

Virtual reality enabled building-data management through the combination of a fully integrated IFC-BIM model and an IoT-based building management system.

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Abstract

Professionals involved in building construction and monitoring increasingly implement new practices made available by Building Information Modelling (BIM), Virtual Reality (VR) and the Internet of Things (IoT). In spite of numerous efforts, most methods integrating BIM and IoT rely on Application Programming Interfaces (APIs) related to Closed Source Software (CSS), which practically exclude the basic BIM Industry Foundation Classes (IFC) standard. Within the fewer methods actively using the IFC data model to VR-enhanced interfaces, we can observe the loss of crucial IFC information. This article describes a workflow of a BIM-IFC to VR-enabled data management definition, articulating a Building Management Systems' (BMS) database or, as an alternative, an IoT system. This workflow is presented through four phases (model making, device inventory, protocol setting, and real-time VR interaction), which correspond to the actual sections of the information flow that we have successfully tested.

Key Innovations

- Integration of IFC model data in VR-enhanced data management using Building Information Models (BIMs)
- Integration of Building Management Systems' (BMS) with VR's immersive and interactive possibilities

Practical Implications

The practical purpose of this research is to develop a Proof of concept for a BIM-IFC to VR-enabled data management workflow. This paper describes a test with a single switch, which is intended to be scaled-up to the entire electric and electronic network of sensors and actuators of a specific building's FM and BMS (SLL, 2021). This building is, in turn, a pilot project for a broader implementation of BIM across the Smart Living Lab campus in Fribourg. The practical interests for this work are:

- To offer a 3D visualisation tool for real-time data collection (BMS).
- To enable FM centralised control of actuators' status through multiple navigation choices including Virtual Reality (VR) and Augmented Reality (AR).

- To enable professionals, clients and future users to, in addition to VR-AR spatial strolling, actually operate and validate the building's electrical and electronic systems before and after construction.
- VR-AR control of electric systems may eventually lead to the elimination of wall-wiring, as actual switches and other wall-based actuators may no longer be necessary as physical objects.

Introduction

Acknowledging the need to integrate BIM, BMS and IoT technologies to effectively link the processes carried-out before and after construction of buildings, certain methodologies have been accurately explored (Jourdan, Meyer, and Bacher, 2019; Nguyen, 2016; Quinn et al., 2020; Tang, Shelden, Eastman, Pishdad-bozorgi, and Gao, 2019). In these methodologies, Building Information Models (BIMs) provide digital data sources to which real objects in space and BMS databases are connected, eventually forming IoT Digital twins. This connection becomes especially relevant in the case of Facility Management (FM) and building-performance monitoring, since it allows visualisation tools and data centralisation, in order to monitor and manage buildings during their operational cycles. In addition to this, successful experiments with VR-enabled environments have shown how virtual and augmented reality technologies may render FM interfaces more reactive and efficient (Chang, Dzung, and Wu, 2018; Jo and Kim, 2019).

Provided that the IFC data model is widely implemented as the BIM open international standard (Kiviniemi, Tarandi, Karlshøj, Bell, and Karud, 2008; Olof Granlund Oy, Jokela, Laine, and Hänninen, 2012; Poljanšek, 2017), Facility Management-enabled Building Information Models (FM-BIMs) should be IFC compatible. Paradoxically, most methods integrating BIM and IoT rely on Application Programming Interfaces (APIs) related to Closed Source Software (CSS), usually excluding the IFC standard (Tang et al., 2019) (Quinn et al., 2020). In turn, IFC-based methods (including our own) that integrate VR-enhanced interfaces, experience crucial loss of IFC information such as mapping textures, IFC hierarchy, and most IFC parameters (Parsanezhad, 2019).

This article focuses thus on two main subjects:

- (1) Definition of a workflow of a BIM-IFC to VR-enabled data management, articulating a number of systems operating in a real building. That is Building Information Models (BIMs), a network of sensors and actuators, the Building Management Systems' (BMS) database (or, as an alternative, the IoT system), and the facility management interface.
- (2) Application case of the IFC-based VR-enabled FM-BIMs workflow, securing the transmission and automatic update of IFC information between the digital model, the FM user's interface, and the live connection to a BMS database. The case is not only relevant for this research, but it may also open new possibilities to enhance IFC usage in other workflows for professional and research practices.

