BIM4EEB

BIM based fast toolkit for
Efficient rEnovation in Buildings

D3.2 A refined, integrated domain ontology for occupants, building services, building energy & acoustics

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D3.2 A refined, integrated domain ontology for occupants, building services, building energy & acoustics

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EXECUTIVE SUMMARY

The scope of this document is to properly define relevant ontology modules covering **occupants' behaviours and comfort**, **energy performance of systems** and **components**, and **acoustics** following the methodological approach as specified in D3.1. Therefore, there are three main pillars that consist of the semantic extension as reported in this document.

Occupants' behaviour and comfort analysis

Considering Occupants' behaviour and comfort, the main objective is to define dynamic **occupancy** and **visual/thermal comfort** models towards facilitating the definition of accurate behaviour profiles for occupants in buildings. These models will be integrated in the holistic occupants related framework for the provision of added value services in the BIM4EEB project.
As reported in the DoA, "*thermal comfort models should consider occupants as dynamically interacting entities within their environment through appropriately controlling their preferences (operational mode and settings), mainly driven by the combination of indoor environmental conditions. The aforementioned models typically incorporate and correlate occupancy profiling parameters, so as to allow accurate modelling of comfort in relation to occupants' presence and, subsequent, enhanced forecasting of occupancy schedules.*" By blueprinting the core dynamics about occupants' behaviour and comfort analysis, we proceed with the detailed ontological modeling analysis in the document.

Energy Performance of systems & building components

As stated in the task description, the focus is at semantically modeling of equipment and material parameters along with building services, focusing on the energy perspective; *incorporating "amalgamated parameters" (e.g. for multi-layer components) as power, economic (e.g. operation and maintenance fixed costs, turnkey costs), environmental and thermodynamic (e.g. heat rate, waste heat factor, air injection rates) parameters considering an LCA-LCC approach.*
The 1st layer of the work is the identification of the different equipment/material and building services to be incorporated in the analysis. Furthermore, a thorough definition of the different modeling dimensions is required in order to proceed with the proper modeling of the building entities. As also stated in the DoA "emphasis should be given on modelling the behaviour of small DERs/storage systems frequently introduced in renovation projects at building level". In addition, LCA-LCC related parameters are considered in the analysis.

Acoustics and IAQ model analysis

There are two extra complement layers associated with occupants' comfort conditions in building premises:

- Acoustics comfort models that are able of representing acoustic conditions from sources may have an adverse influence on occupants' comfort as well as on their intellectual and physical performance
- Indoor Air Quality (IAQ) comfort Models that are able to evaluate indoor hygienic and health/well-being conditions through identifying contamination of the air with various compounds, such as carbon dioxide (CO2), carbon monoxide (CO), and volatile organic compounds (VOCs).

Considering that building acoustics and IAQ modeling is tighly linked with the role of occupants in the building environment, the overall modeling work is performed as part of occupancy modeling framework.

By defining the different pillars for the analysis, a thorough state of the art analysis was performed towards reporting the most relevant modeling work on the way to exploit as much as possible existing concepts (as requested during the review of the project). In addition, a detailed analysis of project requirements (34 in total) was performed to define the competency questions (evaluation in D3.6) and to set the basis for the definition of the ontological models of this task.

The outcome of this deliverable is the delivery of the domain ontologies for occupants' comfort and IAQ, building components, energy systems and acoustics incorporating in the analysis the BIM4EEB project specificities. These ontological schemas will be further incorporated in the overall BIM4EEB ontological framework as specified in T3.1 following the harmonization process to be performed in T3.6. and further inherited in the Common Data Environment as the heart of the BIM management system in WP4.

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LIST OF ABBREVIATIONS

Acronym	**Full name**
BIM4EEB	Building Information Model for Energy Efficient Buildings
IAQ	Indoor Air Quality
BIM	Building Information Model
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
DoA	Description of Action

CHP	Combined Heat and Power
VOCs	volatile organic compounds
SoTA	State of the Art
DNAS	Drivers, Needs, Actions, Systems
HVAC	Heating, ventilation and air condition
RECS	Residential Energy Consumption Survey
OPA	Occupant Presence and Action
BES	Building Energy Systems
KPIs	Key Performance Indicators
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
PMV	Predicted Mean Vote
PPD	Predicted percentage of dissatisfied
DERs	Distributed Energy Resources
SAREF	Smart Appliances REFerence
CEM	Customer Energy Manager
IFC	Industry Foundation Classes
CFD	Computational Fluid Dynamics
OH&S	Occupational health and safety
IEC/IEQ	Indoor Environmental Conditions/ Indoor Environmental Quality
LOD	Level of Details

1 Introduction

1.1 Scope of the Document

The scope of this document is to contribute to the BIM4EEB ontological model (as the base for the BIMMS platform) by properly refining relevant ontologies referring to occupants' behaviour and comfort, energy performance of systems and components, and acoustics. These are core principles that are not clearly addressed by the BIM basic model concepts as specified in D3.1 and thus we consider this work as an extension of the BIM4EEB ontology to further serve the design and development of the applications as defined in the BIM4EEB project.
The main pillars further clustered in 3 categories based on the scope of the project are:

- Occupants' behaviour and comfort analysis
- Systems and building components with focus on energy related characteristics
- Acoustics and Indoor Air Quality (IAQ) model analysis

1.2 Approach

Upon defining the scope and the main pillars of analysis, an extensive state of the art analysis on the most recent literature is performed with focus on the ontologies and data models available in the different domains. In parallel, the project-specific requirements and use cases as defined in WP2 [1] are also considered in order to further set the competency questions towards adapting the ontologies in the context of the BIM4EEB project.
By taking into account the results of the State of the Art along with the BIM4EEB project specificities, an in-depth analysis takes place in order to set the main criteria and parameters for the development of the BIM4EEB ontologies on the basis of the existing models.
The next and final step, is the design of the BIM4EEB - related ontology for **occupants' behaviour and comfort**, **energy performance of systems** and **components**, and **IAQ & acoustics.** By applying standardized modeling methodologies, we proceed with the synthesis of the different models in a semantic framework that will be further incorporated in the BIM4EEB BIM management system.
The overview of the methodology is presented in the following figure.

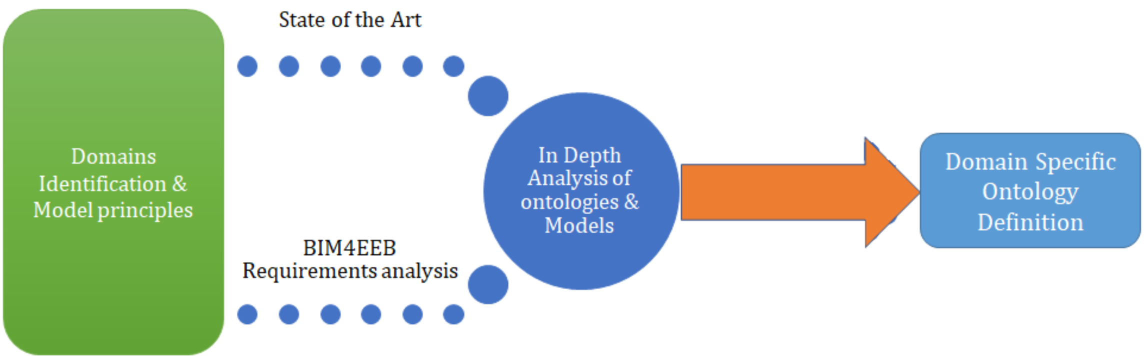

Figure 1: Methodology Definition for semantics analysis

The outcome of this work will further feed the harmonization process, work to be done in T3.6. The different domain-specific classes and properties will be further represented in the Digital Construction Ontologies as part of the BIM4EEB Linked Data and ontology framework.

Overall, the different steps shown in the figure above are briefly presented below:

Step 1: Identification of the domains for analysis and modeling principles
This is the preparatory step that refers to setting the scope of the analysis. As presented above, and following the DoA description for Task 3.2, the focus is to thoroughly analyse occupants' behaviour and comfort, energy performance of systems and components, and IAQ/ acoustics in the building environment towards setting the modeling principles that will be incorporated in the BIM4EEB holistic modeling framework. In addition, the base terminology for information modeling analysis as performed in the deliverable is presented in this section

Step 2a: State of the art analysis of the different domain pillars
The starting point for this analysis is the identification and thorough evaluation of the most relevant models and domain ontologies in the literature. A high-level overview of relevant standards and models is available in the DoA and presented in D3.1. Our work is to go beyond this high-level analysis and proceed with a deep understanding of the relevant standards and models, to be further incorporated in the BIM4EEB framework.

Step 2b: Analysis of BIM4EEB project specific requirements and use cases
While the SoTA analysis is providing a good representation of the domain semantics, the scope of the work is to set a modeling framework that covers BIM4EEB project needs and requirements. Towards this direction, a thorough review of requirements and use cases is performed in order to set the appropriate competency questions as the requirements for the ontology modeling in BIM4EEB project. This analysis is performed in line with the DoA objectives and the list of requirements/ use cases as specified in WP2.

Step 3: In Depth Analysis of selected ontologies and models
This is the elicitation process towards selecting from existing ontologies and data models, the key principles that should be incorporated in our analysis. From the state-of-the art analysis, we should extract a set of ontologies and data models on which BIM4EEB domain ontologies will base (based on specific criteria).

Step 4: Synthesis of the different ontological models
Following the review of literature, the definition of the project specificities and the elicitation process, we proceed with the design of the different ontological models for the pillars examined in the project. Following a bottom-up approach, each domain is examined as a separate view in order to provide a pure ontological framework that incorporates the different modeling features.

The development of the ontology for occupants, building services, building energy and acoustics is not a standalone process. The core principles for the definition of the schema were defined at the very early stage of the project (in T3.1 [2]) and further adopted at the definition of the different ontology domains in WP3 (T3.2 - T3.4). Once the different instances defined, a harmonization process will take place in T3.6 towards the definition of a unified BIM4EEB ontological model based on the project needs and requirements.

1.3 References to other activities and to the state of the art

A main objective of the BIM4EEB is to propose a unified ontological model that will link the different data parameters associated with building performance. This unified model will further serve as the backbone of the enhanced BIM management system towards the development and delivery of added value

renovation-oriented building management services. The different layers of this model should be defined, and this is the scope of the work in WP3.
The core principles and the base BIM ontological model is delivered in T3.1 (D3.1). By taking into account the high-level principles we proceed with the development of the different model extensions in WP3, namely:

- T3.2 Refined domain ontology for occupants, building materials & acoustics, building energy → reported in this deliverable
- T 3.3 BIM representation on different levels of detail corresponding to the renovation process modelling→ in D3.3
- T 3.4 Renovation workflow ontology development → in D3.4

The harmonization of the different ontologies is presented in "T3.6 Harmonisation of ontologies to address the requirements of the renovation domain and semantic mapping/ coupling with external data sources and models" reported in D3.6 to serve as the modeling framework that will serve the application needs of the project as developed in WP4, WP5, WP6 and WP7.
It is evident that the work in this deliverable is clearly related with the state of the art as, starting point for this analysis is the identification and thorough evaluation of the most relevant models and domain ontologies in the literature. A high-level overview of relevant standards and models is available in the DoA and presented in D3.1. Our work is to go beyond this high-level analysis and proceed with a deep understanding of the relevant standards and models, to be further incorporated in the BIM4EEB framework.

1.4 Innovative results and progress

While in Chapter 3 a detailed state of the art analysis is reported, in Chapter 4 the BIM4EEB project specific models are provided. More specifically in chapter 4 we present the domain specific ontological models introducing new concepts that are not covered by existing ontologies while also providing the proper alignments with concepts that already available in existing models (as elicitated on the state of the art work). Thus, apart from the definition of new concepts the scope of this section is to align the different sub domain ontologies for occupants' behaviours and comfort, energy performance of systems and components, and acoustics. This alignment work will further facilitate the harmonization of the different ontologies to the unified modeling framework in D3.6.
Therefore, the main progress and result of the work is the definition of domain specific ontological models that incorporate at a maximum level the concepts as already exist in the aligned ontologies while also introducing new concepts to address BIM4EEB project specific requirements. Also, a main innovation introduced is the adoption of the ontological modeling approach as defined in D3.1.

1.5 Structure of the Document

To address all the aspects relevant to the scope of T3.2, the deliverable has been structured to include the following contents:

- In chapter 1, the introductory section is provided, highlighting the scope, methodology and objective of the deliverable.
- In chapter 2, the review of project specificities is provided in order to define a model that is aligned with project needs and requirements.
- In chapter 3, the state-of-the-art analysis is reported with the focus on the main pillars of the model as defined for this task. In this section, the final elicitation of requirements and data specifications is performed in order to proceed with the modeling work.

- In chapter 4, the ontological model for occupants, building services, building energy and acoustics is presented

In the last chapter, a summary and the main conclusions of the work are reported along with the next steps focusing on the interconnection of the ontology with the BIM4EEB integrated framework.

2 BIM4EEB Relevant use cases and specifications analysis

As already mentioned in the methodology in section 1.2, in order to extract the set of BIM4EEB ontology requirements, the use cases described in WP2 and briefly presented in D3.1 should be considered as input. For that purpose, the content of each use case has to be analysed in order to identify information presentation and exchange needs that could be potentially modelled by the ontology and data model in this deliverable.

Typically, in the ontology engineering field, the ontological requirements are taken in the form of Competency Questions [50] which are natural language questions (interrogative form) that express that question users would like to ask the ontology treating it as a knowledge base. However, sometimes the ontological requirement could be written in the form of affirmative language sentences, like expressing facts. For the case of this deliverable, all requirements have been defined, or rephrased as natural language affirmative facts, and are named “data requirements”.

Overall, the scope of this section is twofold:

- To thoroughly review the list of requirements and use cases as defined in the project so far, with the focus on the domain aspects associated with occupants’, building components, energy systems, building IAQ and acoustics.
- To provide a preliminary list of data requirements (affirmative natural language sentences) that should be further considered as the ontology requirements for the modeling framework established in WP3

The outcome of this analysis will set the input for the modeling work to be reported in the following section of this document.

2.1 Analysis of the BIM4EEB Usage Scenarios

At first, the list of the most relevant usage scenarios (as user stories) is extracted with some key remarks to be further considered for the definition of the modeling framework. A high-level representation of these use cases was presented in D3.1 (as extracted from the BIM4EEB DoA) with the description to be further enhanced with the requirements as identified in WP2.

In addition, and while the analysis performed in D3.1 remains at the conceptual level we proceed with the detailed specifications for the usage scenarios of focus in this task. Therefore, this analysis enables the identification of the relevant data attributes in line with the needs of the BIM4EEB project.

Usage Scenario 1 (US-1)	Establishment of a **comfort preserving framework** for building occupants
Short Description	The scope of this use case is to enable the definition of a comfort preservation framework in building premises considering the occupants behaviour analysis. The incorporation of human comfort in the holistic building management framework is an anchor point of the BIM4EEB project as presented in D2.1, D3.1 and highlighted in requirements analysis in D2.5. Based on the list of requirements as presented in the different documents, the overall framework will take into account: - The different contextual parameters as examined in the project: thermal, visual, air quality and acoustics comfort - The association of contextual conditions with the different building spaces and business processes performed in premises - The need to establish a personalized and adaptive framework, with the end users able to set and update the individual settings about their comfort and IEQ preferences.

	- The continuous updates on the comfort model parameters, incorporating non-static approaches for the extraction of occupants' comfort preferences. - The incorporation of real-time values about contextual conditions in premises and further association with the most relevant IEQ performance indicators. In summary, the high-level objective of this scenario is to establish a user-driven behavioural profiling framework that will be smoothly incorporated in the Building Information Model
Relevant Data Requirements (associated with usage scenario definition)	○ **OC1: Role-specific configuration parameters about** occupants (Age, Gender, Lifestyle, etc.) ○ **OC2: Activity profiling related parameters:** typical activities (actions) that should be incorporated in the overall profiling framework of the project ○ **OC3: Occupancy related profiling parameters** at specific building zones**:** (max occupancy level, presence, level of occupancy, etc.) ○ **OC4: Indoor environmental conditions** at specific building zones: temperature, humidity, luminance, IAQ conditions, sound etc. associated with the related **IoT sensor device** temperature, humidity, CO2, VOC, luminance sensor etc. ○ **OC5: User Settings and preferences about indoor environmental conditions:** Occupant specific settings about Indoor environmental and operational conditions, focus on actuations over device functions ○ **OC6: Occupant comfort preferences:** thermal comfort/ visual comfort and acoustics comfort parameters and the model parameters to be considered for the extraction of occupants' comfort preferences

Table 1: BIM4EEB Usage Scenario 1 - Establishment of a comfort preserving framework for building occupants

In addition, the need of building materials modeling within the context of BIM4EEB project is presented in the following table.

Usage Scenario 2 (US-2)	Establishment of a **modeling framework for building materials**
Short Description	The scope of this use case is to enable the definition of the modeling framework for the building material during the whole lifecycle of the project. As the definition of the material models is well provided in the base BIM ontology considered in the project (ifcOWL[12]), the focus in this document is to address any emerging requirements that are related to BIM4EEB by developing the relevant ontologies. More specifically, the need for modeling is evident at the different stages of a renovation project, with the key parameters about building materials to be extracted from requirements analysis in WP2 along with the preliminary specifications in D3.1. The key points of the analysis related to building materials in the BIM4EEB project are: - To acquire preliminary data and detailed material data from an existing building at the initial stage. - To oversee construction and commissioning processes at the construction phase. - To ensure that all construction works are executed at the operational phase and properly monitored towards the end-of-life phase

	The high-level requirement is to establish a concrete modeling framework about building material that will facilitate the management of the different renovation processes as defined in the project. Special focus on the association of the relevant building information with the different business roles in the overall work process.

Relevant Data Requirements (associated with use case definition)	The list of data requirements considered for the modeling work performed in this section are relate to:
	• **BM01:** Modeling of Building elements that are part of the construction of a building (What are the element, Element name) and more specifically**:**
	    o **Zone elements**: elements that are primarily part of the construction of a building (e.g., wall, column, etc.)
	    o **Distribution elements**: elements that participate in a distribution system (e.g., sensor, controller, etc.)
	• **BM02:** Building Element physical characteristics (e.g. What is the thermal transmittance of the wall element)
	• **BM03:** Material: homogeneous or inhomogeneous substances that can be used to form elements (e.g., concrete, steel)
	• **BM04:** Material physical characteristics (e.g. What is the material and mass density, thermal conductivity, specific heat capacity of a material, What is the material thermal properties)
	• **BM05:** Product representation. How material can be assigned to the building product? (What are the Layer Set and layers of an element, what is the layer name and material, what is the adjacent layer of a layer or in other terms order of layers)

Table 2: BIM4EEB Usage Scenario 2 - Establishment of a modeling framework for building materials/ equipment

Complementary to the modeling task about building material/equipment, we have to define the BIM4EEB project specific needs in terms of energy systems in building premises. The incorporation of energy systems in the BIM4EEB modeling framework is a key prerequisite in order to facilitate energy simulation in a BIM based framework.

Usage Scenario 3 (US-3)	Establishment of a **modeling framework for energy systems** in building premises
Short Description	The scope of this use case is to facilitate the incorporation of energy systems in the holistic BIM framework defined in the project. As this is a rather generic task (with no specific requirements to be reported in WP2), we have to clearly state in this section the project needs and requirements in order to clearly define a modeling framework that addresses the project specific needs. The main principles of the BIM4EEB project in relation to energy systems are: - Energy system models should complement the generic equipment modeling as presented in previous section (as parameters associated with the cost, LCA etc. are inherited from the generic equipment class). - Energy system models should address both energy consuming devices, but also energy generators/storage systems. - Energy system models should focus on local/building level modeling as this is expected to be the main focus of BIM4EEB project.

	- Energy system models should incorporate the input parameters required for the accurate simulation of energy building performance. Such high-level requirements intend to provide a modeling framework that will be: a) generic enough in order to address different types of energy systems, but also b) as a minimum to address the BIM4EEB project requirements about energy simulations in building premises at the demo sites of the project.
Relevant Data Requirements (associated with use case definition)	The list of detailed requirements for the Energy systems in BIM4EEB project is presented: • **ES01: Generic device type class**, specifying the static configuration details of a consumption/ generation device: e.g. name, type, function (including actuator, meter, sensor). • **ES02: Nominal parameters of each energy device,** specifying operational parameters of a consumption/ generation device, e.g. nominal power, system typical performance, etc. • **ES03: Device state** representing the current state of each device along with the indicative enumerations including performance parameters (e.g., reliability) for specific KPIs. • **ES04: Device control/command function** representing the different control commands that may be delivered to a specific device • **ES05: Details about Energy, Power Profile** representing the power behaviour of the device type. It needs to be noted that a dynamic approach should be adopted in order to address power and energy volatility. • **ES06: Device flexible state and action** representing the potential controllability (energy related) over the specific device type; definition of state associated with the load profile • **ES07: Energy Cost** representing the operational cost for the performance of the Energy System. Moreover, the scope of the modeling work is to present the costs at the different steps of the LCC approach (Construction, Product Stage, Use and End of Life), further representing the values of both capital and operational cost as part of the LCC analysis • **ES08: Energy System LCA:** representing the LCA parameters of the DER system in the building environment. In more details the scope of the modeling work is to present the different steps of the LCA approach (Construction, Product Stage, Use and End of Life), further representing the values of the key indicators considered in an LCA analysis (related to energy and environmental impact).

Table 3: Usage Scenario 3 - Establishment of a modeling framework for energy systems in building premises

Along with occupant/comfort behaviour modeling principles, the IAQ model parameters should be incorporated in the holistic BIM4EEB framework. Considering the specific requirements that are of interest in the BIM4EEB project, we proceed with the definition of the usage scenario to address this specific modeling layer in BIM4EEB.

Usage Scenario 4 (US-4)	Establishment of a **modeling framework for Indoor Air Quality conditions (IAQ)**
Short Description	Overall, with respect to **indoor air quality**, we envisage to support the evaluation of indoor hygienic and health/well-being conditions within the integrated BIM framework. There are two main approaches as indicated in the literature (Annex III). - A **data driven approach** where IAQ values are measurable either via specialized or simple measurement devices available in premises. In addition,

	the users' feedback via questionnaires is considered as another way of incorporating real time IAQ values in the BIM framework. In that case, the definition of the IAQ measurement values and the associated KPIs along with the IAQ boundaries as defined in the regulation are considered as part of the model. - A **model driven approach** where the focus is at quantifying occupational indoor air quality during the construction and operational activities and incorporate the occupational indoor air quality assessment into BIM. This model differentiation is also expressed in the list of data specifications expressed in the following lines.
Relevant Data Requirements (associated with use case definition)	• **IAQ01: Building Geometry** (part of the base BIM model) & **usage** (building type) • **IAQ02: Occupancy** related parameters (number of occupants in building zones) • **IAQ03: Air exchange rate** and **external conditions** • **IAQ04: Source emission rate** (correlation with material/equipment) in premises. • **IAQ05: IAQ particles & characteristics** (e.g. size, typical values etc...) and the associated **measurement values** from sensing devices • **IAQ06: IAQ indicators** and **reference values** as defined in the national regulations • **IAQ07:** *For the model-based approach*: definition of **model details and the base parameters** (e.g., mass balance model) for IAQ quantification • **IAQ08: Strategies for design and control of buildings**. A strategy generally takes into account building energy performance, user comfort and health conditions. BIM4EEB intends to create a matrix of different possible strategies, that enables evaluation of possibilities for win-win solutions (excellent IAQ at low energy consumption) as well as other alternatives that will ensure high IAQ.

Table 4: Usage Scenario 4 - Establishment of a modeling framework for Indoor Air Quality

Note: It is not within the scope of the proposed modeling task to specify the exact values for the IAQ KPI boundaries since the definition of the formulas for KPIs calculation is part of the modeling work to be presented in D3.5 along with the detailed presentation of Energy Performance Modeling framework.

Last but not least, the BIM4EEB project specificities about acoustics modeling are incorporated in the analysis. Once again, the modeling task is focusing on the project specific requirements as identified in WP2 (and D3.1) along with the state-of-the-art analysis as presented in previous section.

Usage Scenario 5 (US-5)	Establishment of a **modeling framework for building acoustics**
Short Description	The BIM4EEB project specific requirements in terms of acoustics modeling are reported in this section. More specifically, such requirements consider that: - The acoustic modelling should be based on the EN 12354 approach where the resulting indoor sound environment is determined from the acoustic properties of the building elements.

	- Establishing sound source descriptions for relevant sources in the indoor and/or outdoor environment. - Mapping of the initial state of the acoustic sound class. - Acoustic criteria and targets should be established based on the national requirements and could be process dependent. - Identifying the acoustic properties of materials used in the renovation process - A model-based approach to identify conflicts between energy improvement solutions and acoustic comfort during the renovation
Relevant Data Requirements (associated with use case definition)	• **BA01: Criteria** and **target values** for the relevant acoustic indicators as expressed in the regulation. • **BA02: Building Geometry** (part of the base BIM model) & **usage** (building type) • **BA03: Mapping of building elements and transmission paths**. Characterization of building element types and the format of the corresponding input data. Input data can be provided by manufacturers based on laboratory data, calculated based on the structural data, or measured in the field. • **BA04:** Mapping of the **relevant sources** and **models for sound power levels** for equipment noise. • **BA05: Acoustics related measurements** in the building environment along with the measurement sources (e.g., IoT devices) • **BA06: Acoustic indicators** to evaluate the potential modification of materials and structures in the building environment. • **BA07: Acoustic model parameters/criteria** to enable the selection of materials and solutions taking into account their acoustic properties.

