Saving Energy with Comfort: A Semantic Digital Twin Approach for Smart Buildings

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Abstract

Building Energy Management Systems (BEMS) aim to optimize building assets for saving energy without compromising humans' comfort. BEMS must integrate heterogeneous components and complex architectures for monitoring building conditions and controlling building assets such as lights, heating, and air ventilation systems. To tackle interoperability issues and support heterogeneity in smart environments (smart buildings), semantic technologies have been extensively used. Semantically interlinked/integrated information related to energy optimization and comfort in smart buildings can be effectively utilized in decision support tools/systems, if it is efficiently provided to decision makers, via their digital twins. Visualizing semantically integrated real-time sensor information within the digital asset, and supporting the real-time actuation of semantically annotated assets via the interaction with their digital twin, can support decision making in smart buildings for saving energy with comfort. In this paper, a semantic digital twin approach for smart buildings is proposed, along with a first prototype implementation in the energy-saving domain.

Keywords

BEMS, Semantics, Digital Twin, Smart Building, Comfort.

1. Introduction

Indoor Environmental Quality (IEQ) is today one of the most important observable properties related to building assets, especially during the last years with the COVID pandemic. Improving IEQ is essential during the development and integration of BEMS [1]. IEQ consists of thermal, visual, and acoustic comfort. Mainly, thermal and visual comfort are studied and deployed during indoor optimization processes as they may be easily controlled (i.e., temperature regulation, lights adjustment) through smart actuators (e.g., smart thermostats, smart light switches). BEMS main objective is to maintain ideal and comfortable environmental conditions for the occupants, while mitigating energy consumption [2]. Nonetheless, stakeholders (managers, decision-makers, end-users) are not able either to understand BEMS data-driven optimization processes or follow simulations without visualizing and enhancing the data into a realistic

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simulation environment, like a Digital Twin (DT). The reproduction of actual use cases into digital twin scenarios helps stakeholders to identify and implement the optimal IEQ.

Indicatively, a use case scenario for IEQ thermal actions involves the pre-heating of a room to ensure that the occupants will be comfortable when entering it [3]. Initially, indoor conditions (i.e., temperature and humidity) are retrieved by smart sensors to estimate thermal comfort exploiting a methodology as described in [1]. If the room is cold, then the thermostat temperature will be set at an optimal temperature of 22 degrees Celsius [4] to heat the room. It should be noted that thermal comfort is periodically estimated and evaluated, indicating Predicted Mean Vote (PMV) levels [5]. When the room PMV reaches or even exceeds the desired estimated comfort levels (i.e. $-0.5>PMV>0.5$ [1]) the thermostat may be set at a lower temperature (e.g., 21 degrees) to maintain thermal comfort levels while saving energy. These actions combine both thermal comfort regulation and energy optimization [6]. The visualization of real-life thermal comfort use case scenarios or their simulation via a digital twin using a heat map, facilitates the decision-making actions and increases indoor conditions awareness.

By the same token, another use case scenario for visual comfort regulation through controlled light actions, results in energy savings and IEQ optimization. Likewise, indoor illumination conditions may be measured by a smart sensor and visual comfort is observed and monitored [1]. A forgotten turned-on room light during a sunny day, with increased visual comfort levels, indicates that the room light should be turned off to save energy. In contrast, when low visual comfort levels are recorded (e.g., at night) and at the same time human presence is detected, then there is a clear indication that the lights should be turned on. The digital twin representation or simulation of various visual comfort conditions and controls is of key importance for optimal end-user decisions.

BEMS must integrate heterogeneous and complex architectures for monitoring building conditions and controlling building assets. To support heterogeneity in smart buildings, and to provide a mechanism for interoperability at the application level, semantically interlinked/integrated information related to energy optimization and comfort can be effectively utilized in decision support systems. Visualizing semantically integrated real-time sensor information (e.g., temperature and humidity observations) within the digital asset (e.g., digital room), and supporting the real-time actuation of semantically annotated assets (e.g., heater, lights) via the interaction with their digital twin (e.g., digital switch), can support decision making in smart buildings for saving energy with comfort

In this work, we aim to present a first prototype application of a semantic digital twin approach for smart buildings, focusing on the observation, monitoring and optimization of comfort levels along with energy consumption, in other words, “saving energy with comfort”. The proposed semantic digital twin approach is based on the concept of representing integrated knowledge for both the physical and the digital twin of a smart building, reusing existing related semantic models. The demonstrated prototype emphasizes analytics and comfort level visualization within the Semantic Digital Twin (SDT). However, semantically integrated real-time sensor information and real-time actuation of semantically annotated real building assets are also demonstrated. The work is motivated by recent research reports [7], [8], [9] showing that semantically interlinked/integrated information related to energy optimization and comfort in smart buildings can be effectively utilized in decision support tools/systems if this information is efficiently provided to decision makers via their digital twins.