Methodology

The methodology is composed of four phases:

Phase 1 consists in the generation of a 3D BIM model of a real physical workspace, exported into IFC format, including the definition of the textures applied to the different elements of the model in order to obtain a more realistic VR experience. For practical reasons (mainly skills and educational licence availability), we used Revit 2020 (Autodesk, 2019) which, at the date of launching this study, had a 2.3 release certification for IFC export (BuildingSMART, 2020). We chose to work with Unity version 2019.4.17f1 (UnityTechnologies, 2005), as our experimental VR game engine software. This software efficiently handles the IFC data model, in the sense that all IFC properties of the model elements can be retrieved and exploited in the VR environment.

Phase 2 is to elaborate an inventory of sensors and actuators present in the actual physical space, as well as the consequent creation of the virtual objects representing them on two different databases. One gathering information on the physical elements (characteristics of sensors and actuators), the other storing data strings of the measurements received from sensors and the status of actuators.

Phase 3 is the definition of a complete exchange protocol of information and live data exchanges along the workflow connecting components, databases, digital models and VR interfaces.

Phase 4 consists in the actual testing of the workflow – in a real case – leading to summarising the lessons learned and highlighting future improvements.

Case study

The case study is an individual office located on the first floor and the south façade of the "LE building" at the EPFL campus in Lausanne (Switzerland) (Figure 1). This building is an experimental infrastructure occupied by researchers of the Solar Energy and Building Physics Laboratory (LESO-PB), directed by Professor Jean-Louis Scartezzini.

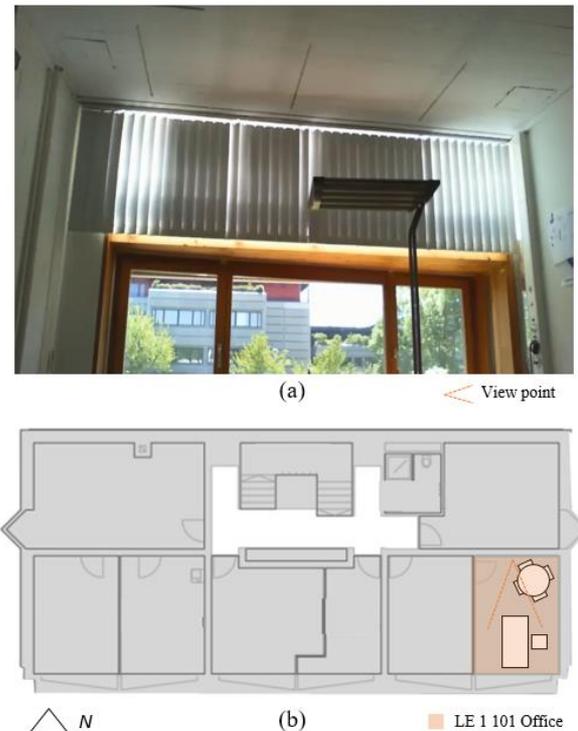


Figure 1: Case study - LE 1 101 office: (a) interior image. (b) Floor plan.

Results

Results are described according to the methodological phases explained above.

Phase 1 | 3D BIM Model, IFC and VR software

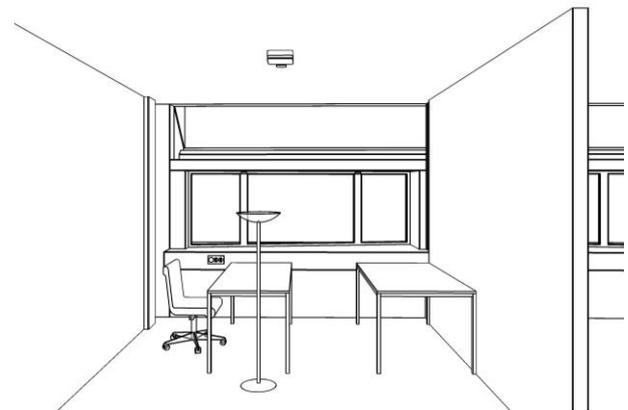


Figure 2: 3D BIM Model of the LE 1 101 office

For all tests presented, we used the digital model of an office space with basic architecture elements (floor, ceiling, walls, and windows) as well as few pieces of furniture (a desk, a chair and a lamp) (Figure 2).

From this model, we exported a standard IFC 2x3, following the software-provider's recommended procedure, which included the pre-installation of a set of Shared IFC parameters. We obtained a satisfactory IFC file, which included the elements' basic properties. Among those, the four IfcRoot attributes, from which we chose to work with two: the IfcGloballyUniqueId and the

IfcName. The first is an identifier that is unique throughout the software world, also known as a Globally Unique Identifier (GUID). We used this attribute as the central identifier to reference each object within the database. The second attribute, the name, which provides explicit information about the object, is used as reference for prompting messages when approaching objects while navigating in VR (Figure 3).

