BUILDING DIGITAL TWINS FOR SMART CITIES: A CASE STUDY IN GREECE

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ABSTRACT:

The recent emergence of the Internet of Things (IoT), the latest technological innovations and the widespread use and embrace of Building Information Models (BIMs) offer several new ideas and decision-making capabilities throughout the life cycle of the built environment. The ability to connect and monitor data from sensor networks remotely in real time as well as the simulation and optimization of engineering systems, have led to the emergence of the Digital Twin (DT) concept of the structured environment. Although BIM lacks semantic completeness in areas beyond the scope of building modelling such as control systems, cadastral systems, networking of sensors, meteorological networks, etc., the DTs aim to achieve the synchronization of big data from various sources and simulate the real world into a virtual platform for the seamless management and control of the construction process, facility management, environmental monitoring, disaster management and disaster prevention, and other life cycle processes within the built environment. DTs in the built environment are still in nascent stages and thus a more in-depth investigation is required to explore and establish the best practices and technologies to serve this evolution. In this paper, we propose a methodology for providing the DT of a building; by crossing from the BIM static world to the dynamic cyber-world of DTs. A practical application is implemented for a two-storey 'smart' building with sensor systems installed in its assets and in the surrounding landscape area. As the practical experiment is successfully completed, we conclude that such an endeavour can actually be achieved at building level offering several economic, environmental and social benefits.

1. INTRODUCTION

The recent rapid urbanization coupled by the economic and social transformations caused by COVID-19, have posed significant challenges to all governments. Today, there is a growing demand for geospatial information and adoption of new technologies in several fields as urban planning, construction, engineering, climate change adaptation and mitigation, land administration, real estate markets, economy, etc. 'Industry 4.0' has been an inspiration to several researchers, setting a paradigm for the development of smart future "products" that can create physical replicas of the real world, monitor physical processes and provide decentralised decisions through computer-driven systems (Smit et al., 2016). Smart cities, Building Information Models (BIMs), DTs, autonomous surveying techniques, artificial intelligence (AI), machine learning, big data, blockchain, augmented reality, automated feature extraction and change detection are some of the key technological drivers of this future 'smart' world (FIG-GIM, 2021).

Integration of geospatial information into architecture, standards and best practices is a prerequisite for smart cities. The widespread adoption of BIM and the recent emergence of Internet of Things (IoT) applications offer several new ideas and decision-making capabilities throughout the lifecycle of buildings and therefore of the broader built environment (UN-GGIM, 2015). Every sensor and device connected to the internet can provide information to distributed environments remotely, while the embedded GNSS sensors offer positional information and help to the orientation and integration of all the various sensor data in a common reference frame (UN-GGIM, 2020).

These technological advances have led to significant changes both in engineering and in cadastral surveying, allowing their implementation either very close to the object or at a distance, including aerial or underground and underwater environments. Therefore, "Construction 4.0" concept appears to promote the extensive application of BIM on a variety of fields such as design and construction, industrial production processes, use of cyber-physics systems, digital supply chain monitoring, site construction and data analysis (Sacks et al., 2020). This new reality naturally includes the field of cadastre and land administration which is directly related to the built environment and is affected by its development over time. 'Cadastre 4.0' aims to manage the complex vertical stratified constructions and safeguard the interests of the right holders, the governments, the economy and the society in general, through setting a link between the virtual and the real world. This transition can create the right environment for the establishment of permanent communication between citizens, professionals, organizations and governments, assisting various decision-making procedures (Páez, 2016).

This urgent need to synchronize the real world across a virtual platform, combined with the advent of IoT and the ability to connect in real time with online sensors, have led to the emergence of the concept of the DT of the built environment. The application range of DTs is wide as it allows the effective management and control of the construction process, facility management, environmental monitoring and other processes concerning the life cycle of the built environment (Deng et al.,

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2021). DTs are considered to be an important step in the development of manufacturing, capable of facilitating the application of the principles of Industry 4.0 (Rosen et al., 2015; Uhlemann et al., 2017). However, research in the DT domain is still in its early stages as the emerging new technologies must first be understood and then a convergent context for the ongoing and the future research should be established.