Table 5: Usage Scenario 5 - Establishment of a modeling framework for building acoustics

2.2 Consolidation of a set of BIM4EEB Data Requirements

Based on the review of the BIM4EEB project usage scenarios and requirements in section 2.1, in total, a number of **34 data clusters of requirements** have been extracted and defined as of interest for the project. As it might be expected, there could be requirements related to other domains, different from the mentioned ones, yet they were not within the context of the specific work. Since there are overlapping data requirements related to more than one domain, the following table summarizes and consolidates the BIM4EEB data requirements that will be used for the purpose of the analysis in this deliverable.

Table 6: List of Requirements & Mapping to Clusters

ID	Natural language sentence	Occupant Behaviour	Building Material & Energy Systems	IAQ & Acoustics
OC-01	Each occupant should be characterized by its role-specific configuration parameters: Age, Gender, Lifestyle, etc.	+		
OC-02	Activity profiling related parameters should be considered in the behavioural profiling model	+		+
OC-03	Occupancy scheduling related profiling parameters: presence, level of occupancy should be part of the model	+		+
OC-04	Indoor environmental conditions: temperature, humidity, luminance, IAQ conditions, sound etc are the driving factors for the behavioural profiling	+		+

OC-05	User Settings and preferences about indoor environmental conditions are also defined as the driving factors for the behavioural profiling	+		
OC-06	Occupant comfort preferences: thermal comfort/ visual comfort/IAQ comfort and acoustics are the detailed model parameters that have to be expressed in the model	+		+
BM-01	Building elements that are part of the construction of a building have to be considered	+	+	+
BM-02	Building elements physical characteristics		+	
BM-03	Material related parameters for the different building elements		+	+
BM-04	Material physical characteristics		+	
BM-05	Product representation and association with material related attributes		+	
ES-01	Generic device type specifying the configuration details of a consumption/ generation device: e.g. name, type, function (including actuator, meter, sensor).		+	
ES-02	Nominal attributes of each energy device, specifying operational parameters of a consumption/ generation device, e.g. nominal power, system typical performance, etc.		+	
ES-03	Device state representing the current state of each device including also the performance of the energy system on key indicators (e.g. reliability)	+	+	
ES-04	Device control/command function representing the different control commands that may be delivered to a specific device	+	+	+
ES-05	Details about Energy, Power Profile representing the power behaviour of the device type. It needs to be noted that a dynamic approach should be adopted in order to address power and energy volatility.		+	
ES-06	Device flexible state and action representing the potential controllability (energy related) over the specific device type; definition of state associated with the load profile		+	
ES-07	Energy Cost representing the operational cost for the performance of the Energy System, LCC, etc.		+	
ES-08	Energy System LCA representing the LCA parameters of the DER system in the building environment		+	
IAQ-01	Building Geometry & usage (building type) should be part of the model	+	+	+
IAQ-02	Occupancy related parameters (number of occupants in building zones) should be considered in the model	+		+
IAQ-03	Air exchange rate and external conditions that affect IAQ values			+
IAQ-04	Source emission rate (correlation with material/equipment) model parameters			+
IAQ-05	IAQ particles & characteristics (e.g. size, typical values etc...) and the associated measurement values from sensing devices			+
IAQ-06	IAQ indicators and reference values as defined in the national regulations			+
IAQ-07	Definition of model details and the base parameters (e.g. mass balance model) for IAQ quantification			+
IAQ-08	Strategies and functions related to the IAQ design and control of buildings is an add on in the model			+
BA-01	Criteria and target values for the relevant acoustic indicators as expressed in the regulation.			+
BA-02	Building Geometry (part of the base BIM model) & usage (building type) are parameters to be incorporated in the acoustics model	+	+	+

BA-03	Characterization of building element types and transmission paths in the building environment		+	+
BA-04	Sources and models for sound power levels to be part of the acoustics profiling in a building environment.			+
BA-05	Acoustics related measurements in the building environment along with the measurement sources (e.g. IoT devices, noise sensors etc..)	+		+
BA-06	Acoustic indicators to evaluate the potential modification of materials and structures in the building environment.			+
BA-07	Acoustic model parameters/criteria to enable the selection of materials and solutions taking into account the acoustic properties.			+

From the aforementioned analysis, it is clear that some of the requirements are associated with specific use cases while there are some model parameters that can be inherited at the different viewpoints examined in this task. These common model parameters could be considered as part of the core BIM4EEB ontology, also highlighting the importance of linking data towards the definition of a homogenized building information model.

3 State of the Art Analysis

In accordance with the methodology adopted for this deliverable and the project specificities, a landscape review of the most relevant work (in terms of models, standards and ontologies) in the domain is performed. In order to set the baseline terminology adopted in BIM4EEB, the different modeling aspects considered for the analysis include:

- Ontologies: formal representations of a set of concepts within a domain and the relationships between those concepts; defining the structure of knowledge for various domains
- Data Models: as an abstract model that organizes elements of data and standardizes how they relate to one another and to the properties of real-world entities. A data model represents the structure and integrity of the data elements of the, in principle "single", specific enterprise application(s) by which it will be used.
- Standardization/ protocols: In this case no formal data modeling work is available in the field but there are standards or working groups that define key principles and concepts that should be considered in the modeling work to be performed in BIM4EEB project.

While there is an exhaustive list of relevant ontologies and models available in the literature over the years, an elicitation approach is followed in order to appropriately select the most relevant work and provide a focused analysis that is oriented to the BIM4EEB project needs and requirements. To this end, the initially collected ontologies and data models were prioritized for analysis on the basis of the following selection criteria:

a. *Relevance* taking into account the preliminary state of the art analysis that was performed in D3.1.
b. *Technical feasibility and alignment to the BIM4EEB project needs and requirements* based on consultation with the BIM4EEB technical partners.
c. *Timeliness* in terms of maintenance by active working groups and/or initiatives.

In addition, taking into account the refined principles for modeling about maximum utilization of existing ontological models while minimizing the level of expressivity to the project needs, the review of the literature was performed as follows:

I. At first, we analyse the **ontological schemas** (with preference on standards-based ontologies that are still in maintenance). Two different levels of detail are considered in the analysis:
    a. A detailed presentation of the most relevant work following the aforementioned criteria. A structured presentation of the available data models and ontologies with:
        i. Summary table including: Title, Publisher (Standardization Organization / Company), Purpose, Focus (addressing the different pillars of analysis), Type (Ontology), Supported Formats, Version
        ii. Short description presenting the key points of the modeling work
        iii. Relevance with BIM4EEB project data specifications
    b. A high-level presentation of additional modeling efforts providing a brief description of the ontology.
II. Along with the existing ontologies, there are major initiatives supporting specific data modeling works, we provide a short overview of these **data models**.
III. As a 3rd step, review of **relevant standardization** is performed to define specific attributes and concepts that are not covered in the previous steps. The focus here is not at the data modeling part, rather on the specification of the model processes (especially in IAQ, acoustics) that have to be considered in the modeling framework following the definition of ontological requirements in previous section.

By providing a thorough state of the art analysis, we screen the landscape for the definition of the BIM4EEB domain ontologies in the following section. We first present the relevant ontologies, then the data models that fit to the data requirements as presented above, and finally some extra standards and modeling efforts that have to be considered in the BIM4EEB literature.

3.1 Relevant Domain Ontologies

As stated above, the focus of the literature is at the review of existing ontologies that are

(a) Strongly relevant to the domains of interest in the task, following the project decision for maximum reutilization of existing models (and with the level of expressivity required for the project)

(b) Highly selected by the technical partners following discussions in T3.1 and further consultation in T3.2.

(c) Well maintained from existing bodies, working groups or initiatives.

The most relevant modeling work available in the literature is reported in this section; analysis performed with the order of the domains of interest: Occupants Profiling and Comfort, Building Material & Energy Systems, IAQ and Acoustics.

3.1.1 Occupants Profiling Relevant Ontologies

Think Home Ontology

Summary

Title – OPM-01	Think Home Ontology (Actor & Processes) Alternative titles: **Users and Preference Information**, **User Behaviour and Building Process Information**
Publisher	TU Wien
Purpose	The modeling work performed in Think home project, focusing on modeling occupants' interaction with the building environment
Focus	**Occupants Profiling and Comfort**
Type	Ontology
Supported Formats	OWL
Version	1.01 &1.14 respectively
Link	https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/

Short Description

This is the ontological model of the ThinkHome project towards the definition of a holistic energy management framework in the building environment. The knowledge base intelligently maintains all relevant data that are considered to be influence factors in a smart home. This is a key point of the project and thus the definition of the relevant ontologies was a main outcome of the project.

The domain ontologies specified in the project are:

- Building Ontology: specifying the building information model
- EnergyResource Ontology: specifying the model for the energy systems of interest in the project
- Process Ontology: relation to Action or Process that is carried out by human actor and cannot be captured on the base of simple sensors (e.g. dancing, reading a book, resting)
- Weather ontology: to present the environmental conditions (indoors, outdoors) as part of the energy modeling framework
- Actor ontology: specifying the role of occupants in the building environment

Occupancy patterns it is a core point of the project as the objective is to incorporate occupants' profiles and activities in the overall management framework. A snapshot of the ontological classes for actor profiling is presented in the following:

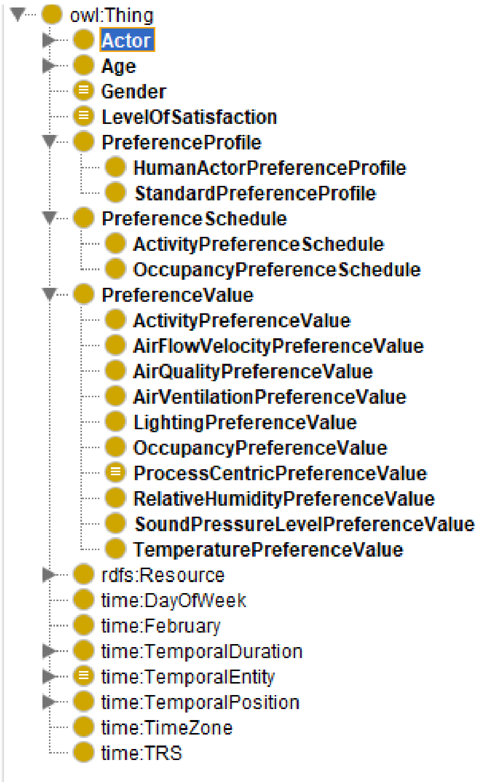

Figure 2: ThinkHome ActorOntology

The key classes of the occupancy ontology are presented:

- PreferenceSchedule class: This class combines more than one user preference value to a schedule and is used when for example different preference values are stored for different days (e.g., occupancy, etc)
- PreferenceValue class: represents user preference values.

<u>Relevance with BIM4EEB project data specifications</u>

Different domains are of interest also in BIM4EEB project. The model domain for Building actor is presented in high detail in ThinkHome ontology and thus the different classes specified could be incorporated in the modeling framework of BIM4EEB occupancy profiling model. Especially in the field of preference values, the model identifies classes of interest for the BIM4EEB project. A snapshot of the different classes is presented in the following figure:

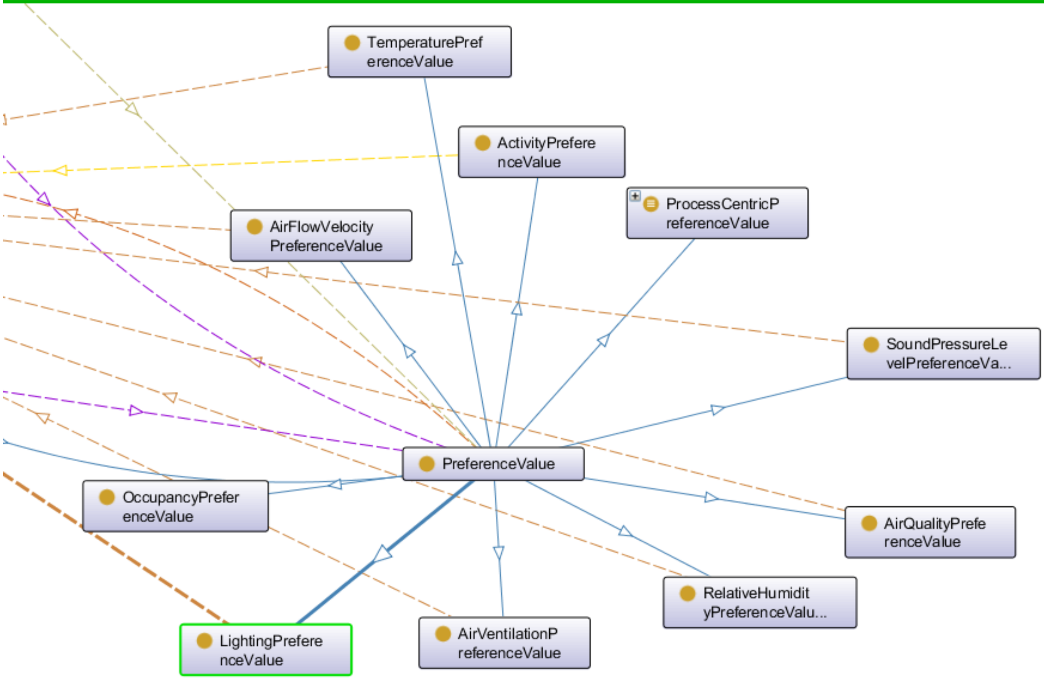

Figure 3: ThinkHome ActorOntology - PreferenceValue Class

Relevance with BIM4EEB[1]	BIM4EEB Data Requirements					
	OC-01	OC-02	OC-03	OC-04	OC-05	OC-06
ThinkHome Actor / Process Ontology	**Actor**	**Process**	**Preference Schedule**	**Preference Values**	**Level of Satisfaction**	**Preference Profile**

Even, this model is detailed enough, is not covering the list of comfort parameters as to be examined in the project. Though this modeling work could stand as a starting point for the BIM4EEB occupancy behavioural profiling ontology as it covers the main data requirements expressed in previous section.

Adapt4EE User Profiling Ontology

Summary

Title – OPM-02	Adapt4EE Ontology
Publisher	Adapt4EE Consortium

[1] *For each cell, the concept(s) from the given ontology that are related to the given requirements are included, if any. Empty cells mean that the ontology does not provide support for that requirement. When more than one concept from a given ontology are involved in the coverage of one specific requirements, they are listed separated by comas ",".*

Purpose	The modeling work performed in Adapt4EE project, focusing on modeling in a building environment
Focus	Occupants Profiling and Comfort
Type	Ontology
Supported Formats	TTL
Version	1.0
Link	http://smartcity.linkeddata.es/ontologies/www.adapt4ee.euadapt4eeresultsontologies.html.html

Short Description

This is a modeling work performed by an EU project; this model was one of the first models of the eeBuildings initiative of the E.C.
The scope of this project is to provide different modeling approaches related to occupants' behaviour and comfort analysis. There are different layers that characterize occupant's behaviour profiling:

- Occupancy detection, presence and schedules definition in the building environment
- Activity and context-based comfort preferences (with focus on thermal and visual comfort) associated with the operational and indoor environmental conditions

The focus of the project is about context driven behavioural profiling (the second layer), though the analysis is covering both layers defined above as the objective is to try to provide an enhanced model that will incorporate also additional occupants' detection attributes / parameters.

As part of the modeling work of the project, a dedicated occupancy ontology was defined and a screenshot of this is presented in the following figure:

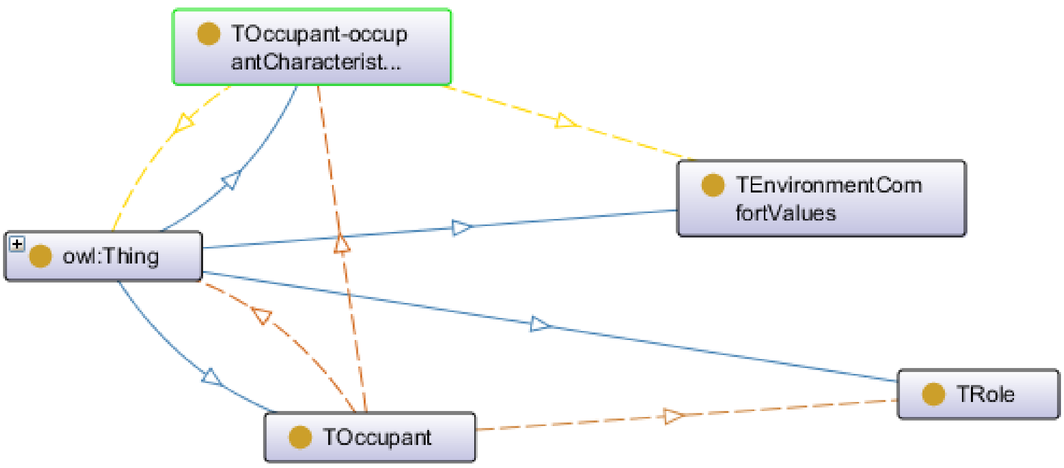

Figure 4: Adapt4EE Occupancy Ontology

Occupancy patterns it is a core point of the project as the objective is to accurately capture and analyze the information of as-is conditions and further define the right patterns for enterprise modelling and simulation. The occupancy ontology is one of the 9 ontological schemas defined in the project. The rest are briefly presented:

- BIM Ontology: As the base ontology expressing the building level information

- KPI ontology: As the model for the representation of KPIs examined in the project
- Event ontology: to represent the different sensor, control, actuator events on the IoT devices
- Device ontology: to represent the different device types of interest in the project
- BPM Ontology: to represent the business processes taking place in the building environment; a main aspect of the project
- CIM Ontology: as the ontology for the energy related parameters and attributes examined in the project

The key classes of the occupancy ontology are presented:

- Occupant class: Specifying the role of occupant in the building environment further associated with occupants' characteristics
- OccupantsCharacteristics class: This is the main class of occupants behavioural modeling specifying the comfort parameters in the building environment that have to be address associated with the respective environmental conditions.

Relevance with BIM4EEB project data specifications

Considering that the focus of this section is about occupancy and behavioural modeling, the model principles provided in Adapt4EE could be inherited in BIM4EEB. This modeling work can provide useful insights for the modeling work of the BIM4EEB project, nevertheless as there is no standard repo of this ontology, will not be heavily incorporated in the modeling work of the project.

Relevance with BIM4EEB[2]	BIM4EEB Data Requirements					
	OC-01	OC-02	OC-03	OC-04	OC-05	OC-06
Adapt4EE Ontology	**TOccupant**	**TProcessType, TSkeletonActivity**	**TOccupant – occupant Characteristics**	**TRelative HumidityValue, TTemperature Value**	**-**	**comfortPreferenceRef, Environment ComfortValues**

BEMS/ Hit2GAP User Profiling Ontology

Summary

Title – OPM-03	BEMS User Profiling Ontology
Publisher	HIT2GAP Consortium
Purpose	The modeling work performed in Hit2GAP project, focusing on modeling in a building environment

[2] *For each cell, the concept(s) from the given ontology that are related to the given requirements are included, if any. Empty cells mean that the ontology does not provide support for that requirement. When more than one concept from a given ontology are involved in the coverage of one specific requirements, they are listed separated by comas ",".*

Focus	Occupants Profiling and Comfort
Type	Ontology
Supported Formats	OWL
Version	1.0
Link	https://raw.githubusercontent.com/HIT2GAP-EU-PROJECT/BEMOnt/master/models/OWL/UserBehaviour.owl

Short Description

This is also a modeling task performed by an EU project; selected for detailed analysis mainly due to the incorporation of the DNAs concept, the IEA - Annex 66 [3] framework for occupant's behaviour in building environment.

The model is based on a main root class OccupantBehaviour branching into five sub-classes Behaviours, Buildings, Occupants, Seasons, and TimeofDay. The OccupantBehaviour root class has an ID and version attribute, indicating a unique ID and version. The sub-classes from the main class provide a choice for specific building, occupant, behaviour, season and time of day inputs, with seasonal and time of day information being optional [3].

- *The **Buildings** class pertains specifically to the inputs related to occupant behaviours in the building. It has a unique ID attribute, and required Type and Spaces children classes. The Type class contains 39 enumeration building types, consistent with those commonly used in BIM schemas. The Building parent class hosts the Systems child class, describing the physical equipment or components with which an occupant may interact. The child classes of the Systems class include the Window, Shade, Light, Thermostat, Equipment, and HVAC control, each with a unique ID attribute, an optional Description class, and an enumeration selection for the Type of control: window→operable or fixed; shade → operable or fixed; light → on/ off, dimmable, two step, three step; thermostat → adjustable, none, fixed; HVAC system → central, zonal controllable, zonal fixed.*
- *The **Occupants** root class describes the occupants within the building. Each parent Occupant class has a unique attribute ID and optional child classes of Name, Age, Gender, Lifestyle, Jobtype.*
- *A **behaviour** ID referencing the Behaviours root class tags an occupant to a specific behavioural action. The topology of the schema for the Behaviours root class branches into Drivers, Needs, Actions and Systems child classes, following the DNAS framework. This is the core part of the modeling framework and as mentioned above, the details are provided in Annex I.*
- *Lastly, the **Seasons** and **Time of Day** classes are optional providing the user the ability to input additional information about seasonal specifics (start month, end month, start day, end day) and details about the time of day (start hour, start minute, end hour, end minute)*

A representation of the occupant model framework as defined in BEMS/HIT2GAP model is presented in the following figure, highlighting the classes of Needs and Actions (Drivers are part of the State class).

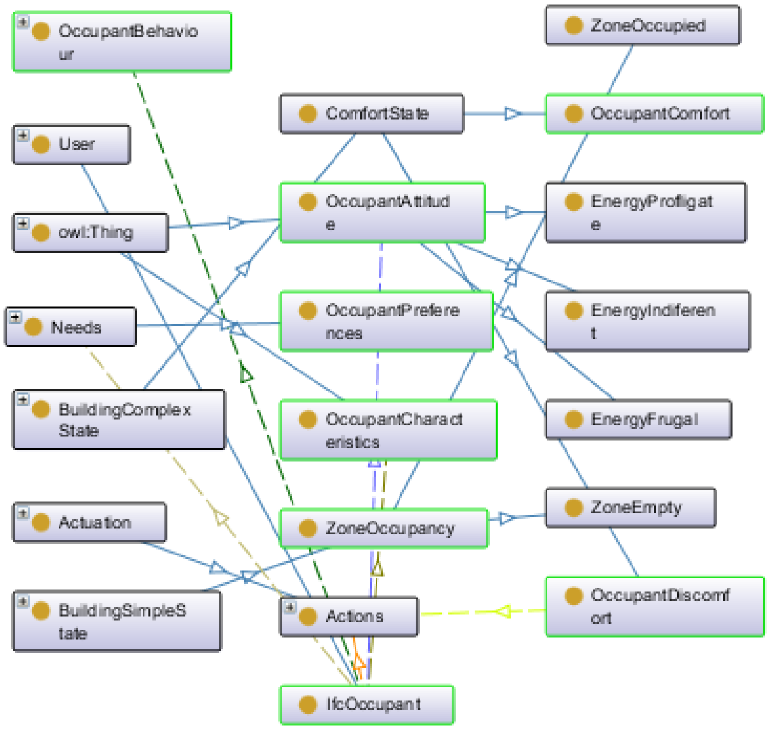

Figure 5: HIT2GAP DNAs based User Behaviour Ontology

Relevance with BIM4EEB project data specifications

We have to point out that the model is clearly addressing the requirements of the project in the field of occupants' behaviour as depicted in the following table.

Relevance with BIM4EEB[3]	BIM4EEB Data Requirements					
	OC-01	OC-02	OC-03	OC-04	OC-05	OC-06
HIT2GAP Ontology	IfcOccupant , Occupant Characteristcs	ActivityModel	Occupant Behaviour	Sensor, Observable Property	Feedback, Actuation	Needs, OccupantPreferences, ComfortState

[3] *For each cell, the concept(s) from the given ontology that are related to the given requirements are included, if any. Empty cells mean that the ontology does not provide support for that requirement. When more than one concept from a given ontology are involved in the coverage of one specific requirements, they are listed separated by comas ",".*

In addition, the model defines linked data with classes of ifcOWL (which is considered also in BIM4EEB project). Therefore, the model could be considered as the starting point of our work in the project, nevertheless we have to always consider that this is not a work from a WG/ standardization body, mainly defined to address the requirements of a specific project.