Properties	Emplacement	Classification	Reports
Nom			Valeur
Element Specific			
Guid			39mNE0BHAVRS7m_bczzfl
IfcEntity			IfcDistributionControlElement
Name			LSO_Prise stores:LSO_Prise stores:303007
ObjectType			LSO_Prise stores:LSO_Prise stores
Tag			303007
Profile			
ProfileName			LSO_Prise stores
XDim			0,176
YDim			0,076

Figure 3: IFC Data Model, example of the two IfcRoot attributes chosen as reference for all objects

Phase 2 | Inventory of the sensors and actuators

Once the IFC data model provided the geometry and attributes for the virtual version of real objects, we needed the inverse input: to be able to identify the real object within a database. More precisely, for practical reasons such as accessibility, security and visibility, this database is in fact two separate databases. The first, called "BBData" (Big Building DATA) (iCoSys-HES-SO/Fribourg, IEnergy-HES-SO/Fribourg, and Smart Living Lab, 2018; Linder, L. et al, 2017), stores data strings of the historic measurements collected by sensors, as well as the status of actuators. This database is accessible by users having certain authorisation and it provides only individualised values of measurement. For instance, a device integrating three different sensors, measuring CO₂, luminosity and humidity, will be registered in the database as three non-correlated values. The second database, which we call the "DB MTI" (Inventory database), collects the graphic and numeric information about the actual physical sensors and actuators, including pictures, location, attributes and other properties. This database plays different roles. First it serves as security enclave: only a restricted group of the system administrators have access, leaving to common users and researchers solely the access to BBData. Second, it contains explicit information of all system components and relationships. It is through this database that, following the example above, one would be able to understand that the three separate measurements registered in BBData come from a single, locatable device. Third, it provides a direct link to the digital IFC-Model, via the GUID and the Name attributes described before. This allows the spatial location of any device within the model. Finally, it is linked to a system of QR code stickers that have been attached to each real element. This allows researchers and users to get information about the devices, the values they inject into BBData, as well as additional augmented reality (AR) information provided by the IFC-Model (Figure 4). The QR Code sticker includes the IFC GUID to secure retracement in case of a system failure.

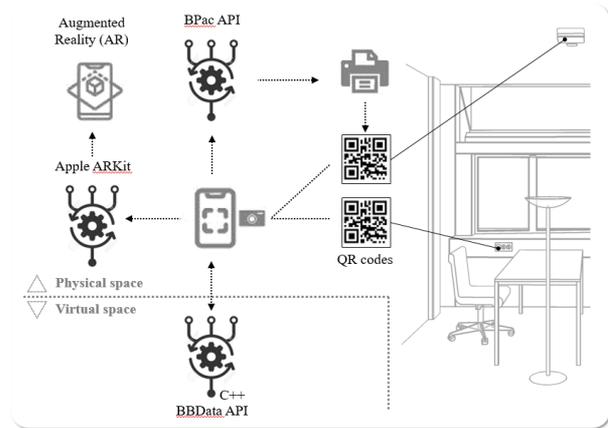


Figure 4: Inventory and virtualisation of actuators and sensors distributed in the physical space, including augmented reality enabled data visualisation

Phase 3 | Information exchange protocol

The information exchange protocol (Figure 5) articulates three interrelated workflows: a) the IFC-Model import into the game-engine software, b) the link between user interface and the databases, and c) the real-time connection between virtual and real sensors and actuators.

- IFC-Model import into game-engine software: a script that allows IFC-data verification and the incorporation of extra information based on the IfcOpenShell schema, which outputs a DAE file (Sony Computer Entertainment - Khronos Group, 2004). A DAE file is a 3D interchange file used for exchanging digital assets between a variety of graphics programs. It may contain an image, textures, or most likely, a 3D model. This format is compatible with game engine software, in our case: Unity (UnityTechnologies, 2005). Through an application of our own making, we were able to transfer IFC data into the VR environment via the DAE file (Duque et al., 2021).
- Link between user interface and BMS (or IoT) databases. An application programming interface (API) to access the two databases: BBData, which stores the values transmitted by the network of sensors and actuators installed in the building space, and DB MTI linking inventory information, digital-model and QR codes.
- Real-time connection between virtual and real sensors and actuators: a code rendering interactive certain model-actuators, such as light switches, as well as a graphic interface making this interaction explicit in the VR environment. The API transmits information from and to the BMS database, managing a two-way control. When touching the light-switch in the virtual environment, the corresponding light in the real space is turned-on in real-time. The actuator state of light and switch automatically update to their new status, and the API transmits the information back to the virtual environment:

virtual light shows switched-on and the switch, by a graphic convention, changes from red (off) to green (on). During this real-time synchronisation, all IFC information remains available.