1.1 Building Information Models

BIM is considered as the most comprehensive and intelligent 3D digital approach able to manage buildings with composite structures, and enable communication between stakeholders with different backgrounds (Atazadeh et al., 2019). Nowadays, commercial products are increasingly supporting open BIM standards and facilitate the broad utilization and exchange of BIMs. This progress is significant as it enables the seamless collaboration between Architecture, Engineering, and Construction (AEC) professionals with BIM applications to be widely applied in building life cycle management, including the design stage (Afsari et al., 2019), construction process (Deng et al., 2021) as well as operating phases (Soust-Verdaguer et al. 2017). Due to the rich geometric and semantic information contained and transmitted by BIM through computer-driven systems, BIM has become a valuable data source for Geographic Information Systems (GIS), which are commonly used for managing, modelling, analysing and visualizing spatial information. Through Industry Foundation Classes (IFC) data format, the rich content of BIM can be exploited by GIS. Converting BIM/IFC data into a suitable format for a GIS environment is a trivial procedure that usually implemented through commercial software tools. However, other interesting open-source solutions have been also developed, enabling BIM data visualization and processing on open-source platforms, such as Cesium (Chen et al., 2018).

Integrating BIM/IFC data with GIS has attracted the increasing interest of 3D Cadastre research community. The potential use of BIM and Industry Foundation Classes (IFC) as a future data source for 3D Cadastres, has been stated by several researchers (Oldfield et al., 2016;2017; Janecka, 2019; El-Hallaq et al., 2019; Gkeli et al., 2021a; b). Although BIM enables the standardized semantic representation of building components and systems, it lacks of semantic completeness in areas such as control systems, including sensor networks, social systems, cadastral systems and other urban systems. Thus, an alternative and more holistic approach able to integrate those factors into dynamic data of different levels is required. Especially in the case of 3D cadastral applications various efforts have been made to link international standards such as the Land Administration Domain Model (LADM) with BIM data (Atazadeh et al., 2019), as well as to enrich BIM with semantic cadastral information through crowdsourced methods (Gkeli et al., 2021a;b).

Although the uses of BIM have been extended to include lifecycle management of built-in assets, the current state of BIM is not yet compatible with big data, IoT and AI integration. Thus, the evolution of BIM should be carefully framed to effectively address this challenge and change its form from a static model with interoperability issues to a dynamically connected data model, where the building product can be fully represented in the form of a DT (Boje et al., 2020).

1.2 Digital Twins

The concept of a DT was introduced in 2003 as part of a university course on Product Lifecycle Management. With the emerge of new technologies, DTs were further adopted in other application fields (Boje et al., 2020). First, the concept was applied in the aerospace sector (Shafto et al., 2010), and then expanded to industrial manufacturing (Negri et al., 2017; Kritzinger et al. 2018, Zhang et al., 2019). So far, DTs are used in several fields including environmental protection, urban management, oil and gas, electric power, health care, automobile, manufacturing, railway transportation; while recently it has attracted the growing attention of the built environment domain (Lee et al. 2016, Natephraa, Motamedib, 2019).

BIMs are the main pillar around which DTs of the built environment evolve. While DTs tend to provide a dynamic representation of the physical environment leveraging the synchronicity of the cyber-physical bi-directional data flows, BIM itself can only provide static data of the built environment without the ability to automatically update its information in real time without additional data sources (Deng et al., 2021). However, the advent of IoT made the integration of real-time sensing data and the static information of BIMs possible. In addition, the wide spread of mobile devices and the development of modern technological solutions that allow the visualization and analysis of data in real time, have enabled the automated update of BIMs semantic information or/and status in real time (Gkeli et al., 2021a;b). These factors have had a major impact in the practical emergence of DTs.