The remainder of the paper is structured as follows: Section 2 presents related work on BEMS and related semantic models. Section 3 presents the proposed approach for a semantic digital twin, discussing our first designs and implementations of a “saving-energy with comfort in DT” ontology and a demo application for selected use case scenarios. Section 4 presents preliminary results generated from the experiments with the demo application. Section 5 concludes the paper.

2. Related Work

A BEMS is a system designed to observe indoor conditions and intervene to electric loads aiming to optimize energy consumption usage without overwhelming residents’ comfort [10]. BEMS must enable interlinking, integration and communication between heterogeneous and disparate components, protocols and assets to perpetually operate [11]. To expedite the interconnections between all those modules and ensure interoperability, semantics must be deployed [12]. Some of the most well-known and deployed semantic models tailored to BEMS and digital twins are presented in this section.

The Smart Appliances REFerence (SAREF) ontology [13] lists the matching of building devices and assets and was used as basis and extension of other widely used BEMS ontologies related to energy and comfort. Such SAREF extensions are for instance SAREF4ENRG [14] mainly extended to the energy sector, and SAREF4BLDG [15] extended to the building domain. Furthermore, other ontologies aim to interlink various BEMS properties, attributes or processes, like BOT [16] building topology related ontology, EEPSA [7] ontology tailored to energy efficiency, and ComfOnt [8] tailored to indoor comfort. Additionally, other ontologies use attributes of aforementioned and other ontologies (e.g. SSN/SOSA [17], Building Management System (BMS) ontology [18]), and add information about specific sectors like museums (e.g. MESO [19], SmartMuseumOnto [9]).

All the above ontologies well-represent BEMS properties, but they lack conceptualizations related to the interlinking of DT, BEMS, and especially extension and deployment with IEQ/comfort. Other related ontologies represent knowledge that is related to DTs. A DT ontology [20] is capturing the fundamental knowledge needed for the DT domain. Likewise, AML4DT [21] is a framework that supports the deployment and description of DTs using AutomationML (AML) models, based on Azure Digital Twins (ADT) [22]. The RealEstateCore ontology [23] is an open-source ontology for smart buildings and Azure Digital Twins. Furthermore, the work proposed in [24] reuses Building Information Modeling (BIM).

In our work, we identify the need for a new model that emphasizes on the representation of knowledge related to energy saving with comfort within a DT simulation environment. In this environment, semantically integrated and visualized real-time sensor data/information (e.g., temperature, humidity, illuminance observations) within a digital asset (e.g., a digital room), is used to support real-time actuation of semantically annotated physical objects (e.g., a smart heater, smart lights) via the interaction with their semantically interlinked DTs (e.g., a digital switch). Such a semantic model is reusing existing ones and may be utilized by DT applications, such as the one demonstrated in this paper, to support decision making in smart buildings for saving energy with comfort.

3. Proposed Approach

3.1. Conceptual architecture

To implement the proposed approach a layered architecture is designed, as depicted in Figure 1. Such an architecture reduces the dependency between its discrete layers, facilitating the portability and the flexibility, while connecting the various layers with semantics. Moreover, these layers may be implemented in parallel or be isolated to run by demand if needed. Finally, the layers of this architecture may be enhanced with more manageable features, if so desired.