Activity Pattern Ontology

Summary

Title – OPM-04	Activity Pattern Ontology
Publisher	Descartes
Purpose	A generic model to address occupants' activities and patterns
Focus	Occupants Profiling and Comfort
Type	Ontology
Supported Formats	OWL
Version	1.0
Link	http://descartes-core.org/ontologies/activities/1.0/ActivityPattern.owl

Short Description

In contrary to the aforementioned ontologies where the focus was about the role of occupants in the building environment, this is a rather generic ontology implementation with the focus on representing activities following an ontological schema.
As stated, two main perspectives on activity modeling can be identified from the literature: a spatiotemporal-centric and a workflow-centric perspective. The first one treats activities as a set of temporally-ordered entities in space and time. The second perspective treats activities as a workflow. This view is often found in planning-related applications, in which preconditions and effects of activities are important. A snapshot of the ontological representation of an activity as reported is presented in the following figure:

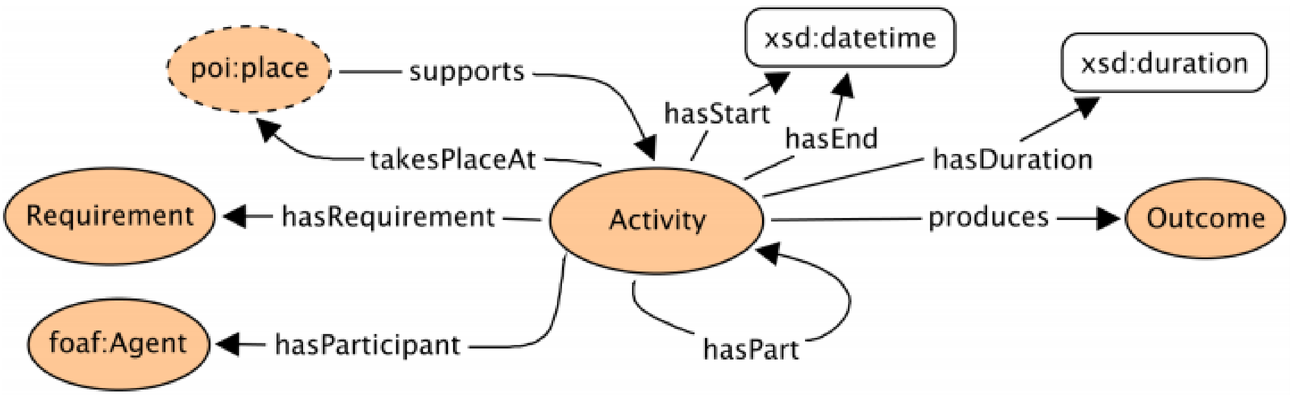

Figure 6: Activity Reasoning ontological pattern[9]

Relevance with BIM4EEB project data specifications

It is evident that the incorporation of activity related aspects in the occupancy behavioural model is an add-on for the **BIM4EEB** project, to further facilitate the interconnection of the occupant's behaviour parameters with the renovation activities (as activities taking place in a building environment).

Relevance with BIM4EEB	BIM4EEB Data Requirements					
	OC-01	**OC-02**	**OC-03**	**OC-04**	**OC-05**	**OC-06**
Activity Pattern Ontology	**foaf:Agent**	**Activity**	**-**	**-**	**-**	**Requirement**

While these generic classes are very useful also for the modeling work of the project, these have been already incorporated in the ontologies presented above. The reason for selecting this ontology is mainly to address the requirement for reviewing ontologies with low level of expressivity (and thus extending generic ontologies with the BIM4EEB specific concepts).

Moving beyond occupants' comfort analysis and modeling in the recent literature, there is a continuous research in the field of building components and energy services modeling with focus on the energy related parameters. An overview of the related ontologies is provided in [10][11]. A non-exhaustive list of them is out of the scope of this document, and thus the focus is on the modeling efforts that will be considered also in the BIM4EEB project (following the review performed in D3.1).

3.1.2 Building Material & Energy Systems Relevant Ontologies

ifcOWL for Building components and Material

Summary

Title – BMES-01	ifcOWL
Publisher	Building Smart
Purpose	An OWL representation of IFC Model
Focus	Building Components and material
Type	Ontology
Supported Formats	OWL
Version	4, ADD2
Link	https://github.com/buildingSMART/ifcOWL

Short Description

A thorough review of equipment/material modeling concepts was presented in D3.1. More specifically, the intro at the prominent meta-data model, namely the Industry Foundation Classes (ifc) was provided. Along with the overview definition of materials and equipment in a building environment, the way to incorporate them in the IFC ontological model is presented. More specifically [12]:

- *IfcMaterialDefinition is a general supertype for all material related information items in IFC that have common material related properties that may include association of material with some shape parameters or assignments to identified parts of a component. Each instantiable subtype of IfcMaterialDefinition may have material properties assigned, or have an external classification of* *its definition. It can be assigned to either a subtype of IfcElement, or a subtype of IfcElementType by using the objectified relationship IfcRelAssociatesMaterial.*

- *Similarly, ifcElement is a generalization of all components that make up an AEC product. Elements are physically existent objects, although they might be void elements, such as holes.*

It is evident that the generic *IfcElement* class may be considered for modeling the physical structural entities in a building environment. The indicative class of *IfcElement* representation is presented in the following schema

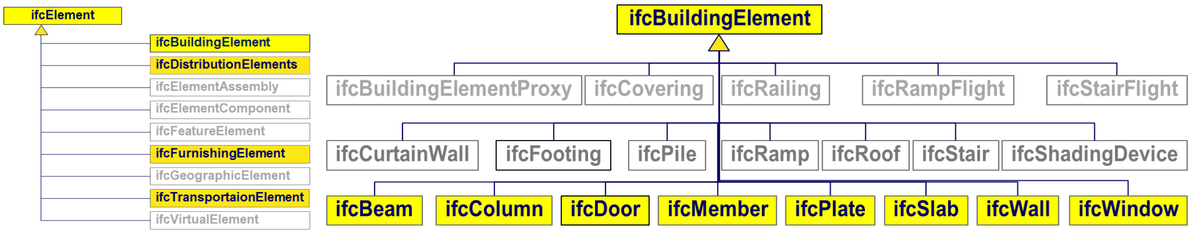

Figure 7: IfcElement model representation

In addition, building specific physical elements like the distribution flow elements and the building automation systems are covered by the existing Ifc models.

Relevance with BIM4EEB project data specifications

As stated in D3.1 the ifcOWL will stand as the base ontology for BIM4EEB project. While ifcOWL is clearly addressing building material and equipment, additional developments should be performed to address the project specific requirements as expressed in previous section. Since ifcOWL is not a modelled ontology, it has limitations as described in the D3.1. Therefore, modular ontology will be developed for addressing the material data and the alignment will be performed with other ontologies in the harmonization process. For Building components ifcOWL will be used as a main ontology.

Relevance with BIM4EEB	BIM4EEB Data Requirements				
	BM-01	BM-02	BM-03	BM-04	BM-05
ifcOWL Ontology	IfcBuildingElement IfcBeam IfcWall IfcColumn IfcWindow IfcTransportElement IfcElectricDistributionBoardTypeEnum	-	IfcMaterial IfcMaterialClassificationRelationship IfcConstructionMaterialResourceTypeEnum	-	IfcProductDefinitionShape

Eurobau Ontology

Summary

Title – BMES-02	**Eurobau**

Publisher	BauDataWeb
Purpose	The European Building and Construction Materials Database for the Semantic Web
Focus	Building Material
Type	Ontology
Supported Formats	OWL
Version	1.0
Link	http://semantic.eurobau.com/eurobau-utility.owl

Short Description

Another example for existing developments in the area of ontologies for construction materials are the **Eurobau Ontology** covering the details of the real business data. This work is part of the BauDataWeb: The European Building and Construction Materials Database for the Semantic Web [13].
While ifc focus is at the modeling/fundamental part, the BauDataWeb is one of the largest and richest public datasets for a well-defined vertical sector that is available on the Semantic Web. It covers a major share of the European market. The details of the BauDataWeb modeling work are specified in the FreeClassOWL with the Eurobau Ontology to act as the extended version of the base ontology in order to serve several use cases. The structure of this modeling framework is presented in the figure.

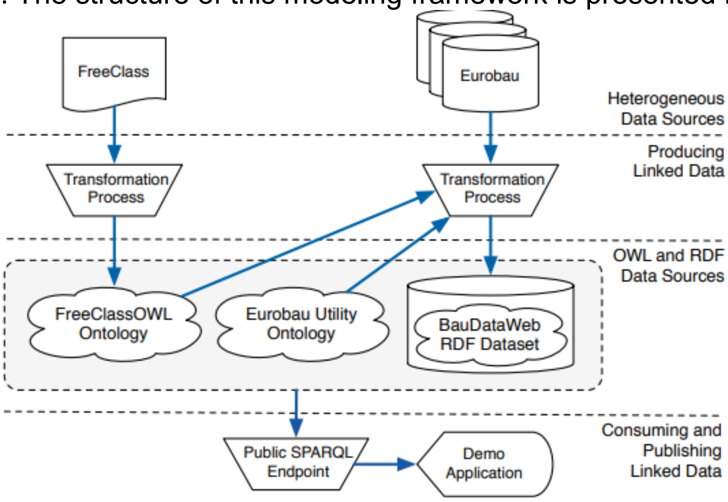

Figure 8: Eurobau Ontology concept

Relevance with BIM4EEB project data specifications

The Eurobau Ontology defines several market-oriented attributes (e.g. price, Warranty Promise) that may be considered as relevant within the scope of the BIM4EEB materials extended ontology. Following the revision of requirements needs as reported in this deliverable, this model is not that relevant to project activities.

Building Topology Ontology

Summary

Title – BMES-03	**BOT Ontology**
Publisher	W3C LBD Group
Purpose	The Building Topology Ontology (BOT) is a minimal ontology for describing the core topological concepts of a building
Focus	Building Material

Type	Ontology
Supported Formats	OWL
Version	0.3
Link	https://w3c-lbd-cg.github.io/bot/bot.ttl

Short Description

While the aforementioned ontologies address the key model aspects of interest in the BIM4EEB project, there are several initiatives in the field proposing additional building material/equipment models. For example, the **Building Topology Ontology** was defined on the way to set a minimal model structure for describing the core topological concepts of a building. As stated by the WG, the main idea behind BOT is the need for a … *minimal, extendable ontology that describes anything in its context of a building; describe some sensor, product, device in the context of the building in which it sits and as the building is itself also a feature of interest in the context of a smart energy management [14].* The hierarchical concept of the BOT ontology is presented in the following figure:

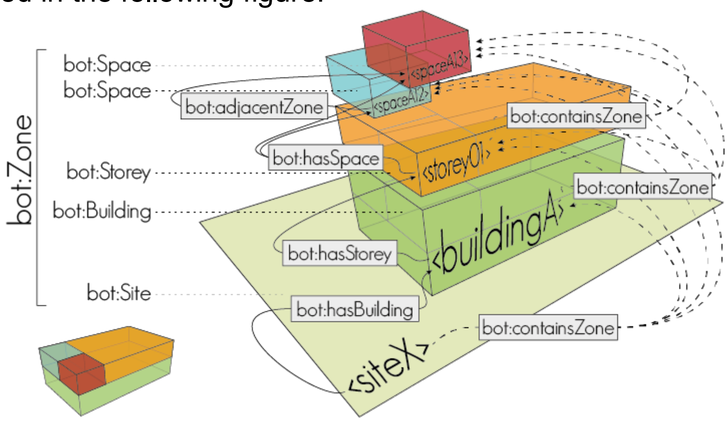

Figure 9: Classes and relationships in BOT ontology

Relevance with BIM4EEB project data specifications

BOT may be considered as a simplified building elements ontology that clearly address the BIM4EEB data specifications. The mapping of BOT classes with the BIM4EEB data specs are provided in the following table. It is evident that the BOT is not covering the requirements of modeling building materials as expressed in this task. Nevertheless, and considering the requirement for less expressivity in the project, there is a consideration of this ontology as the BIM base ontology in D3.1 (BOT was recommended as a good alternative considering the low level of expressivity).

Relevance with BIM4EEB	BIM4EEB Data Requirements				
	BM-01	**BM-02**	**BM-03**	**BM-04**	**BM-05**
BOT Ontology	**Element**	-	-	-	**adjacentElement intersectingElement containsElement**

Moving beyond building (material) related ontologies, there are several ontologies that clearly represent energy systems/DERs in building premises. In order to somehow harmonize this work, there was an initiative by E.C. with the outcome to be the SAREF ontology [22] which has now been expanded with extensions to specific domains.

SAREF & Extensions

Summary

Title – BMES-04	SAREF and Extensions
Publisher	WG established by E.C.
Purpose	The Smart Appliances REFerence (SAREF) ontology is a shared model of consensus that facilitates the matching of existing assets in the smart appliances' domain. Extensions applicable in different domains are also available
Focus	Energy Systems
Type	Ontology
Supported Formats	OWL
Version	1.0
Link	https://saref.etsi.org/

Short Description
The Smart Appliances REFerence ontology (SAREF) [22][24] "*is conceived as a model that facilitates the matching of existing semantic assets in the smart appliances domain, reducing the effort of translating from one asset to another. Using SAREF, different assets can keep using their own terminology and data models, but still can relate to each other through their common semantics".* In other words, **SAREF** is a semantic model that stand as the basis for the representation of the smart appliances at the building environment.

SAREF has been defined following some key model principles as specified also in the documentation of ETSI standardization [22]:

- *"Reuse at the maximum level and alignment of concepts and relationships that are defined in existing assets.*
- *Modularity is an essential principle of the modeling work in SAREF to allow separation and recombination of different parts of the model taking into account the project specific requirements.*
- *Extensibility of the model is also a key principle considered in order to allow further extension of the ontology.*
- *Maintainability to facilitate the process of identifying and correcting defects, accommodate new requirements, and cope with changes in (parts of) SAREF".*

The key classes that are specified in SAREF core ontology (also relevant to BIM4EEB project) are shortly presented:

- **Device**: A tangible object designed to deliver a specific task, i.e., a washing machine, fridge, light etc. Subclasses based on the domain of interest may be defined
- **Command**: A control that a smart device may support to perform a specific function, i.e., OFF action at a switch device.
- **State**: The state of the device after a command

- **Function**: The functionality that needs to be accomplished by a device (task for which a device is designed to perform).
- **Property**: A sensing parameter, a measurement or control parameter in the building environment.
- **Measurement**: The actual value of the measurement made over a property.
- **Service:** Representing one or more functions performed by the device.

Additional classes, not relevant in the context of BIM4EEB project, are defined in SAREF ontology such as: Task, Commodity etc.

The next figure shows an overview of the main classes of SAREF and their relationships.

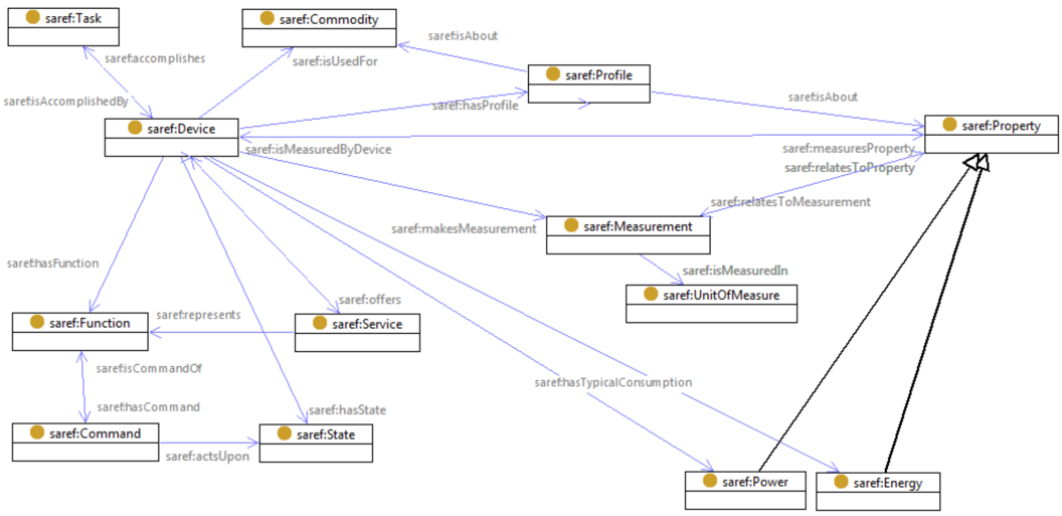

Figure 10: SAREF general overview

With focus on type of device representation, we have the following model:

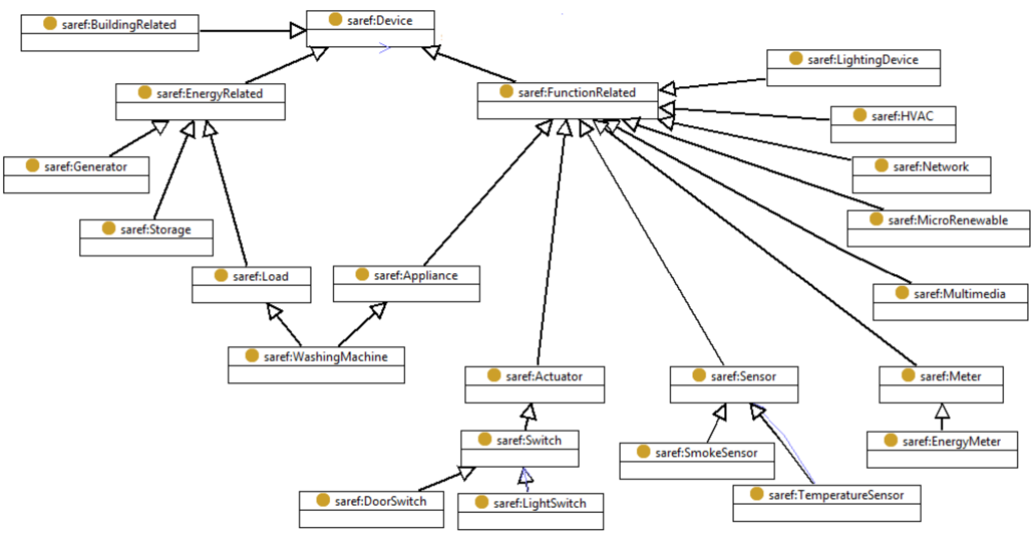

Figure 11: SAREF type of device

A key point is also the mapping of SAREF with ETSI oneM2M ontology, also promoted by E.U.

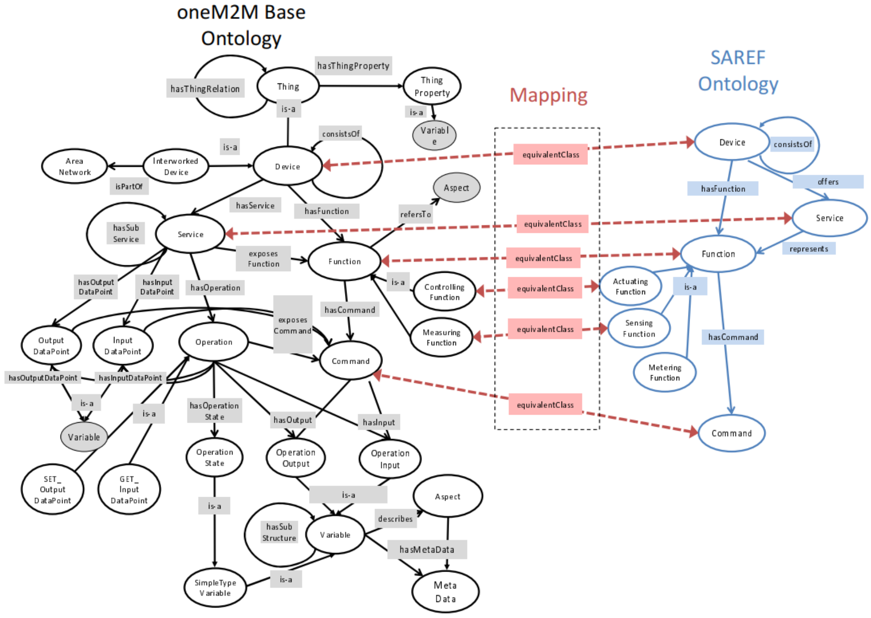

Figure 12: Mapping between SAREF and the oneM2M Base Ontology

As mentioned above, the SAREF ontology is defined as the base ontology with extensions to be required in order to extend the applicability to specific domains. The overall business approach for the exploitation of the SAREF ontology is presented in the following figure:

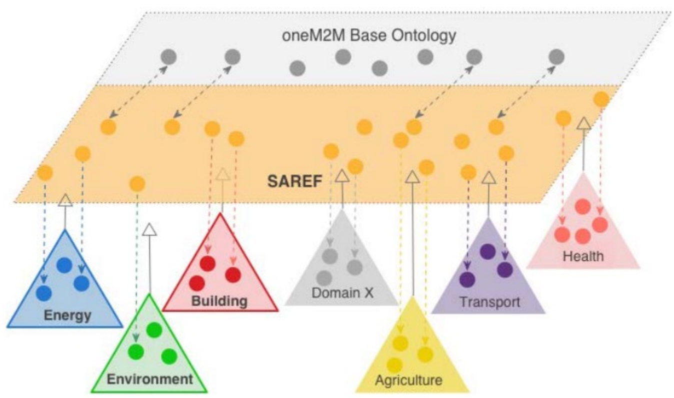

Figure 13: SAREF and its expansions

Extensions of SAREF have been created for the Energy, Environment and Building domains and are highlighted in the above figure (supported by E.U.[24])

SAREF4ENER [23] is an OWL-DL ontology that extends the base SAREF ontology with 63 classes, 17 object properties and 40 data type properties. As specified in the documentation of SAREF4ENER,the model *"focuses on demand response scenarios, in which customers can offer flexibility to the Smart Grid to manage their smart home devices by means of a Customer Energy Manager (CEM). The CEM is a logical function for optimizing energy consumption and/or production that can reside either in the home gateway or in the cloud. An overview of the SAREF4ENER ontology is provided in the next figure, where rectangles containing an orange circle are used to denote classes created in SAREF4ENER, while rectangles containing a faded orange circle denote classes reused from other ontologies, such as SAREF".*

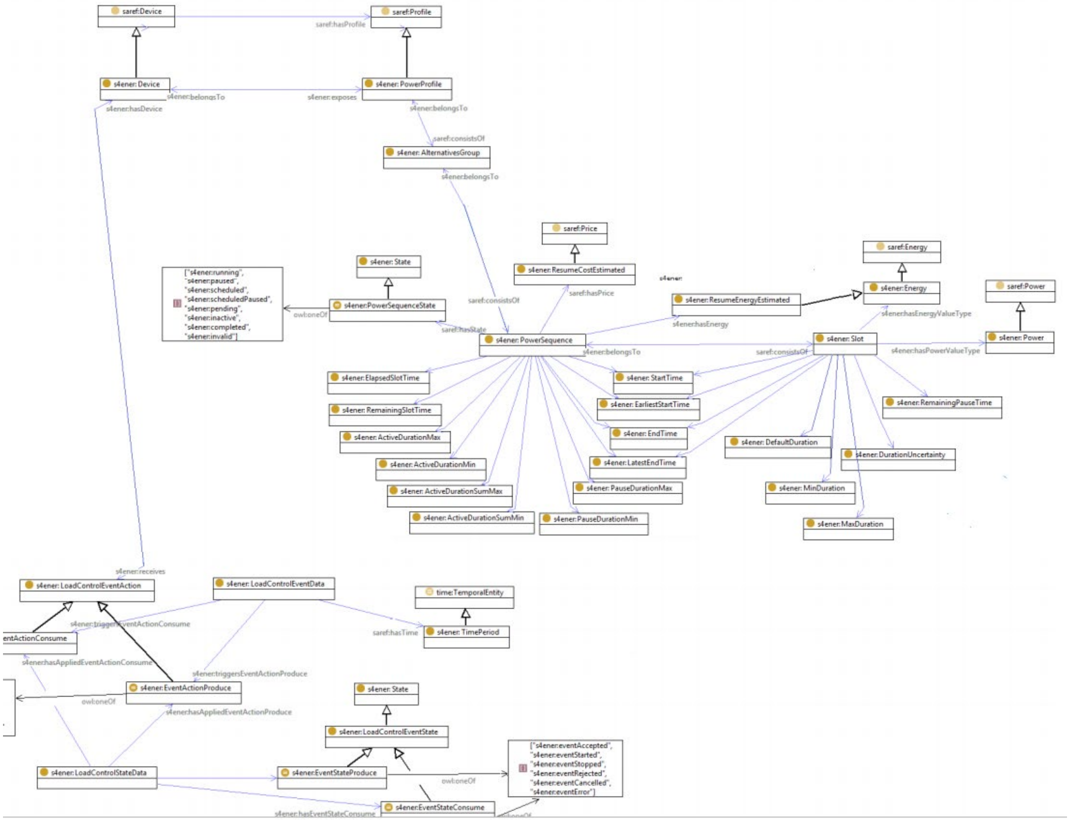

Figure 14: SAREF4ENER extension

More details about this extension available in: https://www.etsi.org/deliver/etsi_ts/103400_103499/10341001/01.01.01_60/ts_10341001v010101p.pdf

Last but not least, the **SAREF4BLDG [25]** ontology "*is an extension of SAREF for the building domain based on the ISO 16739 standard (IFC). As presented in the initial task of WP3, the IFC specification is developed and maintained by buildingSMART International as its "Data standard" and, since its version IFC4, it is published as the ISO 16739 standard. SAREF4BLDG was designed in order to support the interoperability among various actors and applications managing building related information with focus at the different layers of the building life cycle. Therefore, the main scope of SAREF4BLDG ontology is to facilitate manufacturers that support the IFC data to easily communicate about concepts related to smart appliances.*

The next figure presents an overview of the classes (only the top levels of the hierarchy) and the properties included in the SAREF4BLDG extension. *As it can be observed the classes s4bldg:Building, s4bldg:BuildingSpace and s4bldg:PhysicalObject have been declared as subclasses of the class geo:SpatialThing in order to reuse the conceptualization for locations already proposed by the geo ontology. The modelling of building objects and building spaces has been adapted from the SAREF ontology; in this sense, the new classes deprecate the saref:BuildingObject and saref:BuildingSpace classes. In addition, a new class has been created, the s4bldg:Building class, to represent buildings"* [25].