DTs are highly desirable for construction as they drastically aid the decision-making process through well-informed and reliable "what-if" scenarios, preventing failures, reducing losses and delivering the best possible outcome in construction. Recent researches argue that the contribution of DTs may be significant for the digitalization of asset creation, management and delivery in built environment projects. Through the real-time synchronization between the physical model and its virtual replica, the monitoring, prediction and energy efficiency may be improved (David et al., 2018; Grieves et al., 2016). Existing studies have already adopted BIM and IoT technologies for monitoring the construction process and the condition of the internal environment of the building in real time (Lee et al., 2016; Natephraa, Motamedib, 2019).

Although these applications have been investigated under the BIM field, the DT concept requires a more detailed and precise approach, that ranges from small manufactured assets, buildings, city suburbs or even nation-wide DTs. Several cities around the globe have initiated DT projects aiming to support the planning, transportation, environment, energy, healthcare, safety and decision-making processes. The City of Zurich (Schrotter, Hürzeler, 2020), Helsinki, Munich, Rotterdam, Singapore consists prominent paradigms of this effort. The 3D spatial data and models of the cities include various elements such as buildings, bridges, vegetation, etc., creating digital replicas of the real environment, that are being updated when required. A particularly important step in strengthening the DTs concept is to raise public awareness by releasing 3D spatial data under Open Government Data (Schrotter, Hürzeler, 2020).

In recent literature, there are several approaches trying to differentiate and define the individual procedural stages of the DTs development. Boje et al. (2020) argued that the development of a DT in the construction industry can be divided into three main phases. The first phase is described as an improved version of BIM representing its physical view and including all the necessary semantic information. In the second phase, the 3D model becomes a monitoring platform through the establishment of a link between all the installed smart devices of the physical building. Finally, in the third phase, the physical model interacts with the digital one, utilizing all the sensory collected data and using AI, allowing the decision-making process to be implemented effectively (Boje et al., 2020).

Following a similar concept, a five-level ladder taxonomy reflecting the development stages of DTs is presented by Deng et al. (2021). As illustrated in Figure 1, the five evolution levels include: (i) the BIM, (ii) the BIM-supported simulations, (iii) the BIM integrated with IoT, (iv) the BIM integrated with AI techniques for predictions, and (v) the ideal DTs.

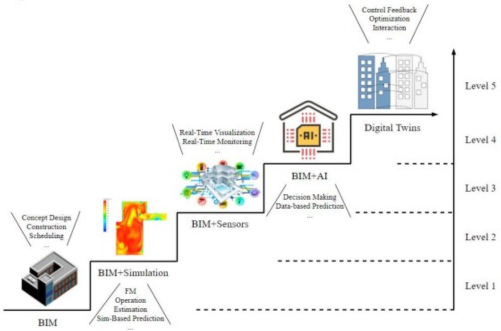

Figure 1. Development stages from BIM to DTs in the Built Environment (Deng et al., 2021)

Nowadays, the most common level of DTs is level 3 which combines BIM with data from deployed sensors. Following, level 4 adds the potential of AI, enabling the DT to combine a vast amount of data, predict possible future situations and suggest the most appropriate solution. The third and last level (level 5) requires the installation of smart devices in all basic operations of the building. In this way, the proposed management solutions provided by AI will be executed automatically. Only in this way the DTs will be able to fully fulfil their purpose and become the dynamic models that not only represent the physical models, but also have the ability to interact and intervene in the physical world. An example of such automated management decision of a DT, could be the adaptation of its operations to external climatic conditions (both real and forecasted) aiming to satisfy the optimal comfort conditions for its users and the minimum possible energy consumption.