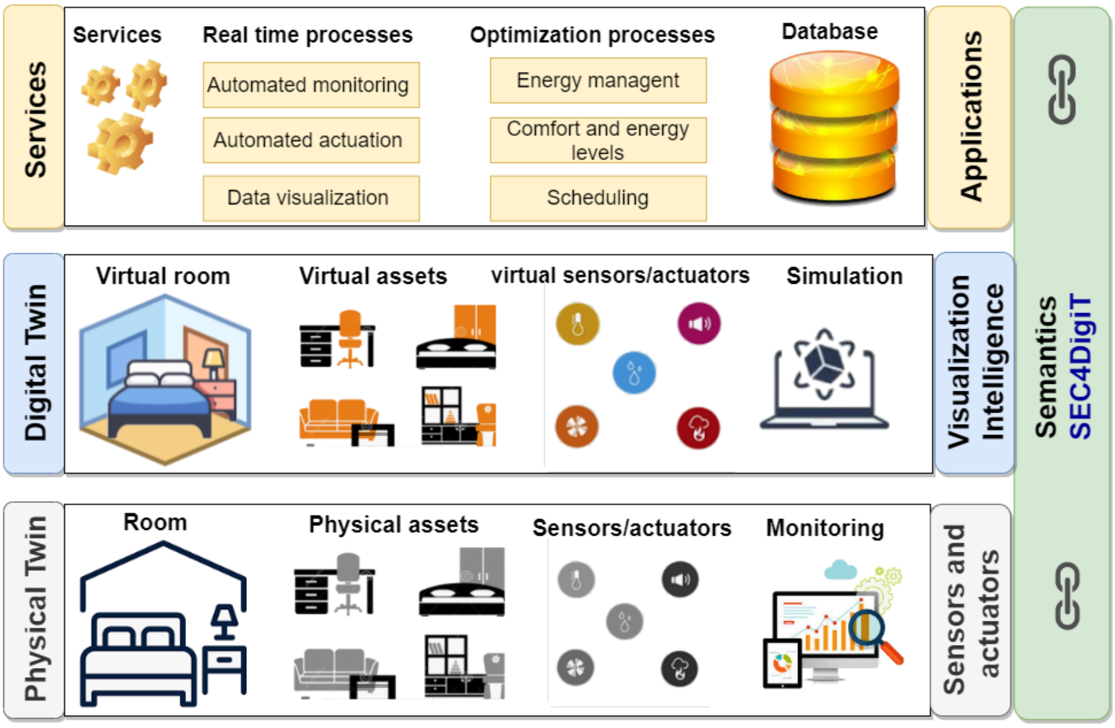

Figure 1: SEC4DigiT conceptual architecture

The *Physical Twin* layer consists of the monitored room and its assets. This layer includes both the physical and the smart room. The physical room is described by features providing details for the room itself (e.g., longitude, latitude, and size) this information could be retrieved by a Building Information Model (BIM) of the respective building. Accordingly, the smart room describes all the smart devices, sensors, and actuators (e.g., energy analyzers, multi-sensors, smart plugs, smart thermostats) installed to monitor indoor environmental conditions, energy consumption and generation. Monitoring at this level is referring to the data streams coming directly from the smart room. Monitoring data from the sensors are pushed to the Semantic Layer. Each physical room is associated with a smart room, which is related to specific devices, sensors and actuators.

The *Digital Twin* layer consists of the virtual room, its assets, and the virtual sensors. The virtual room is a replica of the physical room and represents all the physical assets and the smart room. Furthermore, there are digital sensors and actuators. Digital sensors and actuators may just visualize data streams of the real sensors and actuators, but they may also simulate digital data to facilitate the decision process, and even send control actions to the real sensors. Data streams pushed to the digital twin are deriving from the semantic layer.

The *Service Layer* consists of all processes and applications to manage the smart room, and consequently the physical room itself. In this layer, actual monitoring (i.e., raw sensor data processing to readable data) and actuation services are deployed as a functional part of a BEMS. Moreover, all the optimization processes (e.g., comfort levels, energy levels, energy optimization) are applied in this layer and retrieved by the semantic layer. Finally, a scheduling process is also developed in this layer, to plan actions and interventions.

All the above levels communicate with the *Semantics Layer.* This layer semantically enriches all types of data and information, and interconnects the physical and digital twin, and the Service Layer. Following the proposed approach, end-users and building managers may query all the assets and devices of the physical and digital twin, and make decisions in a more strategic and technical way.

3.2. Semantic model description

Our SEC4DigiT (Saving Energy with Comfort for Digital Twins) ontology is a work-in-progress and available on GitHub [1] along with the demonstrated application. This first draft version developed to support the DT demo application is based on the SSN/SOSA and BOT (W3C) ontologies. Such a conceptualization decision was made, in contrast to the selection of related ETSI [2] ontologies (SAREF/SAREF4ENRG/SAREF4BLDG), since they provide more flexibility in the application-oriented and data-driven development of the model. Nevertheless, future plans include the development of an alternative model, for the same application domain, reusing ETSI ontologies, and evaluating suitability of the related standards selected (W3C and ETSI). To this extend, we will also reuse related knowledge from well-defined and evaluated ontologies, such as EEPSA (candidate knowledge includes External Building Element, Wall, Window, Door, External Wall/Door/Window, Observable quality, Comfort quality, Illuminance, Indoor temperature, Indoor humidity, Meteorological quality, Outdoor temperature, outdoor humidity, wind speed, etc.).

The main definitions of the developed model are summarized below. They are organized in two main modules, the Digital Twin, and the Comfort Observations module. In the first draft version on the ontology, this modularization decision is not reflected, and the conceptualizations of both modules are included in a single ontological model. The developed ontology is used to semantically annotate and integrate the data managed in the DT demo application. The populated version of the ontology includes examples of visual comfort observation data from the visual comfort use case scenario as described in the Introduction, implemented in the demo application. The non-prefixed classes/properties described below are defined in the proposed ontology namespace (the proposed prefix of the SEC4DigiT ontology is sec4dt).