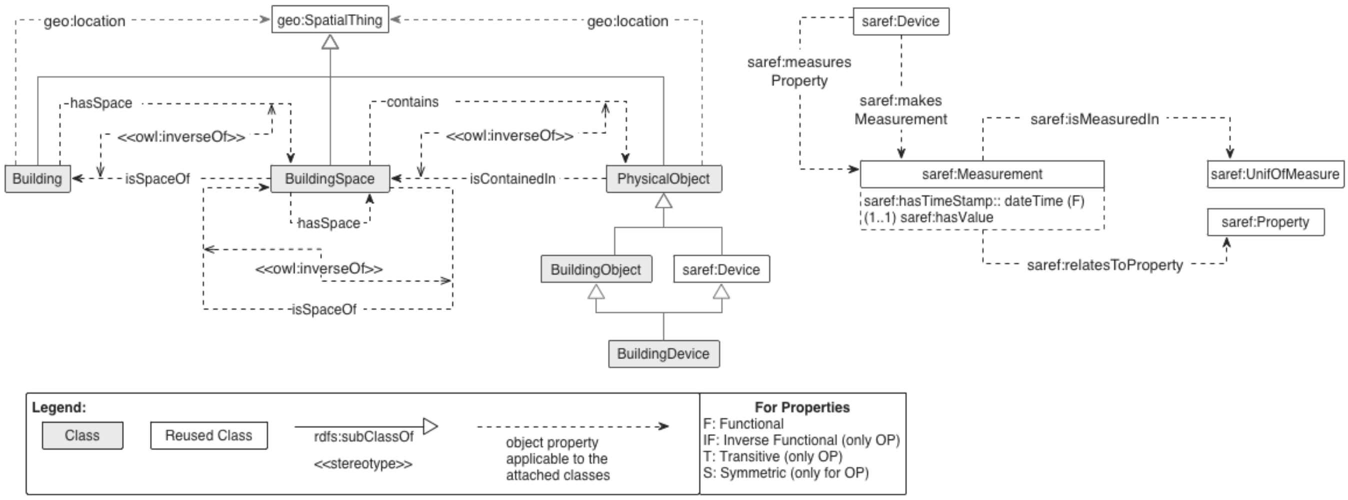

Figure 15: General overview of the top levels of the SAREF4BLDG extension

<u>Relevance with BIM4EEB project data specifications</u>

It is evident that the SAREF model covers the main requirements for this aspect of BIM4EEB project. There are 2 core entities defined in SAREF:

- The starting point of SAREF is the concept of Device (e.g., a switch). Devices are tangible objects designed to accomplish one or more functions in a building environment. The SAREF ontology offers a list of basic functions that can be eventually combined in order to have more complex functions in a single device.
- A Device offers a Service, which is a representation of a Function to a network that makes the function discoverable, registerable and remotely controllable by other devices in the network. A Service can represent one or more functions. A Service is offered by a device that wants (a certain set of) its function(s) to be discoverable, registerable, remotely controllable by other devices in the network. A Service must specify the device that is offering the service, the function(s) to be represented, and the (input and output) parameters necessary to operate the service.

It is also evident that the SAREF4BLDG extension best fits to the needs of the project to address the requirements about material/equipment modeling (while SAREF4ENER[4] fits much with energy systems modeling). Nevertheless, as SAREF4BLDG was defined to address specific attributes in the building environment (not focusing that much on energy systems), the starting point for our analysis is the SAREF ontology.

Relevance with BIM4EEB	**BIM4EEB Data Requirements**							
	ES-01	**ES -02**	**ES -03**	**ES -04**	**ES -05**	**ES -06**	**ES -07**	**ES -08**
SAREF and Extensions	**Device Actuato r Sensor**	**Energy, Power**	**State**	**Comma nd**	**Power profile, Energy Profile**	**Load Control event action**	**-**	**-**

[4] At the time of the review, SAREF4ENER is syntactically not maintained and thus the decision was to focus on SAREF.

	Functio n					**Load control event data Load control state data**		

Smart Energy Aware Systems ontology

An alternative of SAREF ontology is the Smart Energy Aware Systems ontology. This ontology is listed in the energy related ontology repositories and was also elicitated as a good to SAREF alternative.

Summary

Title – BMES-05	Smart Energy Aware Systems ontology
Publisher	ARMINES-Fayol
Purpose	The SEAS knowledge model is a modularized and versioned ontology that describes among other energy systems and their interactions
Focus	Energy Systems
Type	Ontology
Supported Formats	OWL
Version	1.1
Link	https://github.com/thesmartenergy/seas, https://w3id.org/seas/seas-1.1

Short Description

The SEAS knowledge model is a modularized and versioned ontology that describes among other energy systems and their interactions. The core of the ontology is made of four modules [63]:

- *seas:FeatureOfInterestOntology – this module defines a design pattern to describe features of interest (e.g., a room) and their properties (e.g., its temperature) that are qualifiable, quantifiable, observable, or actionable.*
- *seas:EvaluationOntology – this module defines design patterns to describe evaluations (qualification or quantification) of properties, and to qualify these evaluations: (i) what kind of evaluation: (e.g., maximum tolerable temperature, forecasted temperature, mean temperature), (ii) in a spatiotemporal validity context (e.g., temperature of the room between 10 am and 12 am tomorrow).*
- *seas:SystemOntology – this module defines a design pattern where systems are connected via connection points. This design pattern can be instantiated for example to describe zones inside a building (systems), that share a frontier (connections). The properties of a system are typically state variables (e.g., agents population, temperature), the properties of connections are typically flows (e.g., heat flow).*
- *Process Execution Platform ontology, an externalized module that generalizes the SSN ontology and describes pep:ProcessExecutors (sensor, actuator, web service, etc.) that implement pep:Processes and execute pep:ProcessExecutions.*

A screenshot from the modules and their imports is presented in the following figure

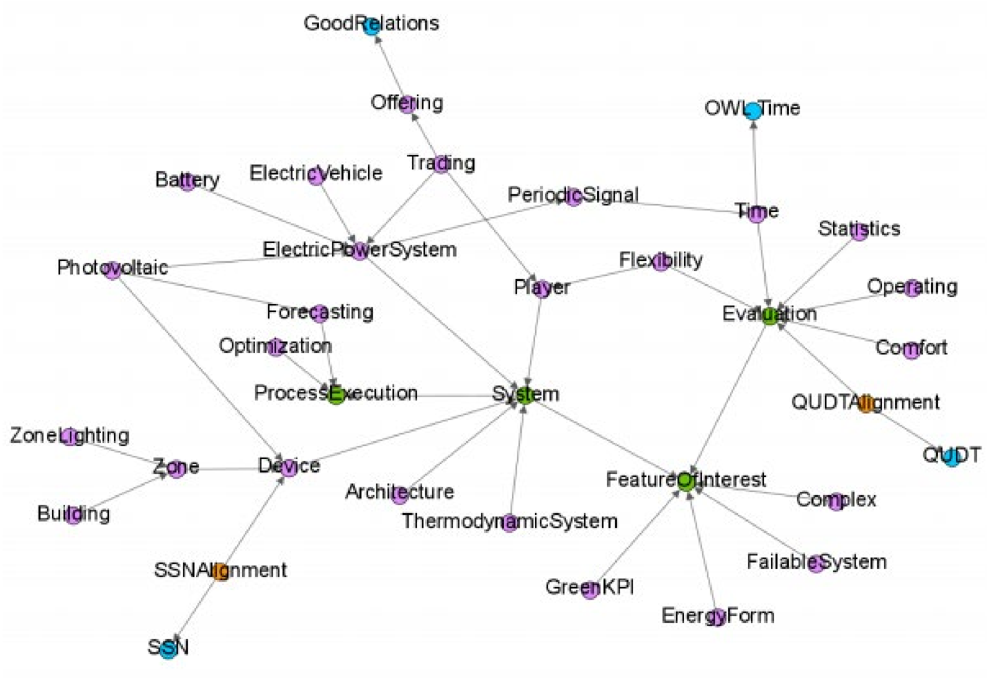

Figure 16: SEAS Ontology - model principles

Green nodes are core modules, pink nodes are the maim modules, orange nodes are alignment modules, and blue nodes are external modules.

A key point of this model is the reusability of existing work, The Semantic Web philosophy encourages the reuse of existing ontologies when appropriate. The SEAS analysis defines models that are common to numerous other projects (e.g., Provenance, Time instants and intervals, Quantities and Units of Measure, Time, Sensor/Actuator description, Sensor Observations, Predictions), or that are not actual subdomains of the Energy domain (e.g., products and offers). As there exists some ontologies for some of these domains, the SEAS group is reusing such existing ontologies instead of developing a whole new ontology that covers every domain. This is a key philosophy to be considered also in BIM4EEB project.

Relevance with BIM4EEB project data specifications

On top of the seas:SystemOntology module, various vertical domain ontologies are defined for specific sub classes of systems and why they may be connected: Battery, Device, Flexibility, Electric Power System are ontological schemas of interest for the BIM4EEB project.

Relevance with BIM4EEB	BIM4EEB Data Requirements							
	ES-01	ES -02	ES -03	ES -04	ES -05	ES -06	ES -07	ES -08
SEAS Ontology	**Electric Power System**	**Sensor**	**-**	**Actuation, Actuator**	**Power profile, Energy Profile**	**-**	**PriceSpecifications**	**-**

Also, an ontological schema addressing comfort in buildings is incorporated in the analysis making this ontological work highly relevant to the topics and concepts addressed in this task. We presented above the base building material and energy systems ontologies available in the field. In the following, the 3rd pillar of analysis (IAQ & acoustics) is addressed.

3.1.3 Indoor Air Quality & Building Acoustics Relevant Ontologies

As part of the work in this task (stated in Section 3), there are two complement layers associated with occupants' comfort conditions in building premises:

- Acoustics models that are able of representing acoustic conditions from sources that may have an adverse influence on occupants' comfort as well as on their physical performance.
- Indoor Air Quality (IAQ) models to address indoor health/well-being conditions, such as carbon dioxide (CO_2) , carbon monoxide (CO), and volatile organic compounds (VOCs) air contamination.

Moreover, building acoustics and IAQ model parameters should be examined in a broader term and further be incorporated in the BIM framework as specified in the BIM4EEB project. There is a series of models specifying the most relevant parameters and how these should be incorporated in a building environment; thus, a thorough analysis of this work is required in order to set the main innovations of the project. We have to point out that the approach is actually in line with the scope of the project towards extending the core BIM ontology with vertical viewpoints that are of interest for specific business stakeholders.

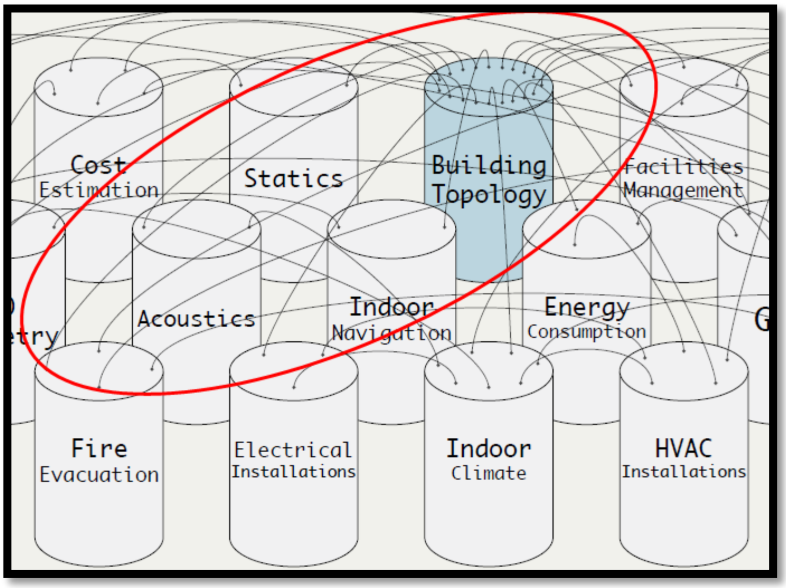

Figure 17: Acoustics integration in BIM ontology

In the field of air quality, there are different attempts available in the literature. While the focus is at urban level air quality, the same principles can be adopted for modeling of IAQ.

hackAIR Ontology

Summary

Title – IABA-01	hackAIR Ontology
Publisher	ITI-CERTH (hackAIR Project)
Purpose	An Ontology-Based model for Personalized Quality of Life Recommendations
Focus	Indoor Air Quality
Type	Ontology

Supported Formats	OWL
Version	1.0
Link	http://mklab.iti.gr/hackair/ontologies/hackairSPIN.ttl

Short Description

This is a recent work towards addressing IAQ in building environment. The model incorporates environmental conditions, occupants' activities, IAQ metrics and the associated rules and actions required for the management of IAQ. A high-level overview of the model is presented:

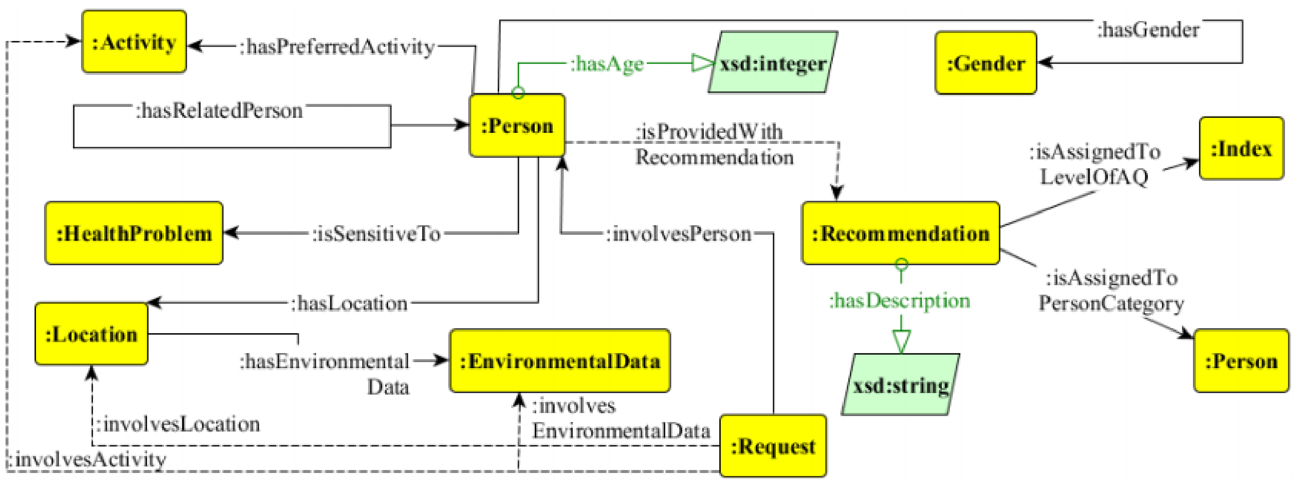

Figure 18: hackAIR Ontology conceptual view

More details about the ontological schema are provided [64]:

- *"hackAIR TBox Ontology: The hackAIR TBox ontology is the basic model that specifies the terminological knowledge (i.e. schema, concepts and relations) of the domain(s) of interest*
- *hackAIR ABox Ontology: The hackAIR ABox ontology imports the hackAIR TBox ontology and contains the assertions (i.e. individuals/instances and values) of real data that comply with the defined schema.*
- *hackAIR SPIN Ontology: The hackAIR SPIN ontology imports both hackAIR ABox and TBox and implements a set of SPIN rules for the interpretation of information stored in the schema (TBox) and the assertions (ABox), in a uniform, automatic and semantically related way. More specifically, its rules handle/perform the automatic inference and personalised recommendation provision by the hackAIR platform."*

The latter is incorporating the different classes of interest for the project as the superset of the previous models. The key classes are presented [64]:

- *"Class Activity represents instances of indoor/outdoor activities. On the basis of rules, recommendations to the users differ according to the nature or intensity of the activity; e.g. in case of harmful AQ conditions, activities like running or biking may lead to increased oxygen uptake and should be avoided or replaced with alternatives.*
- *Class EnvironmentalData represents environmental measurements, i.e. observations from different sources regarding air pollutants, pollen, weather or any other measurable environmental aspect that is involved in the recommendation process.*
- *Class Recommendation represents messages with fixed content, as defined by environmental*

experts for recommendation, together with details on: (a) which type of user such messages concern, and (b) under which AQ conditions they should be informed. An instance of that type may contain the actual message to be inferred to the user. Rules defined in the respective layer of the framework handle the matching between categories of users and defined recommendations."

Relevance with BIM4EEB project data specifications

The ontology presented above is addressing the key data requirements as expressed in previous section. Information about IAQ conditions in building premises, rules/recommendations associated with the IAQ and the activities performed in buildings are key points that can be incorporated in the BIM4EEB IAQ ontology.

Relevance with BIM4EEB	**BIM4EEB Data Requirements**							
	IAQ-01	**IAQ -02**	**IAQ -03**	**IAQ -04**	**IAQ -05**	**IAQ -06**	**IAQ -07**	**IAQ -08**
hackAIR Ontology	**Location**	**Person, Activity**	**Weather Value**	**-**	**EnvironmentalData, EnvironmentalDataType, AirPollutantValue**	**Index**	**Request, RuleProperty**	**Recommendation, Functions**

calidad-aire Ontology

A good alternative was defined in the context of smart cities, though the main principles can be adopted for IAQ modeling in building environment.

Summary

Title – IABA-02	calidad-aire Ontology
Publisher	Ontology Engineering Group - Universidad Politécnica de Madrid
Purpose	This ontology extends the W3C Semantic Sensor Network Ontology (SOSA) with a set of properties that are specific to the domain of air quality.
Focus	Indoor Air Quality
Type	Ontology
Supported Formats	TTL, JSON - LD
Version	1.0
Link	http://vocab.linkeddata.es/datosabiertos/def/medio-ambiente/calidad-aire/ontology.ttl

Short Description

The main objective of this model is to allow representing in a homogeneous manner the air quality observations that are being published by many organisations and individuals as a result of the measurements that are taken by air quality stations and sensors.

There are 4 main classes to be considered for further analysis

- esair:AirQualityObservation to refer to the class of observations about air quality that can be represented.

- esair:AirQualityProperty to group all the properties about air quality that are normally measured. This class has several instances to refer to the types of properties that are normally measured (e.g., benzene, sulphur dioxide, carbon dioxide, etc.)
- esair:AirQualitySensor to refer to the group of sensors that measure the aforementioned properties.
- esair:AirQualityStation to refer to the class of stations that contain air quality sensors and are deployed to make these observations.

A high-level overview of the model is presented in the following:

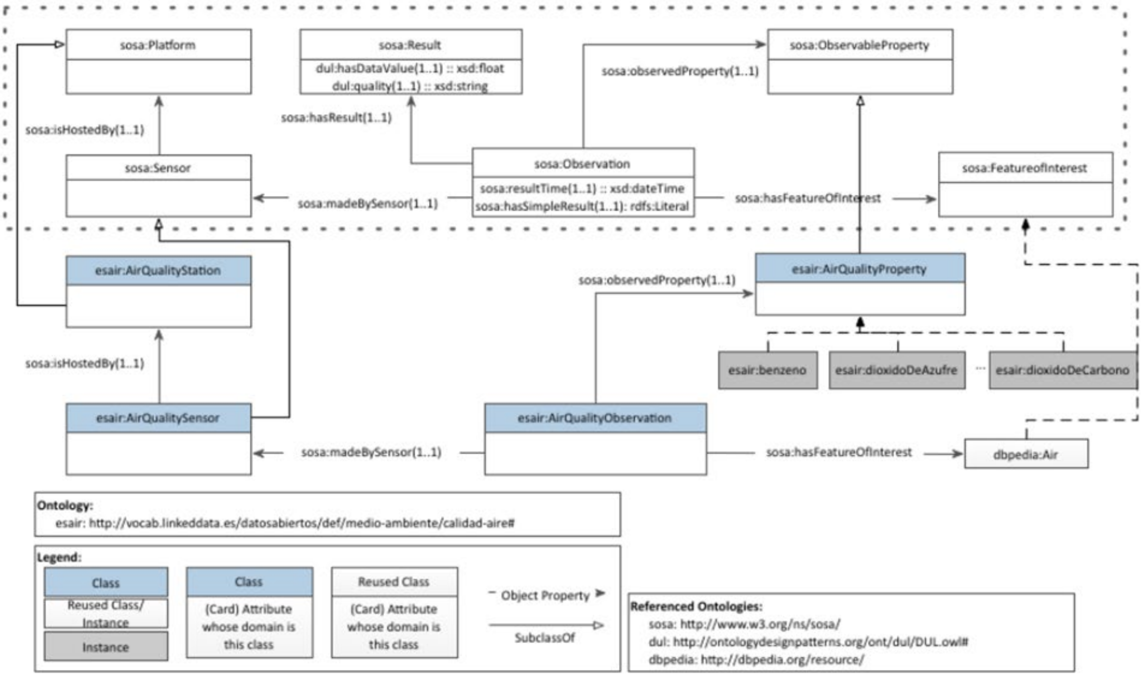

Figure 19: calidad-aire Ontology conceptual view

<u>Relevance with BIM4EEB project data specifications</u>

A minimal structure about AQ modeling is proposed by this ontology. While it does not incorporate actions and activities for the users, the defined classes are of interest for the BIM4EEB project IAQ modeling work. Therefore, the calidad-aire Ontology can stand as the starting point for the modeling work to be performed in BIM4EEB.

Relevance with BIM4EEB	**BIM4EEB Data Requirements**							
	IAQ-01	**IAQ -02**	**IAQ -03**	**IAQ -04**	**IAQ -05**	**IAQ -06**	**IAQ -07**	**IAQ -08**
calidad-aire Ontology	observableProperty, Geometry	-	Sensor, Observation	-	AirQualityStation, AirQualitySensor, AirQualityProperty	AirQualityObservation	-	-

The same analysis applies for building acoustics. This is a field not heavily covered in existing ontologies. Some attempts have been performed but still lacking detailed research in this field.

contaminacion-acustica Ontology

Summary

Title – IABA-03	contaminacion-acustica Ontology
Publisher	Ontology Engineering Group - Universidad Politécnica de Madrid
Purpose	The model extends W3C Semantic Sensor Network Ontology (SSN) with classes and properties to represent the data about acoustic pollution.
Focus	Building Acoustics
Type	Ontology
Supported Formats	TTL, RDF/XML
Version	1.0
Link	http://vocab.linkeddata.es/datosabiertos/def/medio-ambiente/contaminacion-acustica/ontology.ttl

Short Description

According to building standards noise pollution is defined as the presence in the environment of noises or vibrations, originated by any acoustic emitter, involving discomfort, risk or harm to people, during the development of their activities, or goods of any nature, or have significant effects on the environment. Taking into account the mandate to address acoustics as a core parameter in the building environment, the SSN ontology has been extended to address acoustics parameters. The conceptual view of the model is presented in the following:

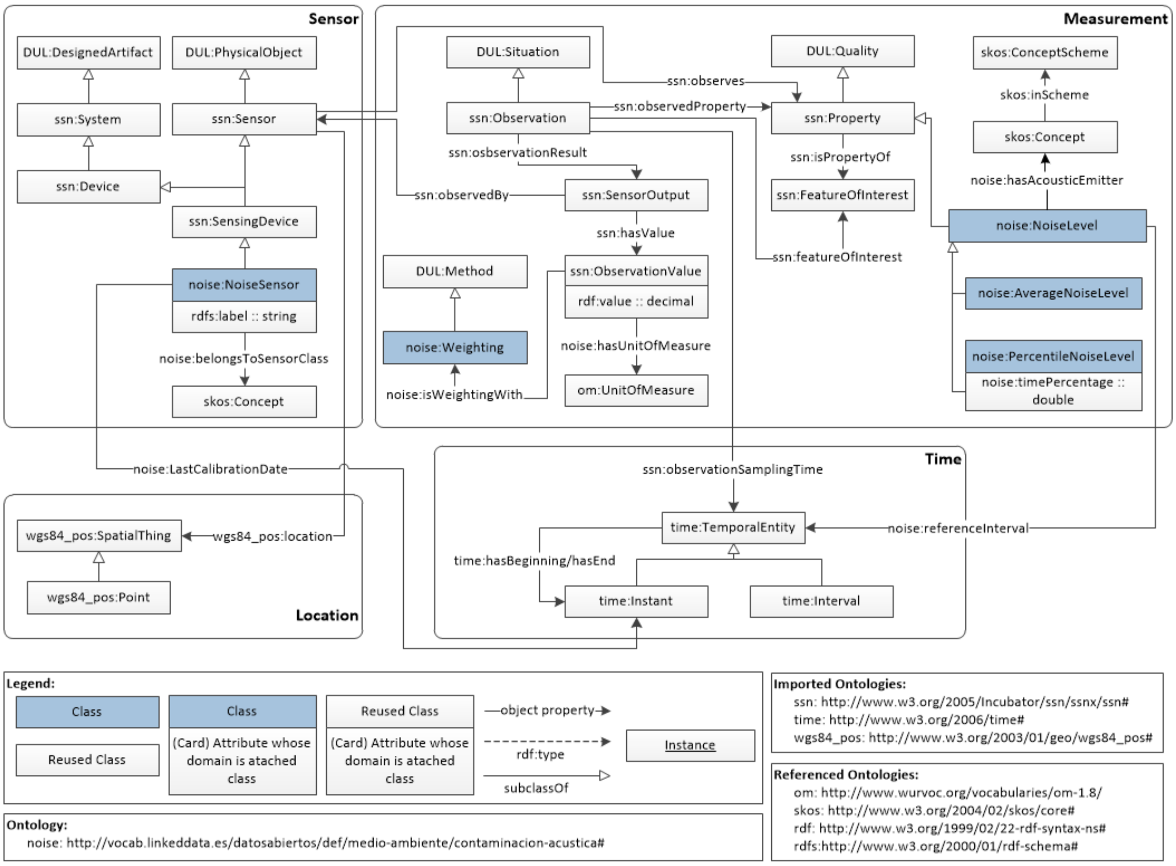

Figure 20: Acoustics Ontology proposed schema

We have to point out that the modeling principles are not different from the calidad-aire Ontology as presented above; the main modules of the model are specified:

- The module "Sensor" models the noise sensor noise:NoiseSensor which collects environmental noise measurements.
- The module "Measurement" models the properties representing the sensor measurements.
- The module "Time" allows the representation of time intervals and instants where the measurements were done.
- The module "Location" represents geographic location.