However, DTs in the built environment are still in nascent stages and thus a more in-depth investigation is required aiming to establish the best practices and technologies to support this evolution. In this paper we develop and propose a methodology that allows the transition from the BIM static world towards a dynamic DT cyber-world, at building level; investigating the potentials of intersecting IoT and sensory data through semantical models. Section 2 presents an overview of the proposed methodology and the systems that need to work in synergy. In Section 3, a practical implementation of the proposed methodology is presented. Finally, Section 4 presents the main conclusions regarding the potential and perspectives of the developed methodology together with an outlook on future work.

2. METHODOLOGY

The developed methodology aims to combine the current research trends, innovative technologies and IoT capabilities to provide a technical model able to support DTs of Level 3 (Deng et al., 2021); integrating BIM data with IoT and data from deployed sensors but without the utilization of AI. The developed methodology consists of three (3) main components: (i) the Physical Environment, (ii) the Web, and (iii) the Virtual Environment (Figure 2).

The physical environment refers to the real environment where the physical object or objects is/are located. In the context of this research the focus is on the built environment and specifically on the buildings. For this methodology to be functional, the buildings under study need to be "smart" in the sense that they should have sensors, smart devices and appropriate systems installed that allow the real-time data to be delivered to other remote computing systems. All the sensors installed in the physical environment should be connected with a central computer that receives, encode, maintain and deliver the constantly updated data to an online database; so the latter are always available to remote computing systems. In this particular investigation the central computer receives the data from the sensors and stores them into a local .csv file which is synchronized with a "twin" file in Googlesheet format through Google Drive.

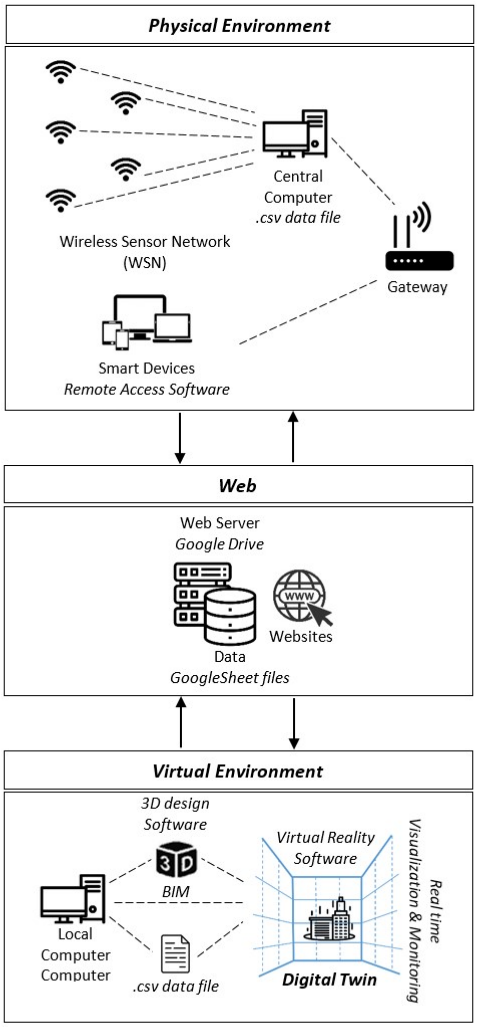

Figure 2. Overview of the developed methodology

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The Web is the second and most significant component of the developed methodology as it allows the communication among all the involved systems and thus, the data flow. The Web includes the Server where the real time data are stored in order to be available in other distributed environments. In addition, it allows the remote access to smart devices located in the building. The only prerequisite for the smart devices, is to have a remote access software installed. This enables a remote user to have access to a smart device in the building, perform an operation or even browse the web and download the data (i.e. weather information).

The last component of the developed methodology is the Virtual Environment. The Virtual Environment refers to the environment of the DT and the software tools that are synchronized for its generation. More specifically, it includes: (i) the local computer which uses the real time data from the Server and loads them to the DT; (ii) the 3D digital software where the BIM of the building under study is generated and maintained; and, (iii) the Virtual Reality software that combines the real time data with the BIM, enabling the real time visualization and monitoring of the building. By defining how all this information should be managed through the virtual environment, the creation of the DT is achieved.