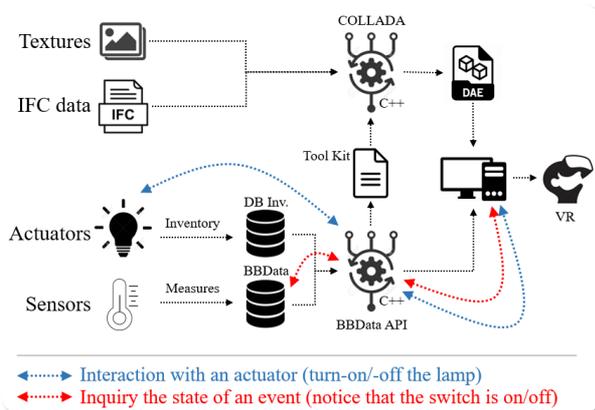


Figure 5: Information exchange protocol.

Phase 4 | Case study test

With the components previously described and applied to the case study, we were able to switch on and off a LED free-standing lamp (Regent, 2021) by virtually pressing a switch contained in the BIM model, which was in turn accessed via the VR environment (UnityTechnologies, 2005). Figure 6 presents a schematic representation of the office space.

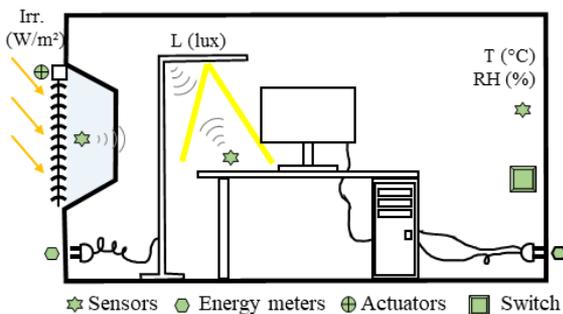


Figure 6: Schematic diagram of case study's sensors and actuators.

In standard operation, the BBDData database shows information about the status of objects. In the case of our lamp, this status shifts between ON and OFF.

The purpose of our test was to measure to what extent we were able to change this status by pressing, not a button in the physical space, but rather its digital twin in a virtual reality environment.

The test focused on demonstrating that the information flow correctly followed the paths illustrated in Figure 5. Cameras were displayed in order to simultaneously record the remote user, the VR navigation environment and the physical space where the lamp was located.

Figure 7 shows four picture-frames of threshold events taking place during the test:

- **Frame 1**, we see the user wearing the VR headset. The Unity 3D environment displays the virtual furniture and the office windows. The lamp in the actual space is switched off (Off mode in the database).
- **Frame 2**, the user takes the controls, and is able to interact in the virtual environment using "virtual hands".
- **Frame 3**, the remote user is about to press the button placed on the virtual wall. The colour of the button is "red" reflecting the status "off" of the object lamp in the database.
- **Frame 4**, the moment the user clicks on the virtual button; he triggers an event that almost simultaneously activates the actuator to turn "on" the real lamp, changes the value of the object's status in the database, and causes the button on the virtual wall to turn "green".