Special reference is delivered on the combination of the different measurements towards extracting the acoustics KPIs of interest (as specified in the literature, e.g. average noise level). The instantiation of this class is presented in the following figure

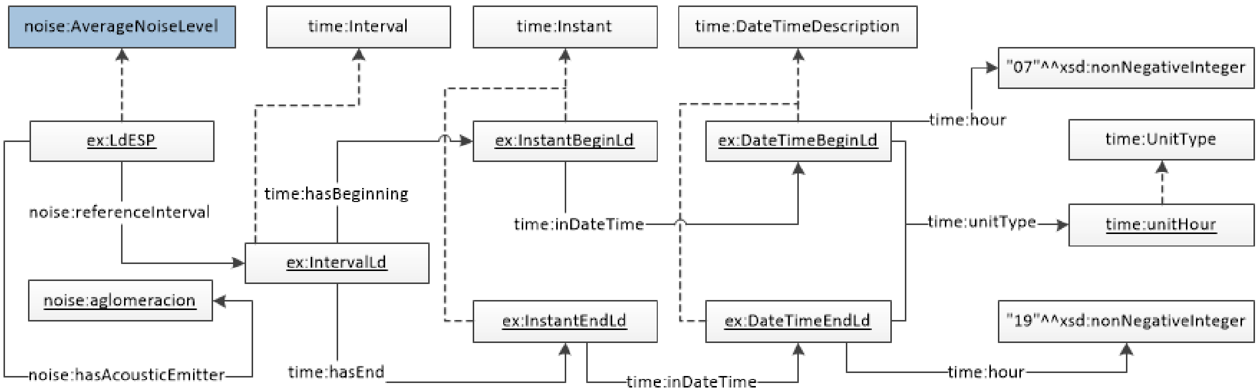

Figure 21: Example of instantiation of the average noise level Ld

<u>Relevance with BIM4EEB project data specifications</u>

The main classes as specified in the contaminacion-acustica Ontology will be incorporated in the BIM4EEB acoustics ontology, taking into account the list of requirements as specified above. Sensor data extensions, measurements and KPIs are among the requirements specified in previous section that should be considered also in BIM4EEB project.

Relevance with BIM4EEB	**BIM4EEB Data Requirements**						
	BA - 01	**BA - 02**	**BA - 03**	**BA - 04**	**BA - 05**	**BA - 06**	**BA - 07**
contaminacion-acustica Ontology	-	Location	Physical Object	DUL: Situation	Sensor, Measurement	NoiseLevel	-

An early work available in the field is also presented as reference for the development of the model in BIM4EEB project.

Indoor Human Comfort Analysis Based on BIM Ontology

Summary

Title – IABA-04	Indoor Human Comfort Analysis Based on BIM Ontology
Publisher	Department of Civil and Environmental Engineering, The Hong Kong University
Purpose	A proposal for ontology to address human comfort and building acoustics
Focus	Building Acoustics
Type	Ontology
Supported Formats	OWL/TTL
Version	TBD
Link	https://www.iaarc.org/publications/fulltext/ISARC_2019_Paper_233.pdf

Short Description

This is not a live ontology, rather a methodology to address building acoustics in a holistic modeling framework. The key point and addition of this work is the identification of metrics and KPIs based on existing PMV methodologies (with focus on the WELL standard which raises high interest and will be examined in D3.5 of the project). More specifically, a list of acoustics metrics of interest are specified in the model and presented in the following table

Index	The Requirement of Index	Standard
Exterior noise intrusion	Average sound pressure level from outside noise intrusion <50 dBA.	WELL Standard
Internally generated noise	Open office spaces and lobbies < 40 dBA; Enclosed offices < 35 dBA; Conference rooms and breakout rooms: <30 dBA	WELL Standard
Reverberation time	Conference rooms: 0.6 s Open workspaces: 0.5 s	WELL Standard
Sound masking	Open workspaces: 45 - 48 dBA. Enclosed offices: 40 - 42 dBA	WELL Standard

Figure 22: Requirement of acoustic comfort index

The snapshot of the ontological model for building performance parameters is presented:

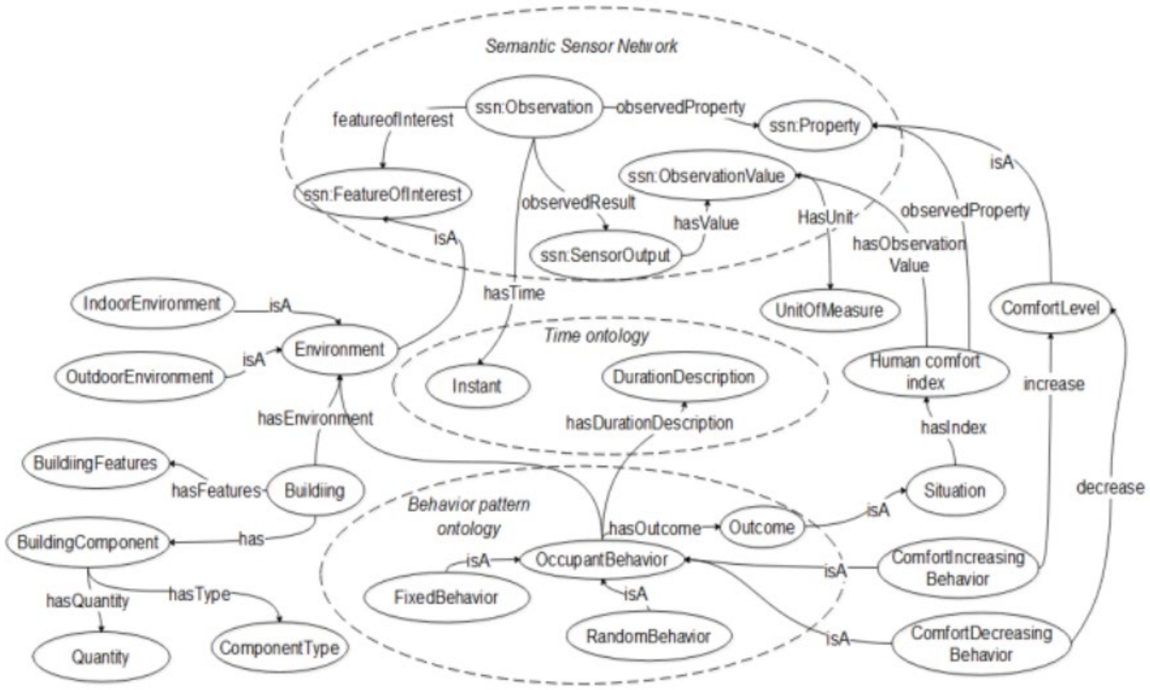

Figure 23: Acoustics Ontology proposed schema [26]

The model is not differentiated from the schemas presented in occupants behaviour section. Thus, the added value of this model is mainly at the level of metrics and parameters to be incorporated in BIM4EEB model.

Relevance with BIM4EEB project data specifications

As stated above, the main focus of this work is not at the definition of the model parameters, rather on the extension of existing model parameter with additional datatypes taking into account the acoustic performance dynamics as specified in the standardization.

Relevance with BIM4EEB	BIM4EEB Data Requirements						
	BA - 01	BA - 02	BA - 03	BA - 04	BA - 05	BA - 06	BA - 07
Indoor Human Comfort Analysis Based on BIM Ontology	-	Building	Building Component	Situation	SensorOutput Observation, ObservationValue	HumanComfort Index, ComfortLevel	-

We presented above the details of the core ontologies to be considered in the context of the BIM4EEB domain modeling. Once again to point out that the aforementioned models where prioritized by taking into account the review analysis in D3.1 and following consultation with the technical partners.

Along with the detailed analysis, a short overview of the ontologies considered at the initial preselection is performed in the following section.

3.1.4 Additional Ontologies

A non-exhaustive list of ontologies available at the different domains was presented above. The selection was performed taking into account the compliance and coverage of the BIM4EEB data requirements. Of course, there are additional models for the different layers of analysis; in some cases, cross domain ontologies covering (at some level) more than one from the aforementioned layers. For example:

- There are also more **generic BIM ontologies** that indicate the occupancy as a role in the building environment without providing extra modeling information. A list is presented in the following:
    - BRICKS [16]: where the different environmental and IAQ conditions are part of the model
    - DERIROOMS [17]: where the occupant is defined as the agent that generally occupies the physical area of the subject resource. Having this property implies being a spatial object. Intended for use with buildings, rooms, desks, etc.
    - SimCore [18]: where the occupant is an actor role in the building environment interacting with the devices available in premises
- Along with the aforementioned BIM related ontologies, there are additional **building material and energy systems related ontologies**. For example, **RealEstateCore [14]** is a common language that will enable control over buildings and development of *new* services – the facilitator of the promises of a digital transformation. RealEstateCore is a domain ontology preparing buildings to interact with the Smart City. A screenshot from the structure is presented:

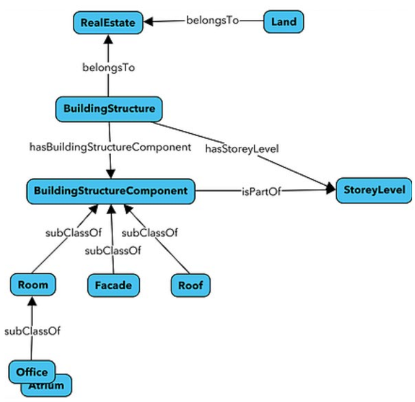

Figure 24: Building data model in RealEstateCore ontology

- SAREF and the extensions serve as the basis for the energy systems. In addition, additional ontologies are available in the field covering at a maximum level the list of project requirements. Indicatively, we name the **SmartEnv** ontology [19] and the **OEMA** ontology [20] covering also the energy systems in the building environment.
- For IAQ models, there are complement classes in human comfort related ontologies:
    - An ontological modeling proposal (https://dl.acm.org/citation.cfm?id=2815816) covering both monitoring and control of IAQ in a building environment, built as an extension of the **DogOnt** presented above. A schema is presented in the following figure

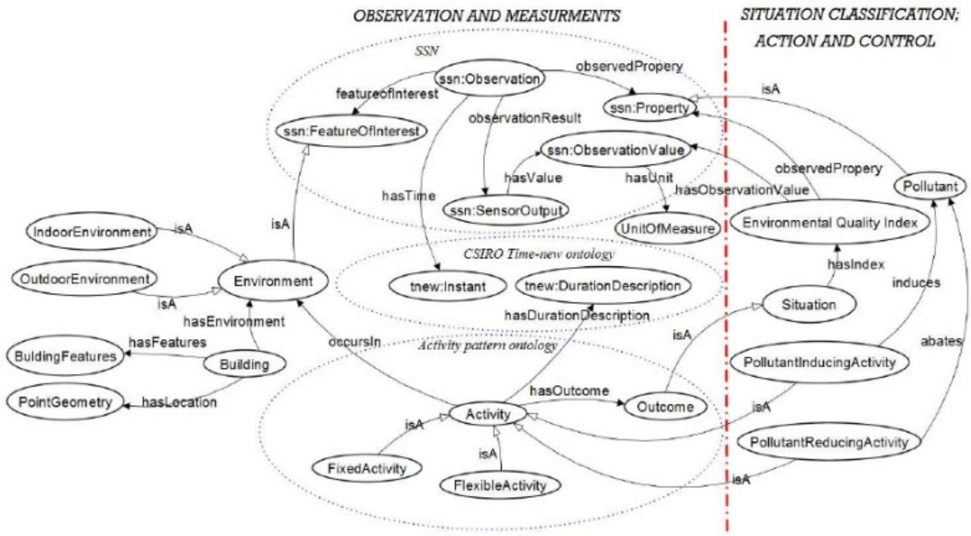

Figure 25: IAQ Ontology proposed schema

- IAQ model principles also incorporated in the ThinkHome ontology as a subset of IEQ in building premises.

- The concept of noise pollution is stated in state of the art sensor ontologies (http://sensormeasurement.appspot.com/ont/sensor/spitfire.owl), (https://www.w3.org/2005/Incubator/ssn/wiki/images/4/42/SensorOntology20090320.owl.xml) though the association remains at the level of indication of noise metric in the building environment that should be associated with occupants behaviour.

A detailed analysis of the aforementioned models is out of the scope of the modeling discussion, nevertheless a review of them was performed towards elicitation the most relevant for the BIM4EEB project needs.

Along with the domain specific ontologies, we present in brief the base ontologies to be considered also in the project. A detailed analysis of them was performed in D3.1. In this deliverable, we name them as highly relevant to specific concepts and data classes of interest for the modeling work. These are:

- QUDT: Quantity, Units, Dimensions and Types Schema
- OWL-Time: Time ontology in OWL
- SSN: Semantic Sensor Networks
- SOSA: Sensor, Observation, Sample and Actuator

SSN, SOSA are directly linked with the data driven approach to be considered in the project and thus will be thoroughly considered for the ontological modeling to be performed in the project.

3.2 Relevant Data Models

The aforementioned analysis indicates that the existing ontological schemas that can clearly address the requirements of the project. Nevertheless, a selective review of data models is performed in order to evaluate also this modeling alternative; while there are many data models available in the bibliography, the focus is on models that are highly relevant with the activities performed in this task and supported by WGs/standardization.

Note: *Considering that the project request was to mainly focus on existing ontological schemas and avoid* *the inheritance of data models (especially when ontological schemas are available), these are presented in brief in the following table, highlighting the core aspects that may be considered in our modeling task in the BIM4EEB project.*

Table 7: List of relevant Data Models

Domain	Data Model/ Schemas	Link	Description	Relevance with BIM4EEB
Occupants Behaviour	obXML	[5]	A schema to standardize the representation and exchange of occupant behaviour models for building performance simulation	+++
	obCoSim	[28]	A schema based on obXML, transformed to be part of the IFC model in Energy Plus	+
Building Material	Eurobau.com database	[29]	European Building and Construction Materials Database and schema	++
	oekobaudat.de database	[30]	An LCA database and model for building material and equipment	+
	GaBi database	[31]	LCA database and model for building material and equipment	+

Energy Systems	IEC 61850-7-4XX	[21]	Generic model for representation of Energy Generation Systems -DER oriented with focus on PVs, CHPs	++
	IEC CIM	[32]	Generic model for representation of Energy Systems -Energy Network Oriented	+
	IEC 61400-25-2	[33]	Model focusing on details of Wind Turbines as energy systems	+
	IEC 61850-90-X	[34]	Generic model for representation of Energy Generation Systems -DER oriented with focus on Batteries	++
	EF-Pi	[35]	Model for Energy Systems -Focus on Energy Services	++
IAQ	Fiware IAQ Model	[36]	Generic model for representation of IAQ pollutants	+++

Acoustics	Fiware Acoustics Model	[37]	Generic model for representation of noise parameters	++
	openMat	[38]	An Open Database for Acoustical Properties of Materials and Objects	++

Some insights about the most relevant work are presented in Annex I (occupants' behaviour) & Annex II (DER modeling). The review of these models was helpful on the way to understand the different domains and incorporate the domain attributes in the modeling framework of BIM4EEB.

3.3 Standardization and Working groups

It is evident that the existing models are covering the list of modeling requirements of BIM4EEB. Nevertheless, some additional details, mainly at the details of the modeling work examined in the task is required. Towards this direction, the literature of the most recent standardization work/WGs is provided in order to evaluate concepts and properties that may be further incorporated in our analysis.

3.3.1 IEA – EBC Annex 66 – Definition and Simulation of Occupant Behaviour in Buildings

This is the WG established to define the core model attributes that have to be considered in the analysis of Occupant Behaviour in Buildings. The main objective of the WG is [6]:

> *… Energy related occupant behaviour in buildings, for example adjusting thermostat for comfort, switching lights, opening/closing windows, pulling up/down window blinds, and moving between spaces, is a key issue for building design optimization, energy diagnosis, performance evaluation, and building energy simulation*; *Having deep understanding of occupant behaviour and being able to model and quantify its impact on use of building technologies and energy performance of buildings is crucial to design and operation of low energy buildings …*

The outcome of this work was the obXML schema presented in previous sections.

> obXML, is an XML schema to standardize the representation and exchange of **occupant behaviour models for building performance** simulation. obXML builds upon the DNAS (an overview of the DNAs concept is presented in Annex I) ontology with a library of obXML files, representing typical energy-related occupant behaviour in buildings, to be developed.

A conceptual overview of occupants' behaviour modeling in buildings as expressed in Annex 66 is presented in the following figure:

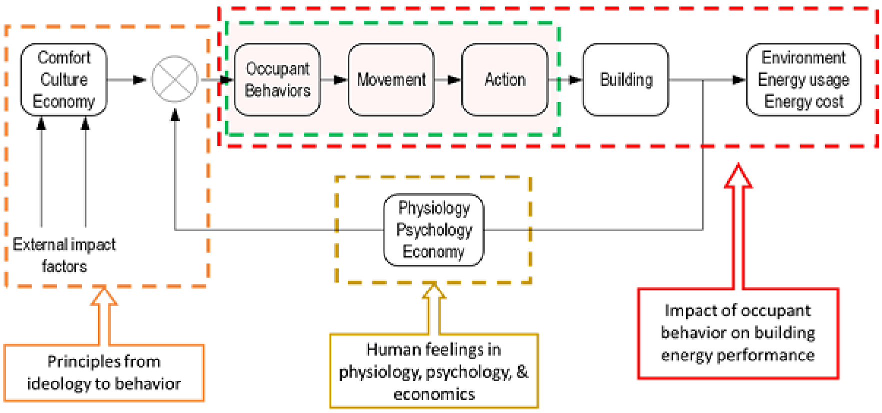

Figure 26: Relationship between occupants and buildings

The latter is a main result towards the definition of the occupants' behaviours and comfort model in BIM4EEB project.

3.3.2 IEA – EBC Annex 79 – Occupant-Centric Building Design and Operation

Annex 79 [4] began in June 2018 as a continuation of Annex 66. It aims to integrate and implement dynamic occupant's presence and behaviour models in the design process and building operation so that both the energy performance and the comfort conditions in the building can be improved. The main objectives are spanning from insight into the potential of various data sources and sensing technologies, data-mining methods and tools for applications within the area of occupant behaviour, advanced occupant behaviour models to proposals for standards and policy support for implementing occupant behaviour in buildings.

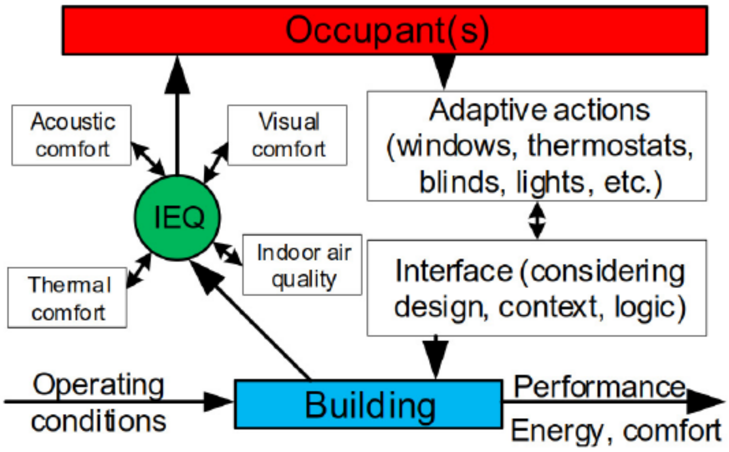

Figure 27: Advanced modelling of occupant behaviour in Annex 79

Annex 79 [4] is separated in 4 Subtasks.

- *"In Subtask 1,* Multi-aspect environmental exposure, building interfaces and human behaviour*, different aspects are addressed such as the multi-aspect comfort and behaviour models, the relationship between the building interfaces and human behaviour, the conduction of field and laboratory studies on human comfort and behaviour, and the research on building interfaces.*
- *Subtask 2,* Data-driven occupant modelling strategies and digital tools, *focuses on developing tools and methodologies for data-driven Occupant Presence and Action (OPA) modeling. The activities of this subtask include developing new occupant data collection approaches, investigating new data-driven methods and developing a platform for sharing data-driven methods related to OPA.*
- *Subtask 3,* Applying occupant behaviour models in performance-based design process, *focuses on improving energy prediction and also, to better understand the occupants' interaction with different architecture and control concepts. Its goal is to develop systematic methods to improve the existing occupant models and improve the overall building design in terms of comfort, usability and energy consumption. The new methods explored regarding the behavioural models can be eventually integrated to BIM.*
- *Finally, Subtask 4,* Development and demonstration of occupant-centric building control, *aims at developing and demonstrating occupant-centric building controls."*

The activities of Annex 79 are very closely related to the occupant's behaviour activities of BIM4EEB project since it seeks to improve the modeling and simulation methods currently available in to ultimately integrated them with BIM. BIM4EEB will thoroughly monitor the progress of the work in this WG in order to incorporate in the BIM4EEB modeling any R& D updates in the domain.

3.3.3 Relevant work on LCA/LCC assessment

A key requirement of the modeling work in the project is the incorporation of LCA/LCC related parameters at the different modeling layers examined in the project, namely the energy systems. Therefore, a brief presentation of the relevant standardization along with some modeling approaches is presented in this section.

Life-cycle assessment is a systematic approach to environmental-impact evaluation to identify and categorize the effects caused by a product (or process) throughout its entire lifetime. An LCA study involves a thorough inventory of the energy and materials that are required across the industry value chain of the product, process or service, and calculates the corresponding emissions to the environment.
Widely recognized procedures for conducting LCAs are included in the 14040 and 15686 series of environmental management standards of the International Organisation for Standardisation (ISO). In particular, ISO 14040:2006 [52] provides the 'principles and framework' for an LCA procedure and specifies four basic steps of the LCA: i) goal and scope definition, ii) life-cycle inventory, iii) life-cycle impact estimation, and iv) life-cycle impact interpretation. The complexity of the different steps of the methodology varies depending on the level of analysis to be performed as part of the assessment process.

With focus on energy systems LCA analysis, there are different model representations [51] [53] [55] available, focusing mainly on the 2nd and 3rd part of the methodology. More specifically, the life-cycle inventory covers the different stages of the element's lifetime, including construction (installation and transport) stage, product (manufacturing and material supply) stage, use (operation, repair, replacement, maintenance) stage and end of life (deconstruction, disposal, transport and waste process) stage. Energy and material intakes take place in the raw materials extraction, DER elements production and DER installation stage, whereas only energy intakes happened in the transportation and waste management stage. The solid material and gaseous emissions are released during several stages such as waste management, DER installation, DER elements production and raw materials extraction stage. The energy output is only found in the DER operation stage. A core part of the LCA analysis is the third step which is the life-cycle assessment, typically carried out based on the ISO 14040:2006 standard. As reported in [54] there are different steps in the assessment process, i.e.: Selection of impact categories, Classification of inventory results, Characterization of impact results. As the scope of this section is to not drill into the calculation details, the focus is about the selection of the methodology that identifies the impaction categories, category indicators, and characterization models with focus on energy systems

There are different methods (more than 20 environmental impact evaluation methods - simplified models, process models, decision-making theory models, and multi-objective optimization models derived from various research institutes) to implement the ISO based life-cycle assessment with focus on energy systems indicatively: ReCiPe 2016, IPCC, Ecopoints, TRACI, AWARE methods etc... Each one of them defines different environmental indicators (e.g. Global Warming, Ozone Depletion, Acidification, Human Toxicity etc..) to be part of the assessment process. For example, the ReCiPe 2016 [56] approach assessing the impacts under 18 categories which is the maximum number among all LCA approaches. The 18 effects obtained by the ReCiPe 2016 approach are resource scarcity (fossil and mineral), human carcinogenic toxicity, human non-carcinogenic toxicity, ecotoxicity (marine, terrestrial and freshwater), freshwater eutrophication, terrestrial acidification, ozone formation (human health and terrestrial ecosystems), global warming (human health, terrestrial ecosystems and freshwater ecosystems), stratospheric ozone depletion, ionizing radiation, water consumption (human health, terrestrial ecosystems and aquatic ecosystems), fine particulate matter formation, and land use. This method also estimates the end-point impacts under three aggregated categories: human health, ecosystems, and resources. The IPCC on the other hand estimates the GHG emissions such as carbon dioxide, methane, nitrogen oxide etc. following a 100-year time-frame. From the different methodologies about energy systems LCA modeling, we have selected the the ReCiPe 2016 methodology for incorporation in BIM4EEB energy systems modeling (and subsequently part of the ontological model) due to the broadest set of midpoint impact categories and KPIs defined; also, suitable to model the LCA details of complex distributed renewable energy system integrating various renewable power generation technologies as also stated in [61][62]. In addition, a key advantage of the ReCiPe framework relative to other approaches is that it uses impact mechanisms that have global scope.