3. PRACTICAL IMPLEMENTATION

For the implementation of the practical experiment of the transition from BIM technology to DTs, a two-storey building located in the city of Larisa in northern Greece, is selected. The studied building consists of forty (40) small apartments with a total area of 1,746 m². The test area covers a wider region beyond the building premises, including a landscaped area with vegetation and trees (Figure 3).

Figure 3. The test building and the landscape surrounding area

3.1 Sensor Data

Each apartment is equipped with a sensor that records the total electricity consumption in kilowatt hours (kWh). Further, a sensor for measuring the water temperature in Celsius degrees (°C) is also installed in the hot water boiler of the building. In addition, three (3) more sensors have been installed in the surrounding area of the building aiming to measure the current ambient temperature, the relative humidity and the air intensity.
The sensor recordings are stored into a .csv (comma-separated values file) file on a central computer which is installed inside the building. In order for this file to be accessible and usable remotely from another computer, it is synchronized with a "twin" file in Googlesheet format through Google Drive. The Googlesheet file is always up-to-date, including information from the latest logs of the sensors and can be automatically exported to any remote computer as a new .csv file utilizing the SheetGo extension. In this case the downloaded file has to be re-synchronized with the one located in the central computer through Google Drive. Thus, the management and processing of the data included into the design program may be implemented remotely; ensuring that the sensors information included in the file will always be updated.

In this study, we use data from a .csv file, as the system of the sensors was already programmed to record and store the data in this format. Of course, PostgreSQL can be also used to store and structure the data, as its extensions provide a rich set of data types, indexing approaches and geometric functions and operations (Aleksandrov et al, 2019).

3.2 BIM Data

For the generation of the BIM representing the test building, the Autodesk Revit 2022 software was utilized. The 3D physical model was created in LoD4 (Level Of Detail) (Gröger et al., 2008), describing the real interior and exterior characteristics of the buildings in detail. Figure 4 illustrates the western and north-western facade of the building (in green) while Figure 5 reveals the internal furnished spaces of the building.

Figure 4. The western and north-western facet of the BIM representing the test building (in green and orange)

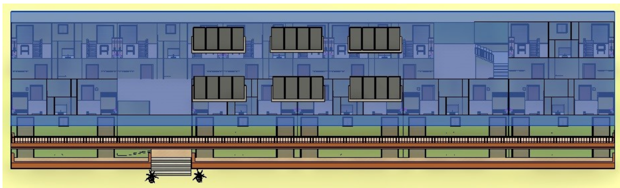

Figure 5. The internal furnished spaces of the BIM

3.3 DT generation

To achieve the transition from the BIM to a DT, a connection between the sensory data and the BIM should be established. This is accomplished through Unreal Engine 4.27 software, that offers the ability of developing real time solutions for the AEC environment. In order to insert the BIM into Unreal Engine environment, the Datasmith add-in is utilized. With Datasmith add-in a connection between Revit and Unreal Engine software is established making the two programs compliant and enabling their synchronization. This means that any changes made to the BIM within the Revit environment are automatically transferred to the Unreal Engine environment and vice versa; retaining the two models up-to-date. It is worth noting that the BIM that is inserted in the Unreal Engine software is accompanied by all of the information defining its properties in Revit, concerning the Textures, Materials, and Geometries for each of its structural elements, maintaining all the valuable information defining the characteristics of the building materials. Thus, following this process the insertion BIM into the virtual environment of Unreal Engine is achieved. To create a more realistic view of the surrounding environment, a panoramic photo of the wider area is inserted as basemap into the virtual environment (Figure 6).