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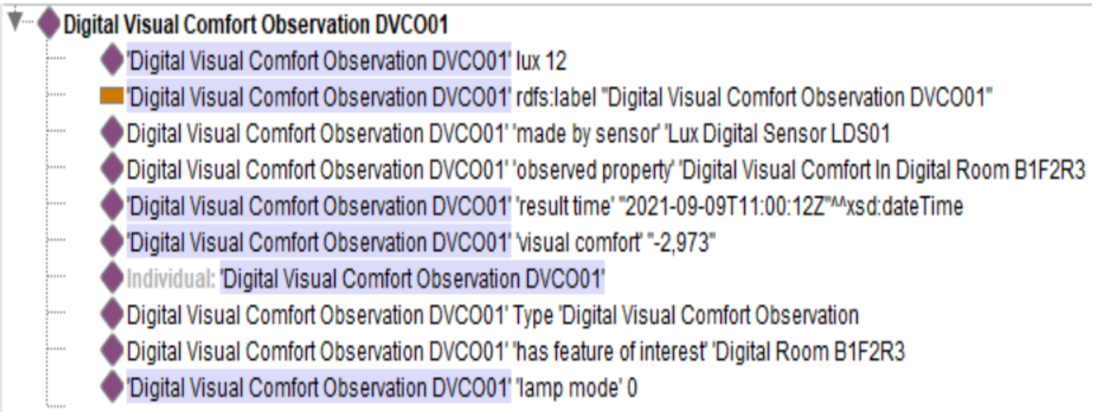
[1] https://github.com/KotisK/SEC4DigiT

[2] https://www.etsi.org/

Digital Twin module. Represents the Digital Twin concept (subconcept of a Digital Asset), distinguished from the Physical Twin concept (subconcept of Physical Asset). Both assets are defined as a sosa:FeatureOfInterest (sosa as prefix of SOSA ontology) and comprises some assets (Digital Assets or Physical Assets respectively). A Digital Twin classifies entities such as a Digital Lamp, a Digital Thermostat, a Digital Room, whereas a Physical Twin classifies the corresponding Physical Lamp, Physical Thermostat, Physical Room. Smart assets such as a Smart Lamp, a Smart Thermostat or a Smart Room are classified as subconcepts of the corresponding physical ones. A Smart Room is a Physical Room classified as a bot: Element (bot as prefix of BOT ontology namespace), and comprises some assets such as a Smart Room Intelligent System, a sosa:Sensor, a sosa:Actuator, etc. All physical, digital, and smart Assets in the ontology are defined as a sosa:FeatureOfInterest.

Comfort Observation module. The concepts of sosa:Observation and sosa:ObservableProperty are utilized to define the proposed conceptualizations related to comfort (visual, thermal, and acoustic) observations in both the digital and the physical twin. As such, a Digital Visual Comfort is a Visual Comfort property, subclass of Comfort and IEQ classes respectively. On the other hand, a Digital Visual Comfort Observation is a Visual Comfort Observation, subclass of sosa:Observation.

As an example (Figure 2), observations, such as a “Digital Visual Comfort Observation DCVO01”, are linked with a) observable properties such as the “Digital Visual Comfort in Digital Room B1F2R3” via the sosa:observedProperty, b) sensors such as the ’Lux Digital Sensor LDS01’ via the sosa:madeBySensor, c) features of interest such as the “Digital Room B1F2R3” via the sosa:hasFeatureOfInterest. Data of the related observations are recorded via appropriate properties such as “lux”, “visual comfort”, “lamp mode”, “result time”. proposed ontology namespace (the proposed prefix of the SEC4DigiT ontology is sec4dt).