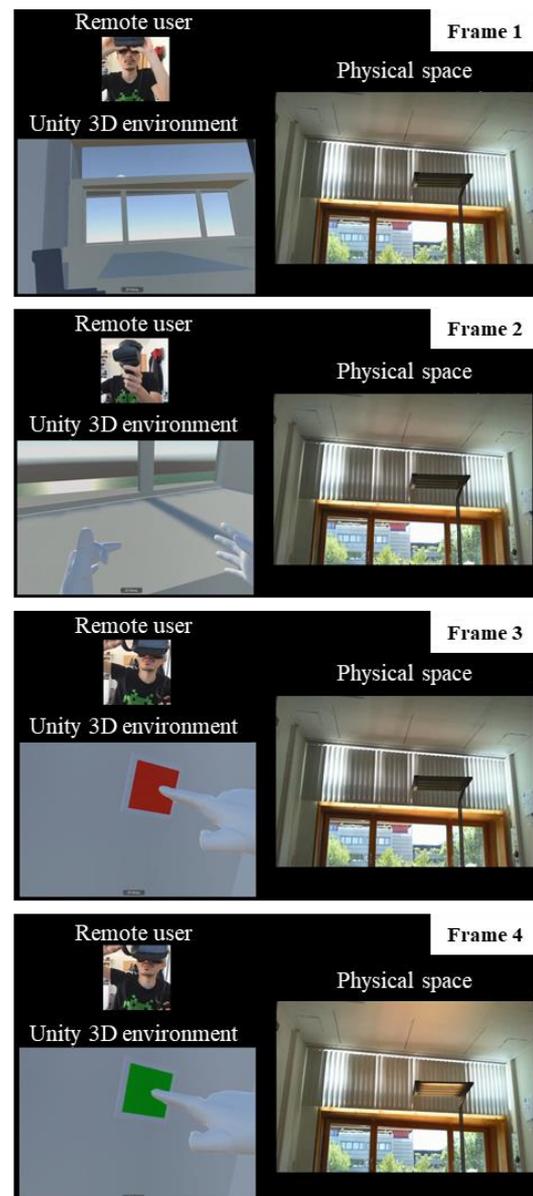


Figure 7: four picture-frames thresholds of a real-time recorded test.

Discussion

The test and validation of the workflow phases described are the main contribution of this article. For the sake of comprehension and fluidity, we have presented these phases and the articulation of the different workflows involved as a harmonic and all-connected whole. In reality, what we have actually tested is separate portions of those workflows, which roughly correspond to the four phases described in the methodology chapter. We have certitude that each piece of the puzzle matches and plays its role with its neighbouring pieces, but we did not put the puzzle together yet. This fact raises questions, uncertainties, and challenges, which can be summarised in three groups: 1) data fluidity in scaled-up version, 2) up-dates management and 3) unforeseen technical obstacles.

1. Data fluidity in a scaled-up version: the real-time test with the lamp and switch described above did not show any latency problem. Both virtual and real status of lamp and switch shifted smoothly as the user interacted. Nevertheless, such information fluidity may not be the same, when all elements will be connected to the information flow, or when the user may apply several actions in a relatively simultaneous way. A slight latency is enough to feel the interaction ergonomically uncomfortable.
2. Updates management: as stated above, one of the main advantages of investing in BIM methodologies and IoT building control is the promise of information flow from one construction phase to the next, including modifications updates after maintenance. In our tests, we have checked that the connectivity between elements is ready to support modification and automatic updates. However, the bridge connecting the virtual and the real world does not always offer full visibility. We already can anticipate some problems that we have faced in our current practice, such as firmware modifications, undeclared replacement of pieces during routine maintenance, and wrong versioning or update failures of digital models. For the time being, we have not set a protocol to verify that all these types of modifications will be automatically updated or, at least, will trigger a sort of alarm. For instance, even if a technician duly declares the replacement of a sensor, it may happen that the sensor provided has changed the embedded firmware. The reference is the same, it will show perfectly connected, but will not send any data, simply because the system protocol does not recognise the new firmware. Such problems must be addressed in time in order to secure a reliable BIM to IoT network.
3. Unforeseen technical problems: it is hard to predict problems, but encountering problems during the process is already a reliable sign that more problems will come as the project progresses. For instance, one obstacle that we faced, was the transmission of material texture into the IFC data model. This issue

led us to create a sort of sub-research, to the point that we ended up creating our own application to overcome a problem which was intrinsic to the IFC definition (Duque et al., 2021). We expect that a number of such problems may arrive as all workflows are connected together.

Conclusion

We have described a workflow for VR-enabled building-data management through the combination of a fully integrated IFC-BIM model and an IoT-based building management system. That is, to be able to immerse in virtual space, interact with sensor data and manipulate real actuators from the virtual environment. In order to achieve that, we have moved through four methodological phases.

First, we generated an IFC file, exported from a 3D BIM model of a real physical workspace. Second, we created a digital inventory of sensors and actuators present in the space, which we stored in a database. Third, we defined and tested a complete protocol to exchange information between the system's components: the IFC-Model, the databases storing inventory of devices and data from sensor-measurements and actuators' status, as well as the VR environment. Fourth, we have been able to set an IoT network, allowing the user a double-way control of objects and data from within the VR environment. When touching the light-switch in the virtual environment, the corresponding lamp in the real space is turned-on in real-time. The actuator state of light and switch automatically update to their new status, and this information is transmitted back to the virtual environment, making the virtual switch and lamp reflect the status change. During this real-time synchronisation, all IFC information remains available.