In order to convert the BIM into a DT, the real time measurements of the building sensors together with information about the current meteorological conditions of the test area are linked with the environment of the Unreal Engine. The meteorological data and more specifically the ambient temperature, the relative humidity and the intensity of the wind are obtained through a website (www.okairos.gr) which receives new updates per hour. The meteorological station of the city operates at a very close distance from the building and thus, the acquired data are quite reliable.

Figure 6. The BIM of the test building on top of a panoramic photo of the wider area

This information is imported into the Unreal Engine through the logs contained in the GoogleSheet file. In addition to the recordings of the sensor measurements, the information related to the aforementioned meteorological data should also be entered in this file. This is achieved through a command, in Google Sheets Script utilizing modern JavaScript, that isolates the necessary data from the meteorological website; enters the corresponding numeric value in the Googlesheet file and updates these values every 15 minutes.

To import the .csv file into the Unreal Engine, the creation of "twin" table similar with the one included in the Googlesheet file is required. This new 'twin' table should contain the same fields and properties with the original one (Figure 7). Once this table is created, the automated re-entry of the up-to-date .csv file located in Google Drive is regulated, making the appropriate setting adjustments into Unreal Engine.

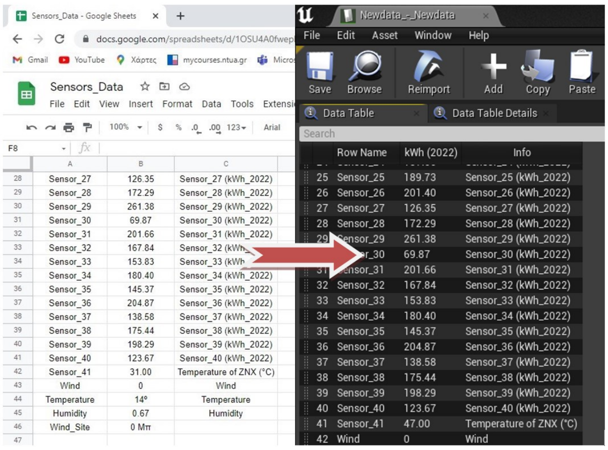

Figure 7. An example of the .csv data and the 'twin' table created in Unreal Engine environment

The visualization of sensor data and the capability to interact with the model, require the creation of the physical entities of the sensors into the virtual environment (Figure 8). Once the creation of the sensor models is completed, the exact actions, the form and the duration that the data will be displayed on the virtual interface are defined through the generation of an Event Graph of Blueprint nodes in Unreal Engine Software (Figure 9). Thus, by clicking/selecting the desired sensor in the DT, the corresponding data are displayed on the screen.

Figure 8. The selected model form to represent the sensors and their placement towards the indoor and outdoor virtual environment

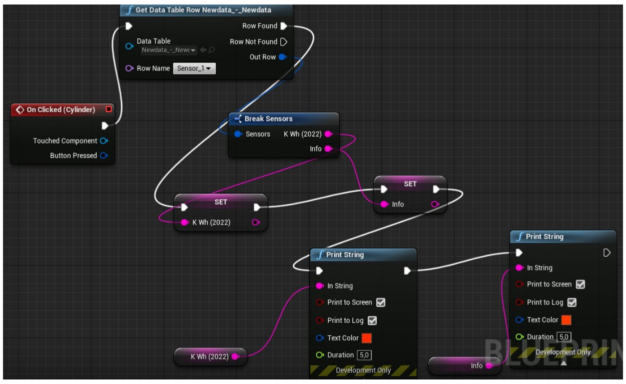

Figure 9. The Event Graph of Blueprint nodes for sensors interaction

Similarly, to simulate the weather conditions in the DT, another Event Graph of Blueprint nodes is developed in Unreal Engine Software, enabling the trees in the surrounding area of the building to adapt their movement according to the real time values of the wind intensity (Figure 10). Thus, the higher the wind intensity the more intense is the movement of the trees.