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Digital Visual Comfort Observation DVCO01
    'Digital Visual Comfort Observation DVCO01' lux 12
    'Digital Visual Comfort Observation DVCO01' rdfs:label "Digital Visual Comfort Observation DVCO01"
    Digital Visual Comfort Observation DVCO01' 'made by sensor' 'Lux Digital Sensor LDS01
    Digital Visual Comfort Observation DVCO01' 'observed property' 'Digital Visual Comfort In Digital Room B1F2R3
    'Digital Visual Comfort Observation DVCO01' 'result time' "2021-09-09T11:00:12Z"^^xsd:dateTime
    'Digital Visual Comfort Observation DVCO01' 'visual comfort' "-2,973"
    Individual: 'Digital Visual Comfort Observation DVCO01'
    Digital Visual Comfort Observation DVCO01' Type 'Digital Visual Comfort Observation
    Digital Visual Comfort Observation DVCO01' 'has feature of interest' 'Digital Room B1F2R3
    'Digital Visual Comfort Observation DVCO01' 'lamp mode' 0
```

Figure 2: Example definition of a digital visual comfort observation (screenshot taken from Protege 5.5

The ontology was developed following the HCOME collaborative engineering methodology, as revised in latest related work[9], supported by Protege 5.5 for personal space engineering, and Web Protégé for shared space engineering tools respectively. In addition, Google docs and

Meet have been used for further collaborative tasks of the ontology specification.

3.3. Application description

To generate the Digital Twin of a room Unreal Engine 4 (UE4) was used, which is a game engine that accelerates the creation of digital worlds. To visualize physical entities, such as the Physical Lamp and the Physical Thermostat, we used the Blueprint Visual Scripting system in UE4. This system is leveraged to define object-oriented (OO) classes and objects in the engine. To model each physical entity, we implemented a corresponding Blueprint (BP) class, which we are using throughout our demo (e.g., BP Lamp for the physical lamp and BP Thermostat for the physical thermostat). Once the digital model is created, the process of visualizing collected data from IoT sensors consists of the following steps:

1. Pre-processing and parsing collected data from sensors to the engine.
2. Building a material shader that defines the way objects look based on given data.
3. Driving parsed data into the material shader.

The data communication between IoT sensors, such as various sensors that are available on Arduino [3] and UE4, can be achieved using an open-source plugin called UE4Duino. In the case of Arduino, sensor data streams are retrieved from an automated process and are printed to its console, and then are processed via a COM3 port on the Blueprint side. When the user posts messages to the console, data streams are pushed to Arduino. The process that is running on the microcontroller is responsible for parsing the console messages to determine the actions that must be taken. To this end, digital twins of physical entities are created since the above workflow provides a two-way communication between sensors and the digital world in the UE4.

Except for the generated Blueprints that model physical entities, two additional BP classes were implemented, namely BP ThemalComfortVisualization and BP VisualComfortVisualization, which are responsible for visualizing the collected data in our Digital Twin. Once data has been parsed, these BPs go through each parsed value in a fixed timestep and send it over to a Material Parameter Collection (MPC). The MPC is used by the material shader of each object in our scene, thus allowing us to change the overall look of the DT in a uniform manner.