Life-cycle cost (LCC) analysis has been defined as 'the economic assessment of an item, area, system, or facility, considering all significant costs of ownership over its economic life, expressed in terms of equivalent currency' [55]. In generic terms, LCC [60] include initial cost (all associated costs such as delivery, installation, commissioning and insurance), maintenance costs, operating costs, replacement or refurbishment cost, retirement and disposal (decommissioning cost, and other costs such as taxes, depreciation, and additional management costs. In addition, cost variables and indicators are specified within the standard. The relation with the LCA analysis has to do with step 2 where the different states of the product/process lifecycle are specified (Life Cycle Inventory) and thus the associated costs per state needs to be considered in the analysis.

By presenting the key parameters of the LCA/LCC methodology to be considered in the project, the next step is the incorporation of these parameters and values as part of the modeling framework of the BIM4EEB project. The detailed list of LCA/LCC metrics and indicators and the way these are incorporated in energy systems modeling framework of BIM4EEB project are presented in Section 4.3.

3.3.4 Relevant work for Acoustics and IAQ model analysis

While existing ontologies are clearly addressing the topics of interest in the BIM4EEB project, some modeling work as reported in the literature is presented in order to get a holistic view on the way to model IAQ and building acoustics in the overall model.

In order to facilitate the modeling, work we take into account the process of the work in **IEA Annex 68** working group (The overall objective of the IEA EBC Annex 68 is to provide scientific basis usable for optimal and practically applicable design and control strategies for high Indoor Air Quality (IAQ) in residential buildings) with the main focus on:

- defining the **metrics & KPIs [39][40]** to enable a proper consideration of IAQ benefit in building design and operation
- gathering **relevant data** and existing knowledge on major pollutant sources and loads in buildings, including models. The work performed under this task is inline with the standardization effort of s (EN) ISO 16000—Indoor air quality as the most relevant standard that specifies methodologies for IAQ calculation and assessment,
- understanding and developing **prediction models** on the impacts of outdoor pollutants, thermal environment, building materials and envelope, and indoor furnishing and occupant activities on the indoor air quality, and the energy necessary to achieve the desired IAQ level in residential buildings, considering the IAQ metrics and pollution loads defined in previous steps respectively.
- Defining **strategies for design and control of buildings** in order to address IAQ parameters and boundaries.

Taking into account the aforementioned high-level principles, we proceed with the review of the most relevant IAQ-related work in a building environment. IAQ is a volatile concept depending on the outside air, the loads on the indoor air, and the air change rate. Although there is not a strong national or international regulation in place, it exists a lot of standards and guideline values that have been defined by organizations or institutes working on this subject. The data from the regulation show that there is a huge gap between the threshold values given for work exposure limits by national regulations and the ones given as guide values by national or international agencies. This phenomenon shows that the authorities have not taken the matter very seriously so far but that there is a trend for the improvement of the IAQ on the long term. Tables presenting the concentration values threshold for professional long-time exposure, compared to concentrations values threshold for short time and long-time exposure are presented into Annex III.

It is evident that a concrete methodology is required for IAQ model integration in BIM. The proposed methodology is built on three pillars: 1) Development of the methodology to quantify and assess the occupational indoor air quality during construction activities; 2) Quantification of the mass balance model parameters by performing onsite air pollutant sampling; and 3) Integration of occupational indoor air quality assessment into the Building Information Model (BIM) by defining strategies for design and control of buildings associated with the IAQ parameters in a building.

This methodology is aligned with the modeling principles as defined in Annex 68.

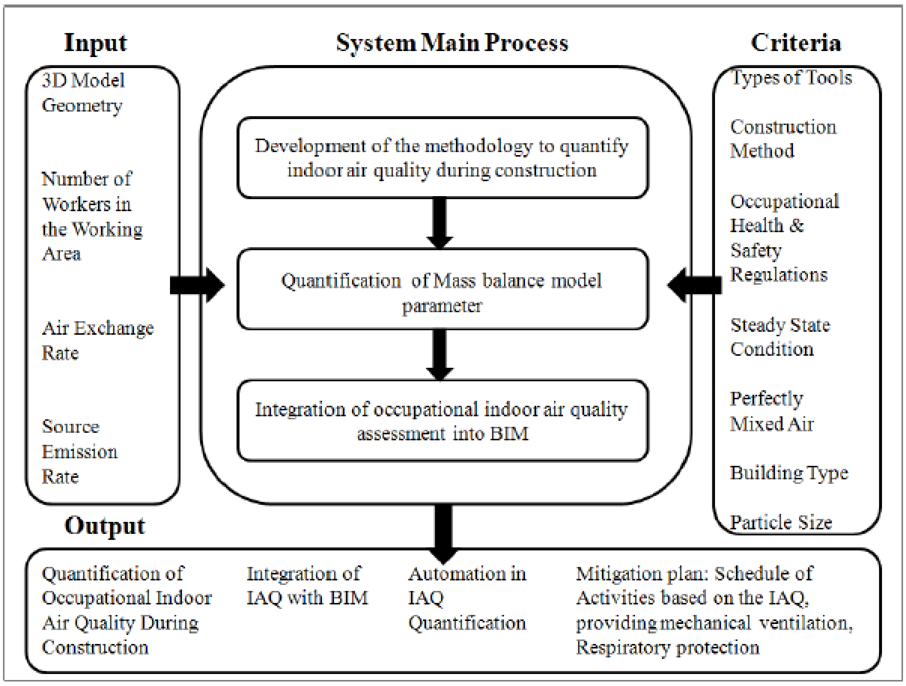

Figure 28: Model based approach for IAQ assessment in BIM context [27]

The main principles:

- The input parameters include a **3D model** which provides the geometry (part of BIM), ***source emission rate***, ***number of workers*** in the working area and ***air exchange rate of the building envelope***.
- Criteria for IAQ assessment are the ***types of tools/equipment, construction/operation method, Regulation, Mixed Air, building type and particle size.***

- A mass balance model (more details in Annex) is the heart of the system and uses mathematical formula which is used to link the occupational indoor air quality assessment to the BIM model.

Last but not least, as stated in the DoA, we should consider IAQ model, parameters from an organizational point of view [41]. According to the recently published ISO45001 *we may specify the requirements for an occupational health and safety (OH&S) management system, and give guidance for its use, to enable organizations to provide safe and healthy workplaces by preventing work-related injury and ill health, as well as by proactively improving its OH&S performance*. This is also highlighted in the proposed methodology as stated in Figure 28 where the focus is on assessing IAQ related parameters. The addition on it is the incorporation of a health and IAQ related recommendations as concepts of the modeling work.

Considering the **acoustic** analysis and how to incorporate them in the BIM4EBB project, the bibliography states that there are fundamental steps required for the analysis, namely collecting necessary data about acoustic qualities, simulating sound propagation, modifying a sound sample with the simulation results, inspecting the sound characteristics both numerically and graphically [46][47] etc... There are four key parameters needed when performing an acoustic simulation of an indoor space: the geometry of the zone, materials of the zone with the absorption characteristics at various frequencies, the sound sources, and the audience and use of the zone ([46]). BIM has the potential to deliver information of room geometry and its material characteristics. Mapping key acoustic parameters such as sound intensity level, reverberation, absorption coefficient and transmission losses to BIM related elements is the anchor point for a building acoustics simulation analysis. Overall, there are two main approaches in research for utilising BIM: the first retrieves only geometry information from BIM and adds acoustical characteristics of spaces using an acoustical database [45]; in the second approach, BIM is first "enriched" by inputting acoustical characteristic parameters into the model and then all of the data is extracted from BIM to a 3rd party software tool (linked to ongoing work in the CEN TC126/WG12 on BIM Acoustics) [46]. The latter is the approach considered in the BIM4EEB project.

Towards enhancing a building information model with acoustics related parameters, a review of the most relevant standards is considered. Acoustic requirements of buildings are today set on a national level, although an international acoustic classification scheme for residential buildings is under development (ISO/TC43/SC2/WG29). As stated in the DoA, the work should consider existing acoustic models and parameters as described in EN12354 [58] (Framework for modelling of the acoustic properties of buildings). The starting point of the work is the review of the EN 12354 series methodology. The methodology described in the EN 12354 (Framework for modelling of the acoustic properties of buildings [42]) model is focusing on the prediction of the acoustic characteristics based on the acoustic properties of the building elements. A series of standards have been defined in order to evaluate the different acoustics related parameters in a building environment, namely[57] [58][59]:

- EN ISO 12354-1:2017 specifies calculation models designed to estimate the airborne sound insulation between adjacent rooms in buildings, primarily using measured data which characterize direct or indirect flanking transmission by the participating building elements, and theoretically-derived methods of sound propagation in structural elements. Two models are provided, one detailed and one simplified, where the detailed model requires input data in third octave bands, while the simplified model is limited to weighted single number quantities, and hence provide a higher uncertainty in the modelling results. Measurement of airborne sound insulation in buildings is done according to EN ISO 16283-1, and evaluated according to EN ISO 717-1, which could be used to verify that the acoustic requirements are met, or to provide input data to the model from existing buildings.
- EN ISO 12354-2:2017 specifies calculation models designed to estimate the impact sound insulation between rooms in buildings, primarily using measured data which characterize direct or indirect

flanking transmission by the participating building elements and theoretically-derived methods of sound propagation in structural elements. Impact noise in buildings is made according to EN ISO 16283-2 and evaluated according to EN ISO 717-2.

- EN ISO 12354-3:2017 specifies a calculation model to estimate the sound insulation or the sound pressure level difference of a façade or other external surface of a building. The calculation is based on the sound reduction index of the different elements from which the façade is constructed and it includes direct and flanking transmission. Measurement of the sound insulation of facades could be made according to EN ISO 16283-3 and evaluated according to EN ISO 717-1.
- EN ISO 12354-4:2017 specifies a calculation model to estimate the sound power level radiated by the envelope of a building due to airborne sound inside that building, primarily by means of measured sound pressure levels inside the building and measured data which characterize the sound transmission by the relevant elements and openings in the building envelope.
- EN 12354-5:2009: In addition, service equipment in buildings varies largely in type and dimensions. The sound levels due to the equipment are caused by various sound sources and various transmission mechanisms, making a prediction scheme rather complex. The sound levels in rooms due to service equipment could be measured in accordance with EN ISO 16032 or EN ISO 10052. The airborne sound power level of sources could be measured in laboratory according to EN ISO 3740 series, and the installed structure borne sound power could be measured according to EN 16567. A preliminary work item in CE/TC126/WG2 is ongoing for the revision of the standard to extend the methods to be able to handle more complex situations.

- EN 12354-6:2004 specifies sound absorption in enclosed spaces and the prediction of sound pressure levels and reverberation time. Reverberation time could be measured in rooms according to EN ISO 3382 parts 1, 2 or 3 depending on type of room, e.g., ordinary rooms in dwellings or open plan offices. Input data for sound absorbing material is measured in laboratory according to EN ISO 354, and can be evaluated as a single number quantity according to EN ISO 11654.

Figure 29 shows a summary of relevant sources in the built environment and how they relate to the EN 12354 standards.

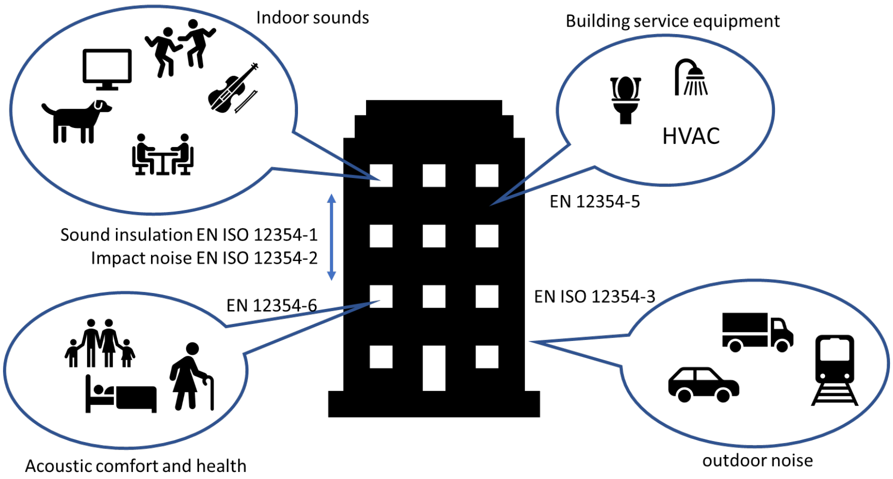

Figure 29: EN 12354 and acoustics in buildings

It is evident, that EN 12354 is focusing mainly on the calculation methods for the prediction of the acoustic parameters in the building environment. For example, in EN 12354-1 and towards the calculation of the Standardized A-weighted sound pressure level difference within rooms (airborne sound insulation, Dn,T), we have to consider a series of equations that estimate the apparent acoustic reduction global index (R'a) as a synthesis of the sound reduction index for direct transmission and flanking sound reduction index for transmission paths (Dn,x) that are defined taking into account the sound reduction index for the dividing or separating element and flanking elements (R), the junction length between the separating element and flanking element, the vibration reduction index for each junction (Ki,j) and the sound reduction index improvement by additional layers (DR).

In the context of the BIM4EEB project, as stated in the DoA, the focus is on the identification of the acoustics parameters - acoustic properties of building elements (e.g. walls, facades, floors) and building services components that should be modelled (acoustic insulation, impact noise level, service equipment noise, reverberation time, sound insulation)- and thus the review of this work was performed in order to show that some key acoustics parameters as considered in the standard EN 12354 (e.g., sound reduction index) can be incorporated in the modeling work performed in the project. In the following figure, a non-exhaustive list of acoustics parameters and indicators as specified in the EN 12354 are presented.

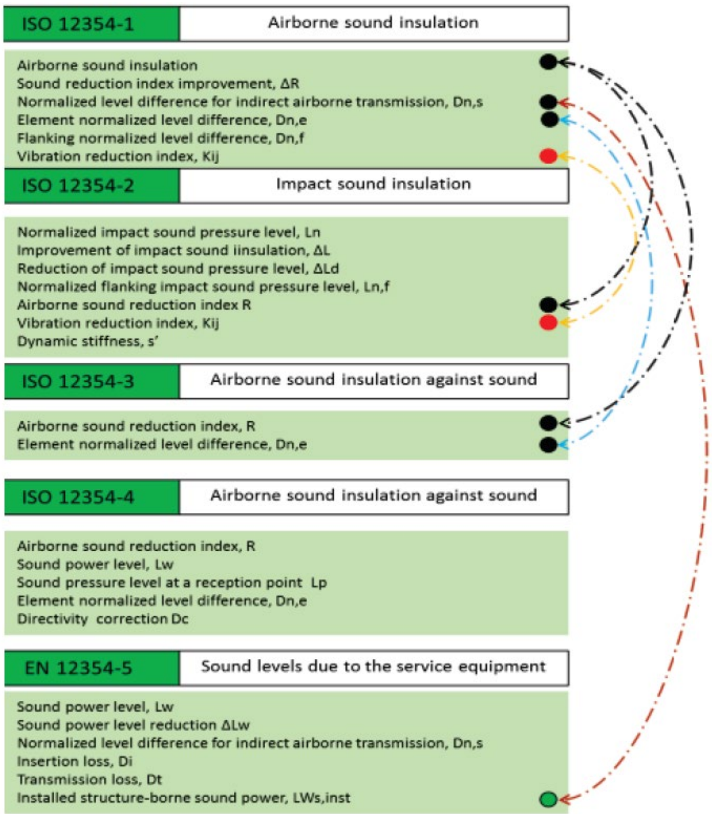

Figure 30: Reference Data standards for acoustics modeling [49]

In [48] a review of the most important acoustics indicators is performed; to understand the concepts of interest in building acoustics modeling and further incorporate these modeling parameters in the BIM4EEB acoustics model. The analysis is performed taking into account the different building elements and the association with airborne and impact sound level calculations. The details of the model are presented in the ontological model.

Note: We have to point out again that EN 12354 goes beyond the modeling work to be performed in the project as the focus of the standard is on calculation techniques which will not be examined in the scope of the BIM4EEB project modeling work.

3.4 Models Elicitation and BIM4EEB data specifications coverage

We presented above the mapping of BIM4EEB data specifications with the selected modeling schemas (focusing mainly on ontological models). As stated above, most of the elicitated models are covering more than one domain. For that reason, a thorough review of the different ontological schemas to the whole list of requirements is performed. An overview of this analysis is presented in the following table in order to clearly show the level of coverage of the BIM4EEB data requirements.

- (+) we state the main focus of the model as presented above.
- (x) we define the level of coverage of requirements for the other domains.

Table 8: BIM4EEB data specifications &Ontologies Mapping

Model	OB-01	OB-02	OB-03	OB-04	OB-05	OB-06	BM-01	BM-02	BM-03	BM-04	BM-05	ES-01	ES-02	ES-03	ES-04	ES-05	ES-06	ES-07	ES-08	IAQ-01	IAQ-02	IAQ-03	IAQ-04	IAQ-05	IAQ-06	IAQ-07	IAQ-08	BA-01	BA-02	BA-03	BA-04	BA-05	BA-06	BA-07
OPM - 01	+	+	+	+	+	+	×	×				×	×	×	×	×				×	×			×					×			×		
OPM - 02	+	+	+	+		+	×					×	×	×	×	×	×			×	×			×					×			×		
OPM -03	+	+	+	+	+	+	×					×								×	×	×		×	×				×			×		
OPM -04	+	+				+																												
BMES-01	×	×	×	×			+		+		+									×	×			×					×					
BMES-02																																		
BMES-03							+				+																							
BMES-04				×	×							+	+	+	+	+	+							×								×		
BMES-05	×	×		×	×		×				×	+	+		+	+		+		×				×										
IABA -01	×	×					×													+	+	+		+	+	+	+							
IABA -02							×													+		+		+	+									
IABA -03																													+	+	+	+	+	
IABA -04	×	×		×	×	×	×	×													×	×			×				+	+	+	+	+	

The aforementioned analysis clearly prescribes that several ontological models can be inherited in our project. On the other hand, it is evident that the perspective of each model is not wide enough to address the heterogeneous domains of interest in this task.

Last but not least, and towards the final selection of the most relevant ontologies, a comparative analysis is performed by defining some objective criteria. These criteria and importance have been defined after consultation with partners and taking into account the updated guidelines for the modeling work (need for compliance with project needs, level of maturity, level of expressivity, standards based and OWL2 compliant). The results of this analysis are presented in the following table.

Model	**Evaluation Criteria**					
	Compliance with BIM4EEB requirements	Expressivity Level	Maturity Level	Reference Level	Support by Standardization Bodies/WGs/ E.C. Initiatives	OWL 2 Validation
Think Home Ontology	++	++	+	++	-	- [5]
Adapt4EE Ontology	++	++	++	+	-	+
Activity Pattern Ontology	-	+	+	+	-	+
ifcOWL	++	-	+	+	++	+
Eurobau	-	+	++	++	+	+
BOT Ontology	+	+	++	+	+	+
SAREF and Extensions	++	+	++	++	++	+
SEAS ontology	++	+	+	++	-	-
hackAIR Ontology	++	++	-	+	-	+
calidad-aire Ontology	++	+	+	+	+	+
contaminacion-acustica Ontology	+	+	-	+	+	?

Table 9: Literature Ontologies - Evaluation Analysis

Notes:

- For the OWL2 validation, as a recommendation from the commission, we used the http://visualdataweb.de/validator/ validator; part of the methodology defined in D3.1.
- Overall, the overall consistency of the ontologies mentioned above was checked with the OntOlogy Pitfall Scanner! (http://oops.linkeddata.es/) towards detecting common pitfalls in ontologies.

The objective of this section was to provide a deep analysis on how well existing resources cover the

[5] Inheritance of the OWL-Time ontology which is not parsed from all reasoners.

identified requirements based on the BIM4EEB use cases reported in the 2nd section of the document. We can say that a resource covers a requirement if there are entities of the resource that are relevant to the requirement, as shown in previous section.

The main results of the analysis are presented:

- There are several models available addressing at a maximum level the project requirements. The thorough analysis is mandatory in order to get a deep understanding of the different domain details and thus adapt this knowledge to the BIM4EEB model.
- Nevertheless, the decision was to focus our review only on standards-based ontologies: BOT, SAREF, ifcOWL have been selected as base ontologies for our modeling work. As stated above, SSN/SOSA are among the generic ontologies considered in the model activities of the project and thus also part of the alignment activities performed in the project.
- Even at the level of existing ontologies; there is still work to be performed to address the BIM4EEB project requirements. The main classes missing from existing work is mainly:
    - BIM4EEB project specifications that should be part of the models defined in the project; this applies mainly at the building materials and equipment ontology along with energy systems ontology
    - Model related parameters associated with occupants' comfort, IAQ and acoustics modeling.
    - Especially for IAQ and acoustics in the building environment (with the focus on energy management) there is not much work available in the literature, focusing only at modeling measurements, basis metrics and performance indicators; thus, additions related to the holistic coverage of building IAQ and acoustics should be considered in the analysis

The next section is focusing on the definition of the domain ontologies by adopting as much as possible the work that already exists in literature, further providing the relevant to BIM4EEB model extensions.

4 BIM4EEB occupants and building components domain ontology

The scope of this section is to provide the BIM4EEB domain ontologies for occupants' behaviour and building components. The starting point for the definition of the different ontological models is the high-level design principles as specified in previous section (state of the art analysis & requirements analysis). By incorporating in the modeling work the BIM4EEB specificities, we proceed with the definition of the BIM4EEB domain ontology.

The modeling work in this task is performed by using Protégé [43]. Protégé is a free, open-source ontology editor and a knowledge management system. Protégé provides a graphic user interface to define ontologies and includes deductive classifiers to validate that the models are consistent and to infer new information based on the analysis of an ontology. Therefore, it fits to the work performed in the project towards the definition of a unified domain ontology that fits to the BIM4EEB ontology requirements as specified in T3.1.
For publishing ontologies, we follow also the instructions of D3.1, publishing ontologies in github. GitHub Pages allows the publication of organization's resources on the Web. In the case on ontologies, GitHub pages can be used to host the ontology files in several different serializations (Turtle, JSON-LD, and so on) and the documentation files in HTML.

As the project evolves and during the harmonization process, the ontologies made available to the GitHub of BIM4EEB project (details provided in D3.1 - https://w3id.org/digitalconstruction/0.5).

By presenting the technical details for the delivery of the work in this task, we proceed with the domain specific modeling in the following sections.

Note: We have to point out that the methodological framework of vertical and horizontal segmentations as has been defined in D3.1 is adopted at the work performed under T3.2 in a total compliance with the description provided in https://www.w3.org/TR/vocab-ssn/#Modularization. The implementation in DiCon ontologies (also the ontological models defined in this document) is fully elaborated in D3.6 where the full list of alignments with existing ontological models is reported in details.

4.1 Occupants' behaviours and comfort ontology

In this section, we are presenting the domain ontology for occupants' behaviours and comfort as defined in BIM4EEB project. Following the updated modeling methodology, the occupant's behaviour modeling concepts are defined, considering also the alignments with concepts as specified in D3.1.

More specifically, the concepts of **dice:ResidentialUnit, dica:Occupant** are introduced in order to contextualize the role of an occupant at a specific building space, while further defining domain specific data properties. Several occupants may occupy a building space, where each occupant can have more than one behaviour. **dicob: OccupantBehaviour** is another top-level class used to represents the details of the comfort profiling framework defined in the project.

Considering that the overall behaviour profiling is based on monitoring contextual conditions in building premises (DNAs principles), the key concepts related to **Observation** (Drivers)**, Actuation** (Actions)**, System (Sensor/Actuator)** (Systems) are introduced in the model through proper alignments. Namely the relevant classes of: **dicp:Observation** over a **dicv:QuantifiableProperty** with a **dicv:PropertyState,**

dicp:Actuation (and dica:ManualActuation) or **dici:StatusUpdate, dice:Actuator, dice:Sensor** are considered for the modeling work in order to set the basis for the context driven occupants' behaviours and comfort profiling framework examined in the project.