Besides sensor and weather data, the DT may also represent media, audio files and content accessible from a web browser. The determination of the form and the definition of the properties of these objects is carried out in accordance with the previous similar event management processes through blueprints (Figure 11). Thus, by selecting/clicking the desired element that represents an installed camera in the physical space of the building, a screen appears on the program interface on top of the DT, transmitting the image captured by the cameras in real time. If a microphone is also physically installed, the captured sound is transmitted along with the image (Figure 12, left). Similarly, it is possible to have access and manage remotely a computer device located in the building, as long as appropriate software allowing its remote use is already installed on this computer (Figure 12, right). Consequently, the management of all the smart devices in the building that can be connected and controlled through a local computer is feasible. The only limitation is the internet connection of these devices which enables the transfer of the necessary data to the virtual environment of the DT.

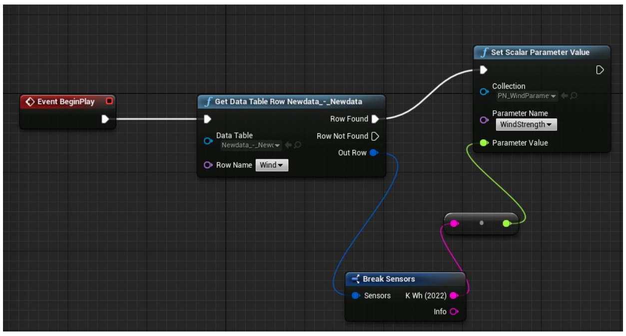

Figure 10. The Event Graph of Blueprint nodes for weather simulation

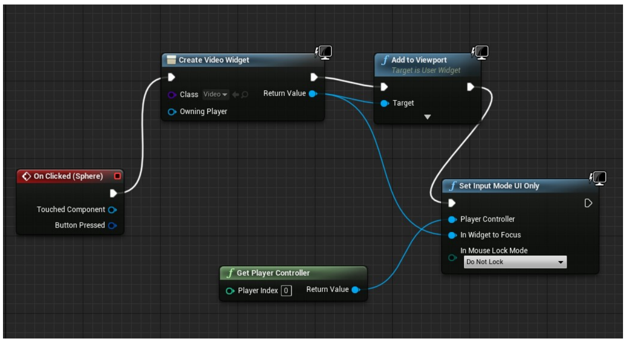

Figure 11. The Event Graph of Blueprint nodes for media and audio management

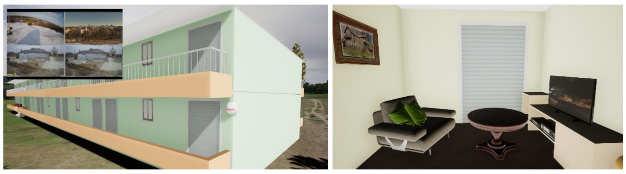
Figure 12. An example of remotely accessing the surveillance cameras (left) and a computer smart device of the building (right)

Unreal engine is not yet widely used as a program for developing DTs. Hence, there are still several issues that could be improved. The development of available and ready-to-use plugins would greatly accelerate the time needed to program the application. These could further include tools to automatically load diverse numerical data/info from the sensors, in the form of active charts. This would provide an active platform where users can monitor parameter changes in real time. However, given the increasing number of users that incorporate unreal engine into their DTs designing, this will be soon resolved. Furthermore, real engine has created Marketplace, offering users the possibility to freely share and use plugins they have created. Thus, creating public, open access tool libraries that make unreal engine user-friendly and suitable for the development of DTs.

4. DISCUSSION AND CONCLUSIONS

The field of DTs may be at its early development stages, however, its potential and benefits are already being revealed. As emerged from the practical implementation, the proposed methodology can provide the DT of a building, as it enables the inclusion, representation and simulation of real-time data. More specifically, the developed DT can include and provide a plethora of numeric data and information collected by sensors, cameras or other computing systems installed in the building. At the same time, it offers the capability of gaining access to the smart devices of the building to set their operation remotely. Thus, through the virtual environment of the DT, several building operations can be controlled, managed or modified in real-time, remotely.