The material shader used in all objects is responsible for blending the default texture of each object with a solid color corresponding to a data value. In order to correlate data values with colors, the data range was remapped, which was originally between [-3,3] to [0,1], thus allowing us to retrieve colors from colormap textures.

Currently, the demonstrated application is using synthetic data for visual comfort observations, provided in CSV format. Next version of the application will retrieve such data from an RDF triple store (e.g., TDB2) utilizing a SPARQL endpoint run on a suitable server (e.g., Apache JENA Fuseki2). To realize such functionality, semantically annotated comfort observation data (using the semantics of Sec4digiT ontology) will be stored and retrieved as RDF triples.

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[3] https://www.arduino.cc/

4. Experiments and first results

4.1. Thermal Comfort use case scenario Digital Twin

As described in the Introduction Section, we have designed and implemented a real-life use case scenario of digital thermal comfort, replicated from a physical building. As depicted in Figure 3, initially (instance th.1), indoor conditions (temperature, humidity) are monitored, and thermal comfort is estimated and visualized to the DT. As indicated from the color map, indoor thermal perception is cold (blue). As a result, an optimization action is performed, and the thermostat is set to 22 degrees Celsius to heat the room (instance th.2). The indoor temperature starts rising and eventually the indoor conditions change from cold to slightly hot (orange) as presented in instance th.3. As a result, an optimization action is performed, and the thermostat is set to 20 degrees Celsius (instance th.4). This action restores the thermal comfort levels to neutral (green), while ensuring energy savings.

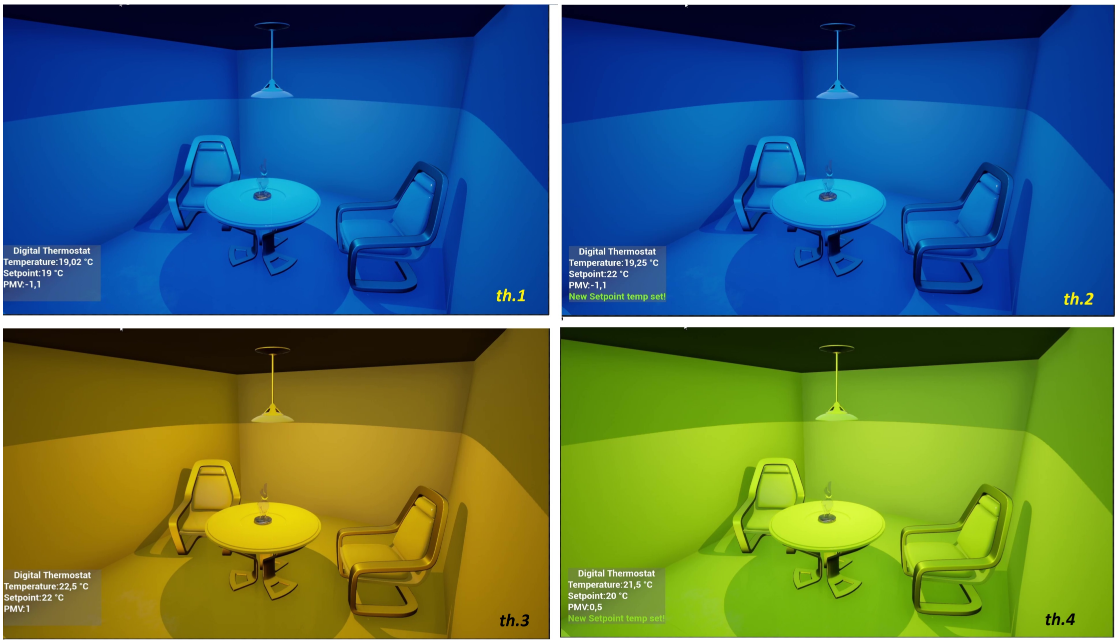

Figure 3: Thermal comfort monitoring, regulation, actions, and visualization

4.2. Visual comfort use case scenario Digital Twin

Likewise, a real-life use case scenario of digital visual comfort replicated from a physical building has been designed and implemented. As depicted in Figure 4, a smart room is given where the illuminance condition and the Visual Comfort (VC) are monitored, VC is estimated and then visualized to the DT. Suppose that initially, indoor visual comfort is estimated as dark (blue), while the sun starts rising (instance vis.1). Since still the daylight is not sufficient and indoor visual comfort is not neutral, the light is turned on (instance vis.2). This control action results in increasing the visual comfort levels. After a while, as the daylight is sufficient an optimization action is performed, and the light is turned off (instance vis.3). As a result, the VC is maintained to a comfortable level while saving energy. During the night, the visual comfort is estimated and visualized to the DT as dark (instance vis.4). If motion is detected in the room a control action is performed and the light is turned on (instance vis.5). This action results in increasing the VC levels.

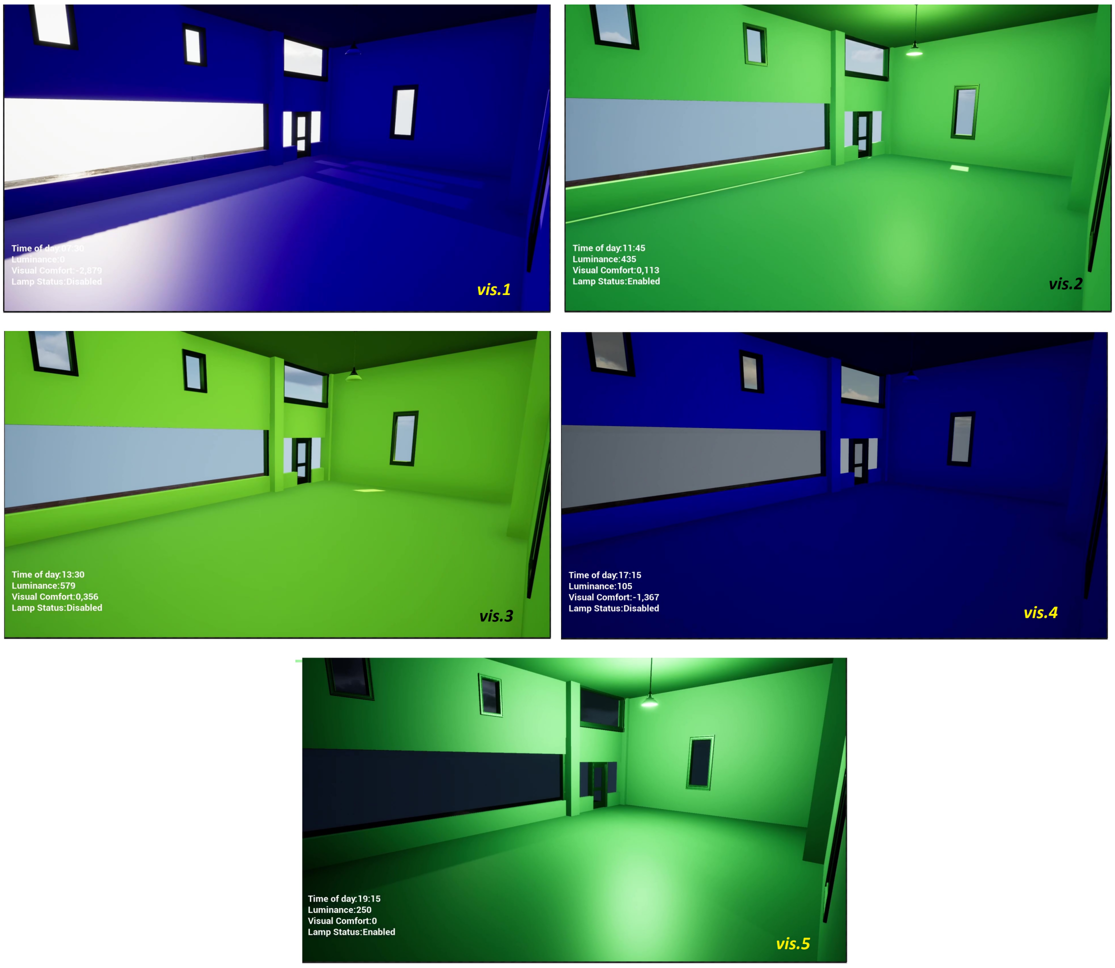

Figure 4: Visual comfort monitoring, regulation, actions, and visualization

5. Conclusions and Future work