On top of these alignments performed, occupants' behaviours specific classes are defined following the basic principles as specified in the DNAs framework presented in Section 3. More specifically, in association with the generic concepts presented above, domain specific concepts are defined as part the model, namely:

- **dicob:TemperatureSensor, dicob:LuminanceSensor, dicob:HumiditySensor, dicob:NoiseSensor, dicob:PresenceSensor** as sub-classes of dice:Sensor
- **dicob:Thermostat, dicob:LightSwitch, dicob:LightDimmer** as sub-classes of dice:Actuator
- **dicob:EnvironmentalObservation** as sub-class of dicp:Observation representing the driver/context conditions in the building environment. environmentalObservation is associated with the sensor device measuring the specific environmental condition.
- **dicob:EnvironmentalProperty** as sub-class of dicv:QuantifiableProperty
- **dicob: userPreference (dicob:thermalStatus, dicob:visualStatus)** as sub-class of dici:StatusUpdate defined to represent the manual preference of the user over specific context conditions as specified by the user. In this case scenario, a value and timestamp represent the status update triggered by the building occupant.

At the heart of the modeling, we have the model class **dicob:OccupancyComfort** class defined to express the Needs of the DNAs. Specific sub-classes of interest in the BIM4EEB project are defined, namely **dicob:ThermalComfort, dicob:VisualComfort** and **dicob:AcousticComfort.** The BIM4EEB comfort profiling framework is characterized by a generic model representation, where the comfort profile of the user is characterized by comfort requirements that could be defined by fixed limits of: min, max parameters as model boundaries expressed in terms of **dicob:EnvironmentalPreference** over specific environmental properties (e.g. temperature, luminance, dB level).

As part of the occupants' behaviours analysis, we consider also occupancy/ presence profiling related parameters at each specific residential unit. The **dicob:OccupancyProfile** class is defined to specify the occupancy profiling model overview over a specific time frame (a specific day in the context of BIM4EEB project), with the model parameters to be specified through the **dicob:occupancyParameters** class.

A visual representation of the ontological model is presented in the following figure.

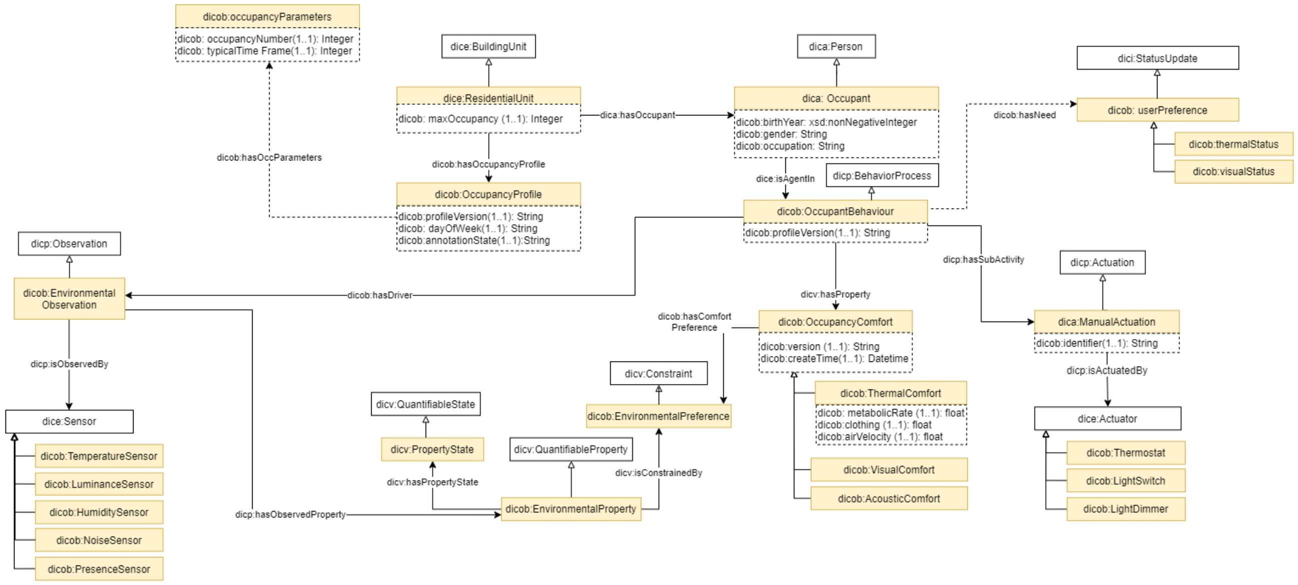

Figure 31: Domain Ontology for Occupants Behaviour and Comfort

The modelling schema for Occupants Comfort is available in the public repo:

https://w3id.org/digitalconstruction/0.5/Occupancy

4.2 Building Components and material Ontology

The scope of Materials Ontology (DICM) is to explicitly define the concepts and necessary relationships between the material and its properties. As such it aims to provide material object structure, material, properties, values and units. The ifcOWL has concepts such as IfcMaterial and IfcPropertySet which are mainly used to represents the material and also associated property sets. But due to complex nature of the ifcOWL, usage of this domain knowledge is limited. So, here we attempted to define a modular ontology for materials by considering IFC knowledge. Since properties are one of the important parameters for the materials, DICM is developed by taking the advantage of Variables ontology (DICV), Entities Ontology (DICE) concepts to express building objects and property concepts.

The ontology as illustrated in the following figure contains the major classes which are **dicm:Material, dicm:MaterialObjectStructure, dicm:MaterialProperty, dicv:BuildingObject, dicv:QuantitativeProperty**. Which also have major object properties, those are dicm:hasMaterial, dicm:hasLayer, dicm:hasLayerSet, dicm:hasAdjacentElementLayer, dicm:hasAdjacentLayer, dicm:adjacentElement and dicv:isPropertyFor. Data properties for material data are also defined.

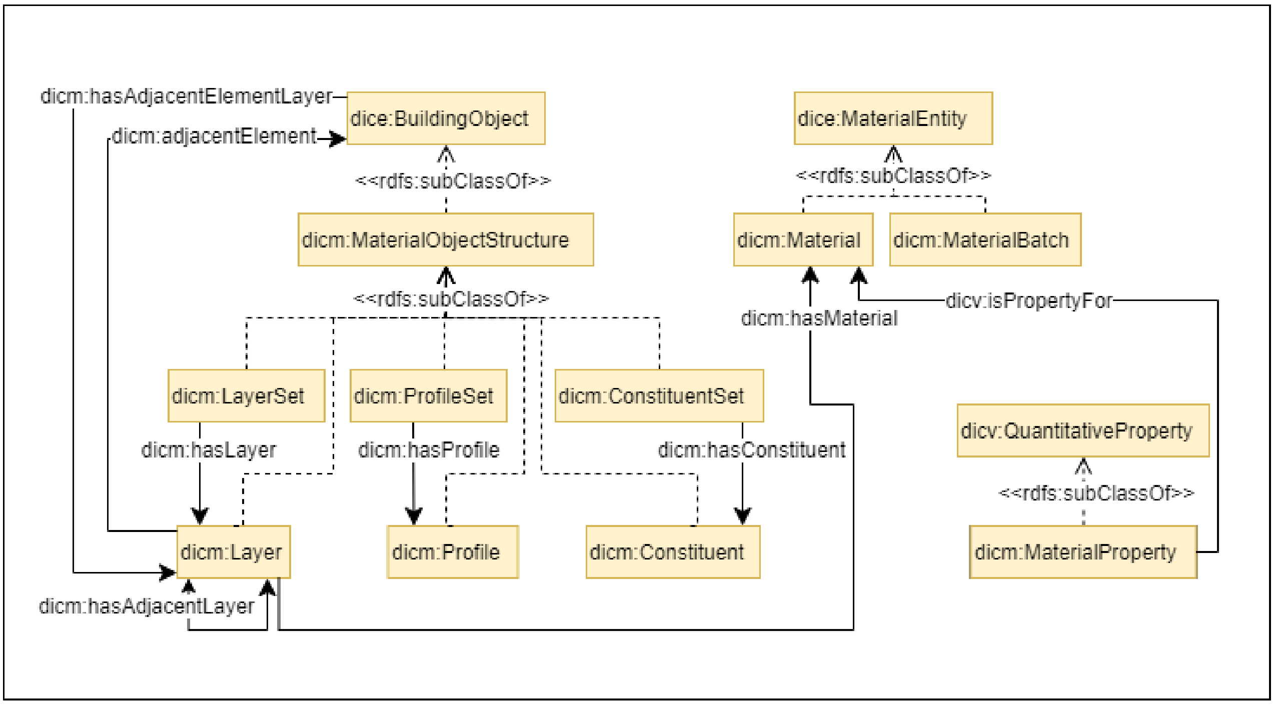

Figure 32: BIM4EEB Materials Ontology (DICM) Overview

The modelling schema for building material is available in the public repo https://w3id.org/digitalconstruction/0.5/Materials

Classes in DICM ontology

The classes defined in the DICM ontology are shown in Figure 33.

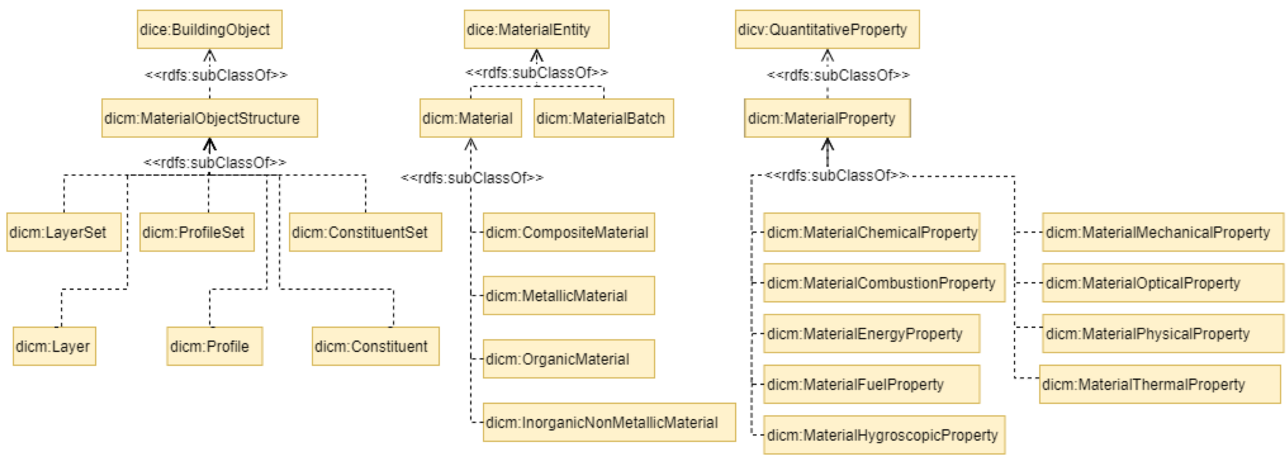

Figure 33: Classes used in the DICM ontology

The class dice:BuildingObject is an entity that forms a part of an existing or designed building. This class have subclass related to the material object structure. The dicm:MaterialObjectStructure is a concept to represent material related information that has material related properties. The classes dicm :Layer, dicm:LayerSet, dicm:Profile, dicm:ProfileSet are the subclasses of dicm:MaterialObjectStructure. However, the primary focus is on dicm:Layer, and dicm:LayerSet. The dicm:Layer is a single and identifiable part of an element which is constructed of a number of layers (one or more) (ISO, 2018). The dicm:LayerSet is a designation by which materials of an element constructed of a number of material layers is known and through which the relative positioning of individual layers can be expressed (ISO, 2018).

The class dice:MaterialEntity is equivalent to the BFO class 'material entity'. It has two subclasses. One is dicm:MaterialBatch, which is defined as a collection of homogeneous physical substance that participates in the construction project as the input of a process. Second concept is dicm:Material, which is used to represents homogeneous or inhomogeneous substance that can be used to form elements. It depicts the material assigned to a product. The dicm:Material has 4 subclasses, they are dicm:CompositeMaterial, dicm:InorganicNonMetallicMaterial, dicm:MetallicMaterial, dicm:OrganicMaterial. dicm:MetallicMaterial is to represents the metals which are crystalline and has a structure consists of crystals and grains. Example individuals of this material type are steel, cast iron...etc. dicm:OrganicMaterial is used to define the organic materials such as wood, polymer, bitumen…etc. dicm:CompositeMaterial represents the constituent materials which are concrete, masonry, reinforced concrete....etc. dicm:InorganicNonMetallicMaterial defines the material types such as glass, natural stones…etc.

The dicv:QuantitativeProperty is a class that can assume quantitative values. The concept dicm:MaterialProperty subclass of dicv:QunatitativeProperty and is used to represents the different properties of materialThe dicm:MaterialProperty have 9 subclasses, which represents different kinds of material properties. These material properties listed as follow.

The dicm:MaterialChemicalProperty – Describes the chemical properties of the materials. Example are acidity concentration, alkalinity Concentration…etc.

The dicm:MaterialCombustionProperty – Defines the material properties generate due to material combustion. Some of those are CO content, N2O content…etc.

The dicm:MaterialEnergyProperty – This class represents the energy properties of the material. Example is solar refraction index, Gas Pressure, visible refraction index…etc.

The dicm:MaterialFuelProperty – Defines the fuel properties of the material. Carbon content, lower heating value …etc.

The dicm:MaterialHygroscopicProperty – Hygroscopic properties of the material will defined under this category. Moisture diffusivity, vapour permeability are few examples of hygroscopic properties.

The dicm:MaterialMechanicalProperty – Defines the mechanical properties of the materials. Example of this this category properties are young modulus, shear modulus, Poisson ratio…etc.

The dicm:MaterialOpticalProperty – Optical properties such as visible transmittance, solar transmittance …etc will fall under this category.

The dicm:MaterialPhysicalProperty – Describes the physical properties of the materials such as density, porosity, molecular weight…etc.

The dicm:MaterialThermalProperty – Defines the thermal properties of the materials. Example of this category properties are specific heat, boiling point, freezing point …etc.

Along with the main classes that consist of the DICM ontology, object and data properties are specified to show the details of the building components/ materials. The list of the properties are provided in Annex IV.

4.3 **Energy (Systems) Ontology**

As stated in Chapter 3, the SAREF model is a well-structured model clearly representing the key concepts of Energy Systems. Digital Construction Energy ontology was defined in conformance with the SAREF Energy, aligning it at specific base concepts and extending it with specific concepts needed in the context of BIM4EEB project (detailed requirements presented in Section 2.2). More specifically, appropriate alignments with SAREF ontology are considered for the concepts of: **Device, Measurement, Property, State, Command and Service** (in line with data requirements ES01-ES06 as presented above). More details about the alignments of SAREF with the BIM4EEB Ontology are provided in: https://w3id.org/digitalconstruction/0.5/Alignment/Saref/saref-dicon.ttl and also in Annex I of D3.6 (where the full list of alignments of Dicon ontology with external ontologies is provided).

Additional classes are defined in order to better express the data specificities of the BIM4EEB project. More specifically, SAREF defines a generic Device class "*as a tangible object designed to accomplish a particular task in households, common public buildings or offices".* Specific examples of this generic class are specified in the BIM4EEB model. The **dices: Generation, dices: Storage** classes are defined as subclasses of the Device class to represent the concepts of: **dices: WindTurbine**, **dices: PV, dices: Diesel, dices: CHP and dices: Battery, dices: EV - Storage, dices: Domestic Hot Water** systems. Also the **dices: Demand** class specifies the devices within the building environment with specific subclass of **dices:HVAC** (as aligned with the saref: HVAC device type)

The same applies also on the list of Function **(dice: DeviceService)** where appropriate subclasses **(ComfortManagement, SelfConsumption, FlexibilityService/ServiceAggregation)** are defined to express the operational modes for the different devices. Also, as subclasses of the **Property** class, we have incorporated the concepts of Flexibility and Reward not covered by the SAREF model. We have to point out that additional metrics associated with the energy system performance can be defined as part of the property subclass, and thus we consider this part of the work open as the project progress with the demonstration activities.

The main addition though in the model (as also stated in the DoA) is the list of concepts defined to address:

- Cost /LCC related parameters for the Energy Systems
- LCA related parameters as part of the modeling framework adopted in the project.

For the LCA/LCC analysis more details about the modeling approach and principles were provided in the state-of-the-art analysis and the review of the relevant standardization (section 3.3.3) where we highlight the role of ReCiPe methodology as a model framework that fits to BIM4EEB model objectives. Within BIM4EEB modeling work, the focus is on Life Cycle Inventory where the different steps of the lifecycle process are defined as well as on the Life Cycle Impact where the key metrics related to assessment are defined

Overall, the different classes that characterize the LCA modeling are: **dices:LifeCycleAssesment** as the generic class representing the general information about the LCA analysis performed (as a subclass of the information content entity class). As specified above, the life cycle assessment is characterized by the **dices:LifeCycleInventory,** naming the different steps of the Life Cycle Assessment and the **dices:LifeCycleImpact** that specifies the different environmental indicators (considered for the LCA assessment under different categories).

The non-exhaustive list of parameters as depicted in the model (following the ReCiPe 2016 approach) are presented in the following table. First the list of **LifeCycleImpact** related parameters defined as classes of the model.

Category	ReCiPe methodology Name	BIM4EEB Ontology	Description
Ecosystems (dices: EcosystemImpact)	LOP	dices: AgriculturalLandOccupationPotential	Agricultural land occupation potential
	ETP	dices: EcotoxicityPotential	Ecotoxicity potential
	FEP	dices: FreshwaterEutrophicationPotential	Freshwater eutrophication potential
	EOFP	dices: EcosystemAffectingPhotochemicalOxidantFormationPotential	Photochemical oxidant formation potential: ecosystems
	TAP	dices: TerrestrialAcidificationPotential	Terrestrial acidification potential
	WCP	dices: WaterConsumptionPotential	Water consumption potential
Human health (dices: HumanHealthImpact)	GWP	dices: GlobalWarmingPotential	Global warming potential
	HTP	dices: HumanToxicityPotential	Human toxicity potential
	IRP	dices: IonisingRadiationPotential	Ionizing radiation potential
	ODP	dices: OzoneDepletionPotential	Ozone depletion potential
	PMFP	dices: ParticulateMatterFormationPotential	Particulate matter formation potential
	HOFP	dices: HumanAffectingPhotochemicalOxidantFormationPotential	Photochemical oxidant formation potential: humans
Resource scarcity (dices: ResourceUseImpact)	FFP	dices: FossilFuelPotential	Fossil fuel potential
	SOP	dices: SurplusOrePotential	Surplus ore potential

Table 10: List of Life Cycle Impact related classes defined in BIM4EEB Energy Systems Ontology

In addition, the classes defined to represent the different stages of LCA analysis as part of **LifeCycleInventory (**dices: DeviceLifecyclePhase**)** and are presented in the following table.

BIM4EEB Ontology	Description
dices: DeviceProduction	The production phase of the energy device
dices: DeviceManufacturing	The stage at production related to manufacturing

dices: DeviceMaterialSupply	The stage at production related to material supply
dices: DeviceConstruction	The construction/ placement phase of the energy device
dices: DeviceTransport	The stage at construction related to device transport to installation point
dices: DeviceInstallation	The stage at construction related to installation of the device
dices: DeviceUse	The use phase of the energy device
dices: DeviceOperation	The stage at use related to actual operation
dices: DeviceMaintenance	The stage at use related to maintenance period
dices: DeviceRepair	The stage at use related to repair period
dices: DeviceReplacement	The stage at use related to device replacement
dices: DeviceEndOfLife	The end of life (post operation) phase of the energy device
dices: DeviceDeconstruction	The stage at end-of-life phase related to device deconstruction
dices: DeviceDisposal	The stage at end-of-life phase related to device disposal

Table 11: List of Life Cycle Phase related classes defined in BIM4EEB Energy Systems Ontology

Last but not least, the Life Cycle Assessment is covering also cost related aspects (**dices:LifeCycleCost**) that are further split into the different cost types defined in the literature (capital, engineering, operational, end of life). More specifically, the different LCC related classes defined are presented in the following table:

BIM4EEB Ontology	Description
dices: CapitalCost	The capital cost (purchase cost) of an energy system
dices: EndOfLifeCost	The cost required for the disposition/disposal of the device (post operation)
dices: EngineeringCost	The cost required for the installation of the equipment on place (pre operation)
dices: MaintenanceCost	The maintenance cost of an energy system (part of O&M costs)
dices: OperationalCost	The operational cost of an energy system (part of O&M costs)
dices: TaxRate	An indicator expressing the tax rate required for the calculation of the final cost
dices: CostParameter	A class expressing the list of parameters required for normalization of cost indicators
dices: InterestRate	An indicator expressing the interest rate required for the calculation of the levelized cost

Table 12: List of Life Cycle Cost related classes defined in BIM4EEB Energy Systems Ontology

A visual representation of the ontological model for energy systems is presented in the following figure.

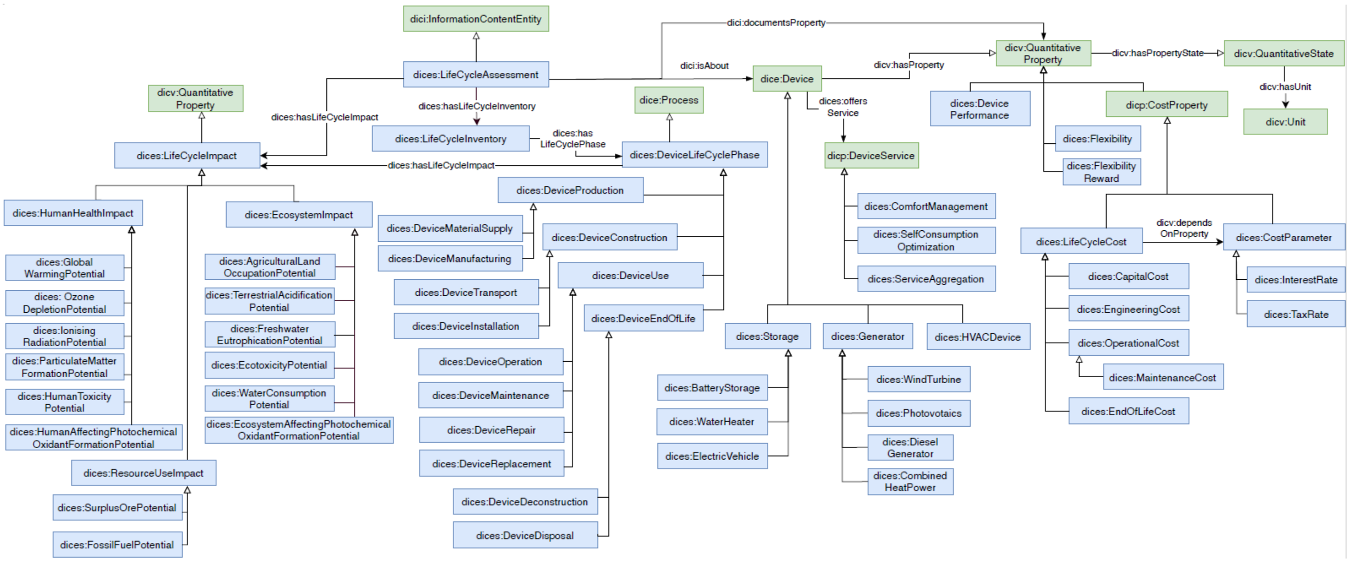

Figure 34: Domain Ontology for Energy Systems

In addition, new concepts associated with a Device Performance are defined in order to express base statistics over specific measurements (over properties) of each specific device. A class of **dices:EnergyMeter** is defined (linked with the associated device or external data source via **dices:DeliveredEnergyMeteringData**) expressing consumption data. Additional classes based on the type of the meter are defined (dices:DistrictHeatMeter, dices:ElectricalEnergyMeter, etc**..**). Specific meter related static characteristics are defined as data properties (e.g. **dices:hasPrimaryEnergyFactor** etc…) while individuals about the different types of consumption data (**dices:EnergyConsumption**) as examined in the project are also defined (dices:ApplianceConsumption, dices: HeatingConsumption etc..).

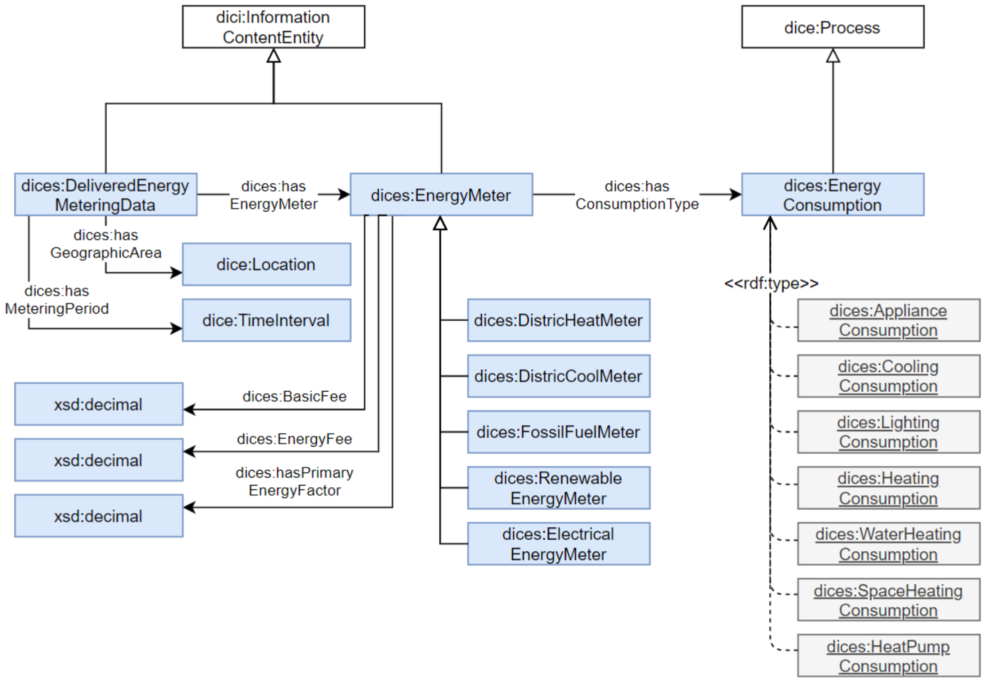

Figure 35: Domain Ontology for Energy Data

The modelling schema for Energy Ontology is available in the public repo:

https://w3id.org/digitalconstruction/0.5/Energy

4.4 Acoustics and IAQ model ontology

The role of this section is to set an extension of the base ontologies incorporating building acoustics and IAQ as part of the holistic modeling framework with focus on the role of the occupants at the building environment (and thus the concepts defined are part of the https://w3id.org/digitalconstruction/0.5/Occupancy). The methodological details were already presented in previous section along with the SoTA analysis. The short documentation of the domain specific ontological models is presented in the following sub sections.