As said, this workflow remains to a certain extent hypothetical, since our research has actually tested all the partial connections of the information flow, but not the whole. Nevertheless, these partial achievements show enough evidence that future developments and practical applications are feasible. In a near future, we will be able to use immersive experiences provided by Virtual Reality as well as in-situ interaction favoured by Augmented Reality, to realise different validation and control operations such as: 3D inspection of building MEP systems; 3D visualisation of real-time data collections; and remote control through 3D navigation for Facility Management operations. As mentioned, VR and AR real-time interaction may also change the way we currently build. Who needs wires and real switches upon walls when lights can be controlled from your mobile or a nearby screen?

References

- Autodesk. (2019). Autodesk Revit Software. Retrieved from <https://www.autodesk.com/>

- BuildingSMART. (2020). Industry Foundation Classes (IFC). Retrieved January 28, 2021, from <https://technical.buildingsmart.org/standards/ifc/>
- Chang, K. M., Dzeng, R. J., and Wu, Y. J. (2018). An automated IoT visualization BIM platform for decision support in facilities management. *Applied Sciences (Switzerland)*, 8 (7).
- Duque, S., Aguacil, S., Stoll, A.D., Deschamps, L. (2021). Texture mapping and IFC material retrieval for virtual reality applications. Proceedings from: Building Simulation 2021 Conference. Bruges (Belgium), 1-3 September 2021.
- iCoSys-HES-SO/Fribourg, IEnergy-HES-SO/Fribourg, and Smart Living Lab. (2018). *BBDATA – Big Building Data. A cloud platform for data storage and processing for Smart Living Lab*. Retrieved from <https://www.smartlivinglab.ch/fr/infrastructures/bbdata/>
- Jo, D., and Kim, G. J. (2019). AR enabled IoT for a smart and interactive environment: A survey and future directions. *Sensors (Switzerland)*, 19 (19).
- Jourdan, M., Meyer, F., and Bacher, J. P. (2019). Towards an integrated approach of building-data management through the convergence of Building Information Modelling and Internet of Things. *Journal of Physics: Conference Series*, 1343 (1).
- Kiviniemi, A., Tarandi, V., Karlshøj, J., Bell, H., and Karud, O. J. (2008). Review of the Development and Implementation of IFC compatible BIM Executive Summary. *ERA Build*, 1–2.
- Linder, Lucy, Damien Vionnet, Jean Philippe Bacher, and Jean Hennebert. (2017). Big Building Data-a Big Data Platform for Smart Buildings. *Energy Procedia*, 122, 589–94. <https://doi.org/10.1016/j.egypro.2017.07.354>.
- Nguyen, H. T. (2016). Integration of BIM and IoT to improve the building performance for occupants ' perspective.
- Olof Granlund Oy, Jokela, M., Laine, T., and Hänninen, R. (2012). Series 12: Use of models in facility management. Common BIM Requirements 2012, 23.
- Parsanezhad, P. (2019). Towards a BIM-enabled Facility Management: Promises, Obstacles and Requirements.
- Poljanšek, M. (2017). Building Information Modelling (BIM) standardization. JRC Technical Reports.
- Quinn, C., Shabestari, A. Z., Misic, T., Gilani, S., Litoiu, M., and McArthur, J. J. (2020). Automation in Construction Building automation system - BIM integration using a linked data structure. *Automation in Construction*, 118 (May), 103257.
- Regent. (2021). Level Office Lamp (LED free-standing luminaire). Retrieved January 28, 2021, from <https://www.regent.ch/en/products/product-finder/line/freestanding-luminaire-level-office/>
- SLL (2021). Smart Living Lab. Retrieved April 14, 2021, from <https://www.smartlivinglab.ch/en/infrastructures/smart-living-building/>
- Sony Computer Entertainment - Khronos Group. (2004). COLLADA.
- Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-bozorgi, P., and Gao, X. (2019). Automation in Construction A review of building information modeling (BIM) and the internet of things (IoT) devices integration : Present status and future trends. *Automation in Construction*, 101 (June 2018), 127–139.
- UnityTechnologies. (2005). Unity cross-platform game engine. Retrieved January 28, 2021, from <https://unity.com/>