In this paper we have presented a preliminary work on energy saving with comfort in semantic digital twins. Specifically, we have presented the implementation of the proposed approach, i.e., a) the Sec4DigiT ontology for the representation of semantically described integrated data related to a digital twin that focus on saving energy with comfort and b) a digital twin application that simulates scenarios related to visual and thermal comfort observations, as those are represented in the Sec4DigiT ontology.

Future work includes the implementation and the integration of further semantics in the application logic. Then, a complete alignment of ontological classes with application functionality/logic will be approached. As such, the full extent of SPARQL and SPIN technology for managing represented knowledge (sensing, actuating, comfort, energy) will be exploited. Last but not least, we have already designed the evaluation of the proposed approach in two real scenarios that involve a smart home research infrastructure and a smart museum respectively. In this evaluation setting, working with real-time and big data, we will identify and tackle potential limitations of the approach, such as scalability, querying response time, persistent and in-memory storage of RDF triples, reasoning capabilities, etc.

References

[1] A. Dimara, S. Krinidis, D. Tzovaras, Comfit: A novel indoor comfort inference tool (2021). doi:`10.1049/icp.2021.1228`.

[2] Z. Chen, Y. Chen, R. He, J. Liu, M. Gao, L. Zhang, Multi-objective residential load scheduling approach for demand response in smart grid, Sustainable Cities and Society 76 (2022) 103530. doi:`https://doi.org/10.1016/j.scs.2021.103530`.

[3] H. Stopps, M. F. Touchie, Perceptions of thermal conditions in contemporary high-rise apartment buildings under different temperature control strategies, Science and Technology for the Built Environment 27 (2021) 1492–1504. doi:`https://doi.org/10.1080/23744731.2021.1929465`.

[4] A. Dimara, C. Timplalexis, S. Krinidis, C. Schneider, M. Bertocchi, D. Tzovaras, Optimal comfort conditions in residential houses, in: 2020 5th International Conference on Smart and Sustainable Technologies (SpliTech), IEEE, 2020, pp. 1–6. doi:`10.23919/SpliTech49282.2020.9243788`.

[5] J. Ren, J. Yang, Y. Zhang, X. Xiao, J. C. Xia, X. Li, S. Wang, Exploring thermal comfort of urban buildings based on local climate zones, Journal of Cleaner Production 340 (2022) 130744. doi:`https://doi.org/10.1016/j.jclepro.2022.130744`.

[6] C. D. Korkas, M. Terzopoulos, C. Tsaknakis, E. B. Kosmatopoulos, Nearly optimal demand side management for energy, thermal, ev and storage loads: An approximate dynamic programming approach for smarter buildings, Energy and Buildings 255 (2022) 111676. doi:`https://doi.org/10.1016/j.enbuild.2021.111676`.

[7] I. Esnaola-Gonzalez, J. Bermúdez, I. Fernandez, A. Arnaiz, Eepsa as a core ontology for energy efficiency and thermal comfort in buildings, Applied Ontology (2021) 1–36. doi:`10.3233/AO-210245`.

[8] D. Spoladore, A. Mahroo, A. Trombetta, M. Sacco, Comfont: a semantic framework for indoor comfort and energy saving in smart homes, Electronics 8 (2019) 1449. doi:`https://doi.org/10.3390/electronics8121449`.

[9] K. Zachila, K. Kotis, E. Paparidis, S. Ladikou, D. Spiliotopoulos, Facilitating semantic

interoperability of trustworthy iot entities in cultural spaces: The smart museum ontology, IoT 2 (2021) 741–760. doi:https://doi.org/10.3390/iot2040037.

