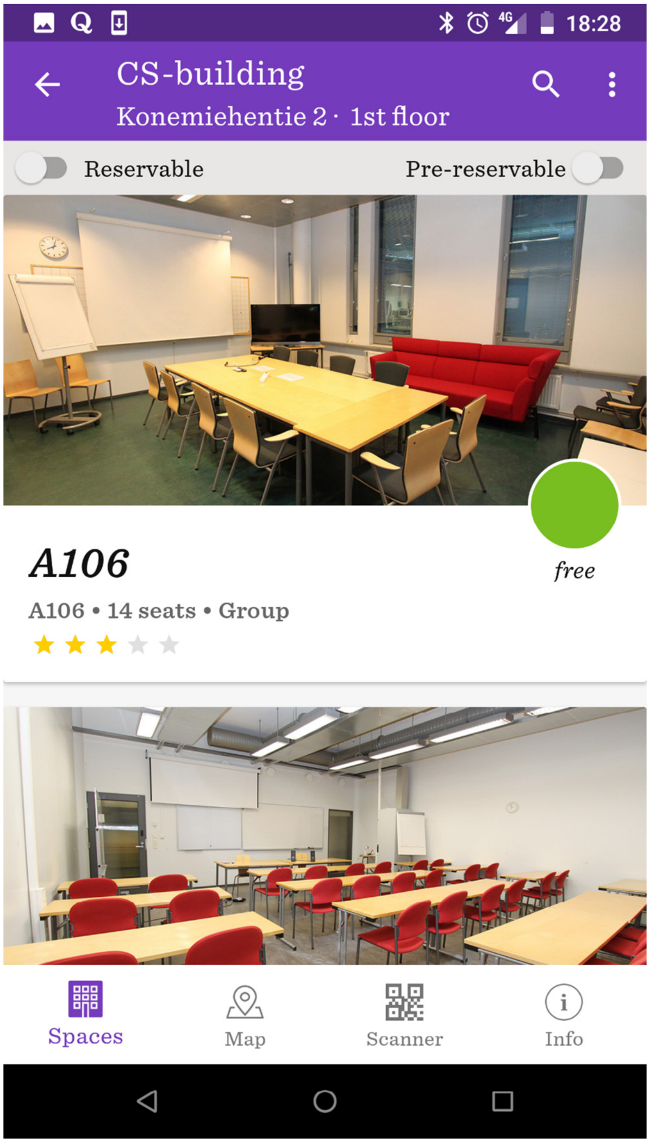


Fig. 11. Aalto Space room selection.

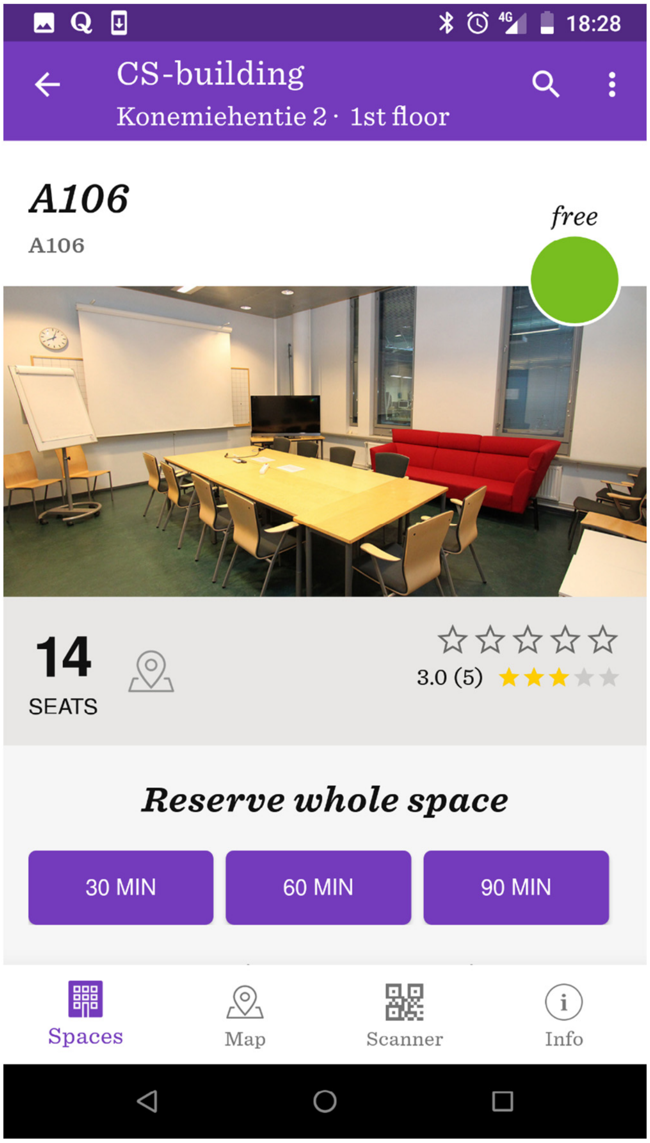


Fig. 12. Aalto Space room reservation.

emphasised in the EU due to various regulatory and research programmes. One of the main benefits of the Aalto Space app is to enhance facility management by integrating IoT sensors to provide real-time control and information availability for better decision making. Aalto's Campus and Real Estate department is one of the active members of ReadyGO project, and is planning to systematically integrate IoT sensors with the building information in order to better manage the facilities and improve the experience for campus inhabitants. For example, based on collective feedback received through the Aalto Spaces app, the Aalto Campus Real Estate department will be able to improve the facilities and prioritise maintenance events. By integrating real-time controls with the Aalto Space app and integrating these with sensors, there is a potential to improve user comfort and space utilisation. Also, by integrating the Aalto Space app with the campus' facility booking system, the HVAC systems can respond directly to the user demand and switch off when not in use. This will lead to direct cost savings over a period of time.