The installation of sensors in each apartment of the building can help to monitor the power consumption both in each apartment and in the whole building. In this way, effective decisions can be made regarding the reduction of energy consumption and consequently the improvement of the energy footprint of the building. Also, the awareness of the current temperature of the consumed hot water, helps to regulate and limit the operation of the electric resistance of the boiler, when this is not necessary.

This holds great potential for the future use of DTs, where additional sensors detecting smoke, air quality, motion, ambient temperature, humidity etc, could be further included in the technology. The real time monitoring of the building, through the installation of cameras and microphones, may have several advantages. For instance, workers operating in dangerous areas or using hazardous materials without the appropriate safety measures may be detected and possible accidents may be prevented. Risk management can be also introduced in the rest of the lifecycle of the building, through the installation of sensors for the development of early warning systems in case of an accident (especially with elderly residents), fire, earthquake, poor air quality, break-ins etc. Even in the construction stage, real time monitoring may allow the contractor to control the surveys progress according to the initial directions and directly control or correct the distribution and use of the materials, the equipment and human resources - when and if needed.

Through such inter-connected data networks, the digital space approaches the real world, allowing the systematic management, development and maintenance of infrastructures throughout their lifecycle. The real time monitoring and updating of DTs changes the processes of digitizing the real world where the third dimension is captured, stored and visualized with consistency. The use of 3D geospatial data will be expanded through DTs while at the same time this new knowledge can be utilized for internal and external administrative uses. Such spatial data may be Open Government Data to promote dissemination and create new modern applications (Schrotter, Hürzeler, 2020). With the advent of Cadastre 4.0, which is based on fully automated processing on a network of people and devices integrated into technological intelligence, this new trend is already introduced in land administration. The main objective of Cadastre 4.0 is to get to a self-operating structure based on smart devices and data collection processes, enhancing the sense of security and trust for citizens. Incorporating cadastral data into DTs facilitates the visualization of the spatial extent of the Rights Restrictions and Responsibilities (RRRs); the dissemination and updatance of the ownership status; and, the transparency of the procedures (Schennach, 2017).

However, the success of this endeavor depends directly on communication. The way in which the data is presented and promoted through the DTs should be attractive and effective for different stakeholders. The access, search, creation and update of information should be simple, automated and understandable increasing public acceptance. Hence, DTs can open up new opportunities for the city administration to motivate citizens to participate in planning. The DT can be utilized to test different scenarios for future planning, predicting the effects of possible changes in climate, population, traffic, mobility etc., on the urban environment. These results will open new possibilities for discussion and decision-making within the administration and the external project participants. Thus, citizens can be informed about the open projects and topics in the city and get involved (Schrotter, Hürzeler, 2020).

DTs do not only simulate a fixed situation in time but also promise perpetual and predictive analysis. A DT effectively enables the prediction of the future and determines where and when errors are likely to occur. This allows for fully optimized diagnosis and maintenance, in contrast to the reactive model with which we are mostly familiar. Thus, the DT offers incalculable possibilities of cost savings, waste and risks avoidance. The development of a DT across an entire city would take the form of a system-of-systems connecting all the individual twins. Thus, municipal leaders will be able to model a variety of scenarios and make predictions about the future (Digital Transormation, 2022).

However, there is still a long way for the smooth integration of a variety of data into a solid DT. As data speaks many languages, it is necessary to establish a global standard that will be followed by all individual sub-systems. The development of such a standard will allow the dissemination of data, the communication between systems or even their effective integration – if needed. Due to the abundance and sensitivity of the data that can be managed by DTs, special attention should be paid to the protection of personal privacy, that may be affected by the modern reality of the IoT. DTs provide a new innovative future where stakeholders can visualize and collect all the data needed to support effectively the decision-making procedures. Hence, it possible to steadily move to a new digital reality of DTs both on local and global level.

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