[10] M. A. Hannan, M. Faisal, P. J. Ker, L. H. Mun, K. Parvin, T. M. I. Mahlia, F. Blaabjerg, A review of internet of energy based building energy management systems: Issues and recommendations, Ieee Access 6 (2018) 38997–39014. doi:10.1109/ACCESS.2018.2852811.

[11] A. Dimara, C.-N. Anagnostopoulos, K. Kotis, S. Krinidis, D. Tzovaras, Bems in the era of internet of energy: A review, in: IFIP International Conference on Artificial Intelligence Applications and Innovations, Springer, 2021, pp. 465–476. doi:https://link.springer.com/chapter/10.1007/978-3-030-79150-6_37.

[12] A. Jozi, T. Pinto, Z. Vale, Contextual learning for energy forecasting in buildings, International Journal of Electrical Power & Energy Systems 136 (2022) 107707. doi:https://doi.org/10.1016/j.ijepes.2021.107707.

[13] L. Daniele, F. d. Hartog, J. Roes, Created in close interaction with the industry: the smart appliances reference (saref) ontology, in: International Workshop Formal Ontologies Meet Industries, Springer, 2015, pp. 100–112. doi:https://link.springer.com/chapter/10.1007/978-3-319-21545-7_9.

[14] SAREF4ENER, Saref4ener: an extension of saref for the energy domain created in collaboration with energy@home and eebus associations, 2022. URL: https://saref.etsi.org/saref4ener/v1.1.2/.

[15] SARE4BLD, Saref extension for building, 2022. URL: https://saref.etsi.org/saref4bldg/v1.1.

[16] M. H. Rasmussen, M. Lefrançois, G. F. Schneider, P. Pauwels, Bot: the building topology ontology of the w3c linked building data group, Semantic Web 12 (2021) 143–161. doi:10.3233/SW-200385.

[17] A. Haller, K. Janowicz, S. J. Cox, M. Lefrançois, K. Taylor, D. Le Phuoc, J. Lieberman, R. García-Castro, R. Atkinson, C. Stadler, The sosa/ssn ontology: a joint w3c and ogc standard specifying the semantics of sensors, observations, actuation, and sampling, Semantic Web-Interoperability, Usability, Applicability an IOS Press Journal 56 (2019) 1–19. doi:http://semantic-web-journal.org/system/files/swj1804.pdf.

[18] A. Kučera, T. Pitner, Semantic bms: Ontology for analysis of building automation systems data, in: Doctoral Conference on Computing, Electrical and Industrial Systems, Springer, 2016, pp. 46–53. doi:https://link.springer.com/chapter/10.1007/978-3-319-31165-4_5.

[19] K. Zachila, K. Kotis, A. Dimara, S. Ladikou, C.-N. Anagnostopoulos, Semantic modeling of trustworthy iot entities in energy-efficient cultural spaces, in: IFIP International Conference on Artificial Intelligence Applications and Innovations, Springer, 2021, pp. 364–376. doi:https://link.springer.com/chapter/10.1007/978-3-030-79157-5_30.

[20] S. Singh, E. Shehab, N. Higgins, K. Fowler, D. Reynolds, J. A. Erkoyuncu, P. Gadd, Data management for developing digital twin ontology model, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 235 (2021) 2323–2337. doi:https://doi.org/10.1177/0954405420978117.

[21] D. Lehner, S. Sint, M. Vierhauser, W. Narzt, M. Wimmer, Aml4dt: a model-driven framework for developing and maintaining digital twins with automationml, in: 2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), IEEE, 2021, pp. 1–8. doi:10.1109/ETFA45728.2021.9613376.

[22] D. Twins, Digital twins – modeling and simulations | microsoft azure, 2022. URL: https:

//azure.microsoft.com/en-us/services/digital-twins/#overview.

[23] RealEstateCor, Realestatecore full, 2022. URL: https://doc.realestatecore.io/3.3/full.

[24] Z. Chevallier, B. Finance, B. C. Boulakia, A reference architecture for smart building digital twin., in: SeDiT@ ESWC, 2020. doi:`http://ceur-ws.org/Vol-2615/paper2.pdf`.