It should be noted that without the use of open standards such as O-MI/O-DF, it would be quite challenging to integrate all the information sources such as, Aalto's campus booking system, heating and ventilation controls and sensors by Fidelix and Fourdeg, and building data through Aalto Space and Otaniemi3D as highlighted in the case here.

5.2. *Future integration*

With sensors installed, integrated with spatial information and providing live data in a real-life setting through an open framework, researchers and students can use this to conduct analysis to support research projects, for example identifying user comfort patterns or energy usage patterns with changing sensor data, outside temperature and variety of other factors. Alongside Aalto Space app, there are other similar initiatives in progress, where the data available through the Otaniemi3D platform is being utilised in projects funded by Tekes (Finnish Innovation funding body) in collaboration with Aalto's Electrical Engineering, Civil Engineering and Computer Science department. The results from this will be disseminated in future publications.

6. Conclusions

A large proportion of IoT devices are deployed in the built environment providing an opportunity to develop interfaces that allow user interaction through open, intuitive interfaces. There is a growing concern that closed, proprietary standards and systems deployed in siloed environment will hamper wider, bottom-up proliferation of IoT

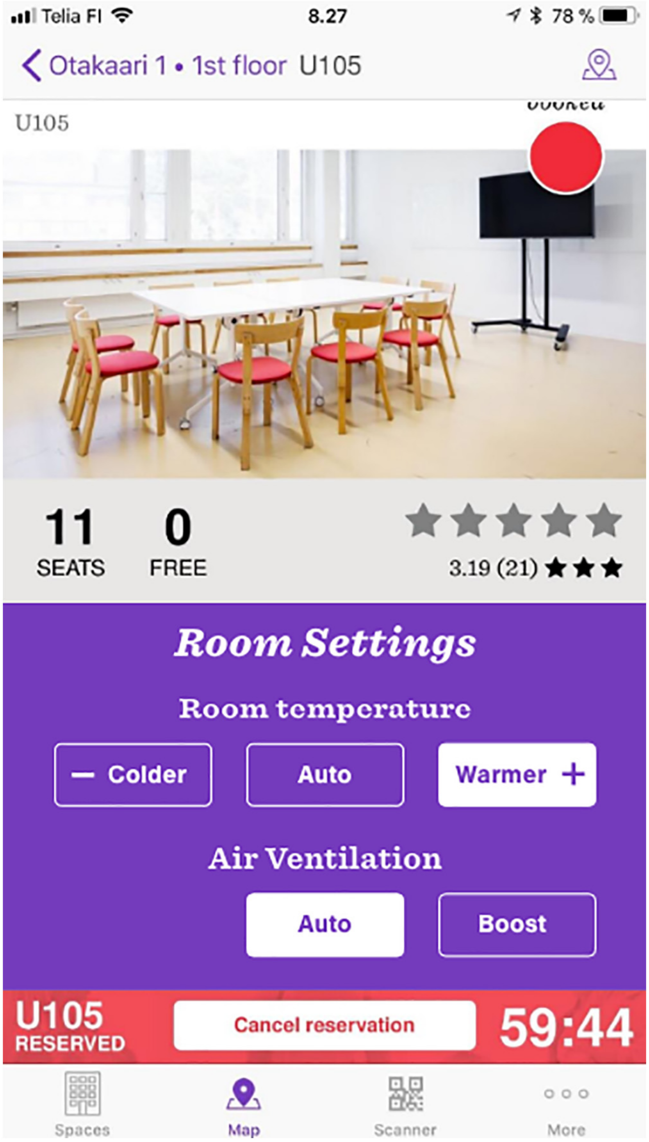


Fig. 13. Aalto Space room booking and control.

How satisfied are you with the indoor conditions of this room?

Fig. 14. User feedback following the booking.

deployment. This research shows that it is possible to engage wide range of stakeholders with IoT devices by integrating them with building information data. The communication takes place through Open Messaging interfaces eliminating the need to depend on closed proprietary systems that hinder scalable deployment of such systems and through intuitive interfaces.

The proposed system provides a range of interfaces to help end users navigate and explore the information available to them. As demonstrated by the case study, the proposed framework encourages other researchers and stakeholders within the campus to innovate using the open standards available to them through APIs. There are several challenges that present themselves while developing such a platform and especially in implementation. Without standardized export guidelines for IFC files, and parsers to export this data for web, it is challenging to map sensor data to objects in IFC. Additionally, developing open yet secure interfaces at the campus level (with diverse user profiles) poses an additional challenge along with the detection and prevention of rogue nodes. Data capture, storage and analysis is also a challenge in such a distributed and heterogeneous environment, which needs to be tackled at the technical architecture design level. Subsequently, ethical and user privacy issues in data capture pose a risk that needs to be managed actively in order to develop real-world applications. In future, researchers can develop more detailed implementations that address these challenges and address real-life requirements.

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