Building Acoustics Ontology

As stated above in Section 3, the scope of the modeling work in BIM4EEB is to: (a) incorporate criteria and target values for the relevant acoustic indicators as expressed in the regulation, (b) to define acoustic model parameters/criteria in order to evaluate the potential modification of materials and structures in the building environment and to (c) incorporate in the model acoustics related measurements in the building environment along with the measurement sources (e.g. IoT devices) further associated with the relevant sound sources.

While acoustic indicators and parameters defined in the EN 12354 standards as presented above in SoTA analysis, additional concepts related to the structure of the building and the placement of acoustics sensor devices are incorporated in the model through proper alignments with building element related concepts.

The overview of the building acoustics model is presented in the following figure.

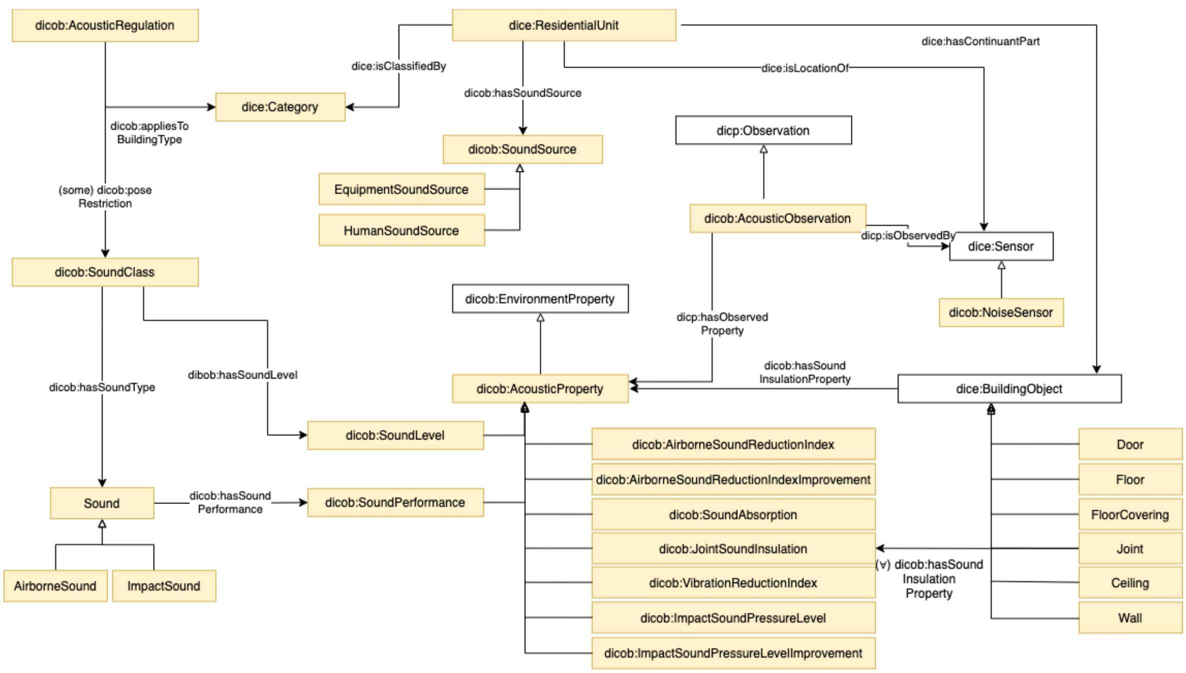

Figure 36: Domain Ontology for Building Acoustics

More details about the different concepts defined are presented in the following.

Classes in Building Acoustics Ontology

The classes about **dicob:acousticObservation, dicob:noiseSensor, dicob:acousticProperty** are defined to show the acoustics related parameters that are monitored in the building environment. This modeling work is associated with the installation of noise sensors to measure the db level (acoustic observation) over the noise property. Moreover, **dicob:soundSoure** related entities are defined as the entities that generate sound with specific instances: **dicob:HumanSoundSource, dicob:ServiceEquipmentSoundSource**

Additional classes related to sound performance (**dicob: soundPerformance**) in a building zone are defined, namely classes about **dicob: soundClass** (that is defined per building category and Regulation-**AcousticRegulation**) and the linked **dicob: SoundLevel** incorporating criteria and target values for the relevant acoustic indicators as expressed in the regulation. As sub classes of soundPerformance we specify acoustics indicators as defined in EN 12354, namely: **dicob:AirborneNoise, dicob: ImpactNoise**. Last but not least, some key building elements (as subclasses of the generic BuildingObject class) are defined and further linked to the acoustics quality parameters (as specified in EN 12354 standardization) in order to cover the acoustic model parameters/criteria required for the simulation analysis. A non-exhaustive list of acoustic parameters (defined as acoustic properties) is presented: Airborne Sound Reduction Index, Airborne Sound Reduction Index Improvement, Impact Sound Pressure Level Improvement, Impact Sound Pressure Level, Joint Sound Insulation, Vibration Reduction Index, Sound Absorption.

The modelling schema for Building Acoustics is available in the public repo:

https://w3id.org/digitalconstruction/0.5/Occupancy

Note: We have to point out that the building elements geometrical characteristics are not examined in this model as this information is related to building geometry and not acoustics related properties. In addition, additional acoustics parameters (absorptionLevel, reflectionLevel) that are associated with building material (and not building elements) are not be part of this model but can be easily added as data properties of the structure presented in material ontology.

Building Indoor Air Quality Ontology

As stated above in Section 3, there are similarities of IAQ modeling work with the modeling details of occupants' comfort ontology presented above. Concepts related to the structure of the building (**dice:ResidentialUnit**) and the associated sensing devices (**dicob: indoorAirSensor** as subclass of **dice:Sensor**) are incorporated in the model through proper alignments with concepts defined in base ontologies. As presented also in occupants comfort ontology, each sensing device is related to the observations (**dicob:IndoorAirObservation**) over specific properties (**dicob:AirQualityProperty** as sub-class of the generic dicv:QuantitativeProperty).

On the other hand, domain specific class related to IAQ performance are also part of the model. As stated above (defined in SoTA in Section 3), IAQ emissions is typically associated with activities performed in the building environment (e.g., cooking etc…) Therefore the **dicob:OccupancyActivity** class is defined in the model which is characterized by a IAQ source rate (**dicob:IndoorAirEmmissionRate**).

In addition, the IAQ performance level (as defined by the regulation - **dicob:AirQualityRegulation**). is incorporated in the modeling framework of BIM4EEB. More specifically the **dicob:AirQualityIndex** is defining the performance over a specific IAQ property while the boundaries for this IAQ level are defined (per regulatory framework) by the **dicob:RangeConstraint.**

Two IAQ domain specific classes are defined in the ontological model: the **dicob:AirQualityIssue,** as a detected problem/abnormal value over a specific IAQ Property State, which may be further associated with the **dicob: HealthProblem** (a health problem which is linked to the specific value) or an IAQ related notification **(dici: Notification)** as a message to inform recipients in a controlled manner about a situation they need to be aware of.

The overview of the building IAQ model is presented in the following figure.

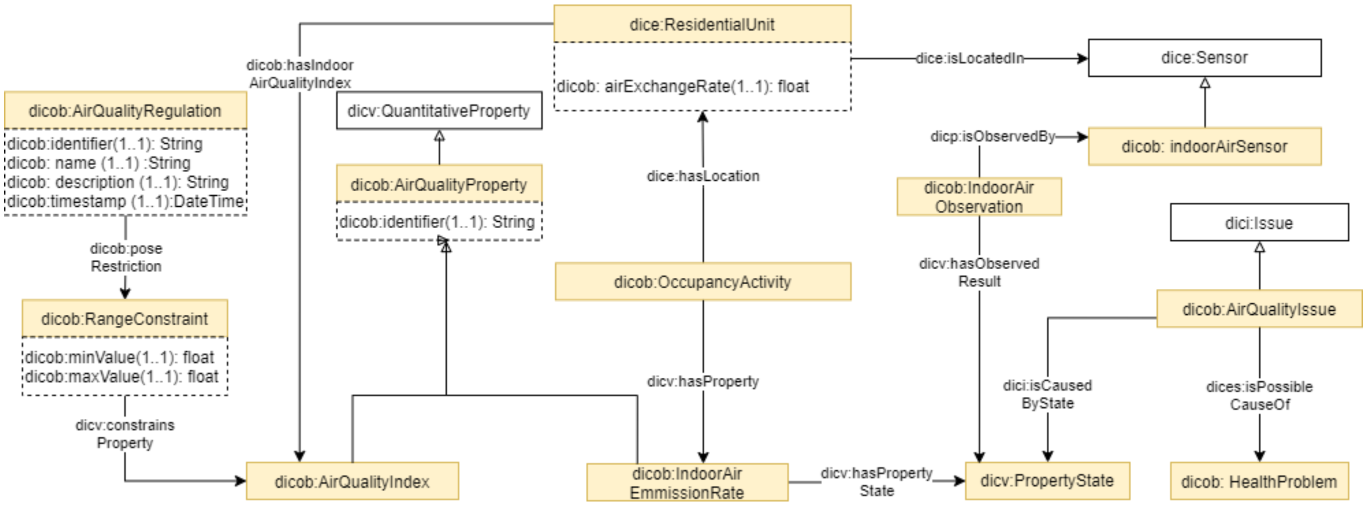

Figure 37: Domain Ontology for Building Indoor Air Quality

The modelling schema for Building IAQ is available in the public repo:

https://w3id.org/digitalconstruction/0.5/Occupancy

By presenting the different layers of the modeling work to be performed in this task, we proceed with some conclusions and key remarks (in the following section) to be considered at the harmonization of the different ontologies in the upcoming tasks.

Once again to point out that the work performed in this task is about the provision of a model for occupants, building materials and energy systems as a synthesis of concepts already defined in available models (DiCon ontologies are aligned with multiple existing ontologies - IFC, Saref, SSN/SOSA and so on) as well as the incorporation of new concepts that required in the context of BIM4EEB project, not defined in pre-existing models. The details of alignment of the BIM4EEB concepts with concepts already available in existing models is reported in D3.6.

4.5 BIM4EEB domain ontologies – Key Remarks

As stated in the DoA and also in WP3 definition, the main objective of this task is to extend already existing domain ontologies incorporating additional concepts in order to provide the extended functionality as envisioned in the project. The overall schema definition towards this integrated approach is in line with the high level/conceptual methodology as specified in D3.1 addressing the specific layers of analysis defined in the BIM4EEB project.

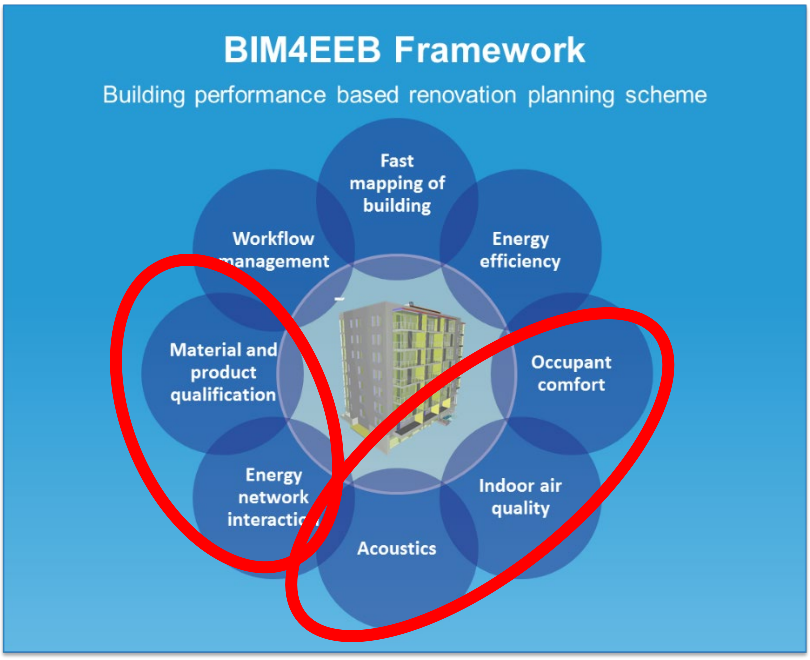

Figure 38: BIM4EEB Modeling Framework

In this task, the focus in specific pillars/domains as presented above and the associated models were defined to comply with the standard approaches and good practices for ontology modeling as redefined in the project (updated version of D3.1). More specifically:

- The detailed definition of ontological requirements was performed at the early phase, taking into account the review of project requirements and use cases.
- A State-of-the-Art analysis was performed focusing mainly on existing ontologies (with focus on standardized work). A structured approach was adopted towards presenting the results of State of the Art. From the state of the art, the elicitation of the most relevant work was performed to stand as the basis for the modeling work of the BIM4EEB project.
- Interrelated ontologies are defined as a suite of modular ontologies so that each ontology has clear purpose and domain. The different domains are defined as modules with independently reusable ontologies. If further updates apply during the project; these should be reflected in the ontological schemas to be considered in the project.
- More specifically, the overall design was performed taking into account the modeling as redefined in the project (updated version of D3.1); reusing as possible existing ontologies instead of re-defining concepts, and keeping the expressivity at its lowest necessary taking into account BIM4EEB project requirements (representation of competency questions using natural language).

As a next step of the work, the work performed in this task will complement the modeling work in other tasks of WP3 (T3.3 - T3.4) towards the definition of the holistic modeling framework that will facilitate the development of the BIM management system in WP4.

5 Summary

This deliverable describes the different ontologies developed to address the topics of occupants' behaviour and comfort, energy performance of systems and components, and acoustics as stated in the DoA. This work is considered as a main extension of the base ontology of the BIM4EEB project towards incorporating additional concepts that provide added value for the different services as examined in BIM4EEB project. At first a review of the most relevant modeling work was performed, along with the review of the BIM4EEB project requirements and specificities towards the extraction of the ontological requirements to be considered at the modeling work. A thorough analysis of the different layers to be examined is reported in the document. More specifically:

- Occupants' Behaviour and Comfort Modelling aims to provide a modelling concept to support the integrated analysis of qualitative feedback from apartment occupants and quantitative feedback based on sensor and meter readings. A model about **Occupants' Behaviour and Comfort** is defined to address BIM4EEB project requirements on the basis of already existing and refined work.
- The same approach holds for **building materials** and **energy** systems. It is envisaged to extend existing ontologies about building systems representation by incorporating "amalgamated parameters" (e.g. for multi-layer components) such as power, economic (e.g. Operation and Maintenance fixed costs, turnkey costs), environmental and thermodynamic (e.g. heat rate, waste heat factor, air injection rates) parameters considering an LCA-LCC approach. Therefore, the focus is at incorporating in existing ontological models, additional parameters focusing on the energy characteristics of the different building sources. The SAREF ontology stands as the base for the modeling work about energy systems, further expanded to incorporate the different viewpoints considered in the project. For the materials modeling, extensions and specifications at the ifcOWL/BOT base ontology were considered.
- The building level ontology should be further enriched with physical and mental health aspects, which will be correlated with indoor environment quality metrics, **Indoor Air Quality**, and **acoustic** requirements of buildings. For that reason, a thorough analysis of the relevant standards (IAQ and Acoustics comfort) was performed towards identifying the different concepts to be part of the model in BIM4EEB. In addition, a review of the standards EN 12354 series was performed to define also relevant to BIM4EEB concepts required for building level acoustics modeling.

We have to point out that the development of the ontological model is in line with the common approach and modeling principles as agreed among the partners in D3.1 and will be adopted in the rest of the work in WP3. In addition, the interconnection of the different modeling layers with the base ontology is a key task of the project and thus the detailed specifications for this process were reported in this document.

The homogenization of the different ontological pillars in the unified BIM4EEB model framework will be reported in D3.6 Integrated Linked Data Modelling and Sharing framework and the resulting model will be further inherited in the Common Data Environment as the base of the BIM management system to be reported in WP4.

Note: While the reporting version of the different ontologies is considered as final and mature version in order to address project needs, updates may apply as the project evolves (especially during the customization period in order to address demonstration specific requirements). Therefore, we may consider this modeling document as a living document to be updated during the whole project period.

6 References

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Annex I - IEA Annex 66 DNAs presentation

The IEA Annex 66 Task [3], *“a large research effort involving several partners has been undertaken towards developing and validating user behaviour models able to describe and predict user actions or user activities that affect the final energy use in a building, thus improving building design optimization, energy diagnosis, performance evaluation, and building energy simulation services. A detailed and extensive State of the Art analysis of most of the aspects of user behaviour modeling can be found on the references and publications sections of Annex 66 webpage”.*[6] .

A comprehensive review of the theory/methodology and the results of Annex 66 can be found in [3].According to this work, four key components of the human-building environment interaction are identified (Figure 39): Driver, Need, Action, System, i.e. the so-called DNAS framework.

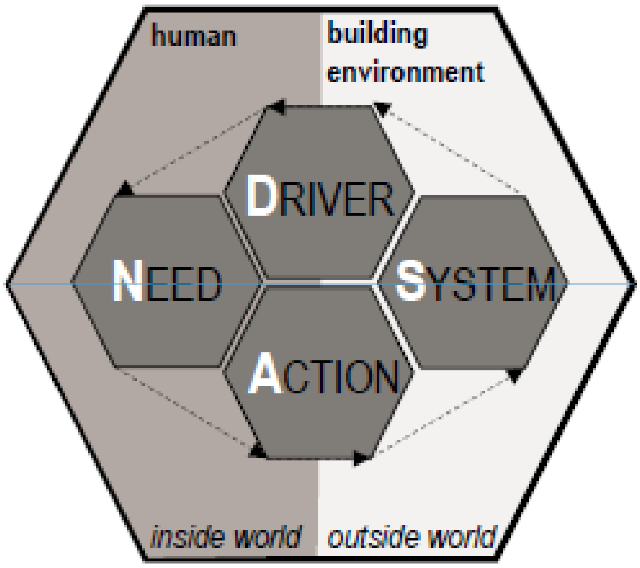

Figure 39: The four key components of the human-building environment interaction, according to Annex 66 results

“The key principles are briefly presented:

- *a set of drivers (or events or triggers) are the stimulating factors that provoke energy-related occupant behaviour. A comprehensive list of all the identified divers is shown in Figure 40. From all these, only the dynamic components, allowing the development of near real-time and adaptive user behaviour models are relevant to BIM4EEB, i.e.: calendar information; indoor/outdoor/weather conditions; and HVAC system state(s).*

[6] http://www.annex66.org/

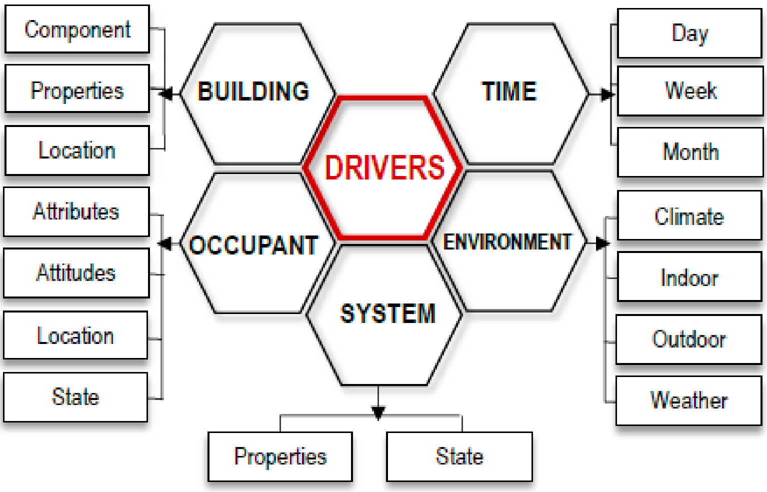

Figure 40: Drivers behind energy-related occupant behaviour, according to Annex 66 results

- *Needs are the requirements of the occupants that need to be met in order to ensure satisfaction with their environment. The main needs identified within Annex 66 are shown in Figure 41; from these the ones referring to Thermal comfort, Visual comfort, Acoustics and IAQ are relevant to BIM4EEB project.*

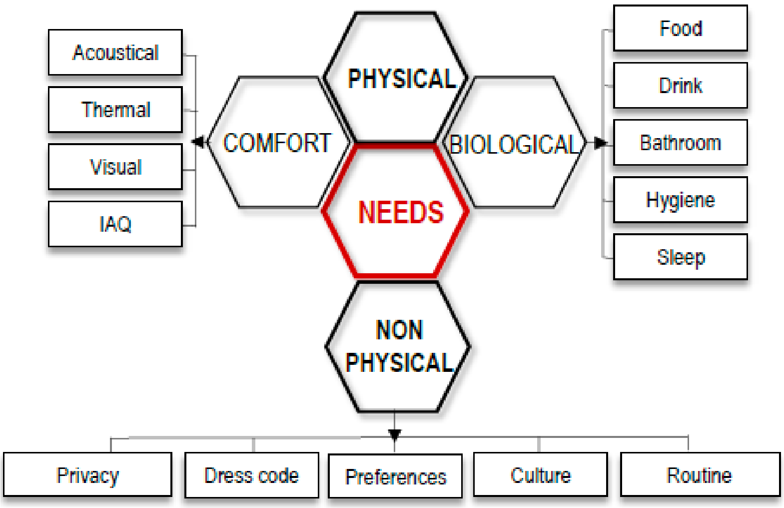

Figure 41: Needs of building occupants that may result in an action that affect the building energy use, according to Annex 66 results

- *Actions are interactions of occupants with their environment (controllable elements of the building, such as windows, blinds, thermostats, etc.) as well as activities (e.g., changing clothes, drinking water, etc.), in order for the occupants to satisfy their needs. Within BIM4EEB project – as also analysed later in the deliverable – all categories of actions identified by Annex 66 (Figure 42) are covered.*

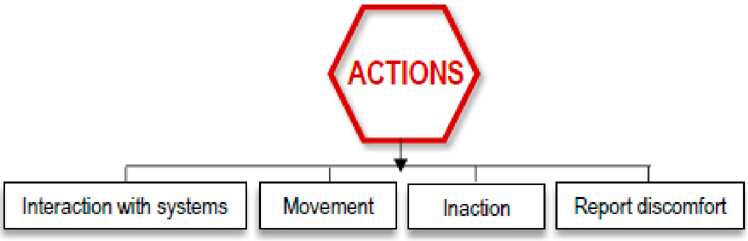

Figure 42: Actions undertaken by building occupants when their needs are not met, according to Annex 66 results

- *Finally, a set of controllable building elements / building systems have been identified and are shown in Figure 43. Within BIM4EEB, as will be analysed in the present deliverable, adaptive/dynamic user behaviour models will be developed only for the occupants' interactions with the lights and the HVAC, as well as models for the space occupancy, since the required sensors for the development of these models is (or will be installed) in the target buildings. This is required, since even though Annex 66 contributed several pre-trained user behaviour models, it has been evident that adaptive models, trained using real data from the target building will always outperform the static models in terms of accuracy "*

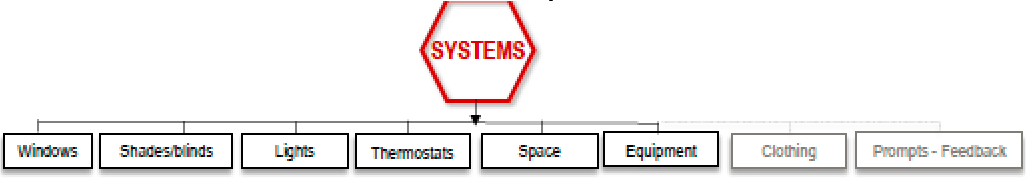

Figure 43: Building systems with which an occupant may interact causing a change in building energy use, according to Annex 66 results

The **DNAS framework** set the skeleton for the BIM4EEB Behavioural Profiling Models as defined in the document. The main principles of DNAS are also incorporated in the proposed model towards the delivery of the BIM4EEB user-oriented framework. Based on the above analysis, the scope of the remaining of the section is to proceed with review of specific approaches and models related to occupant's behaviour profiling. These approaches will further facilitate the definition of innovative BIM4EEB models to be considered in the project. The starting point of this analysis is the review of the latest **occupancy profiling** work while the following step is about typical **thermal and visual profiling models** as examined in the project.

Annex II - List of Energy Systems Modeling

As stated in the DoA, the initial scope of the work was to review the energy ontologies as found in EU Ready4Smartcities (incoherent, focus has mainly on electricity domain) in order to define concepts that are missing from existing models. The emphasis should be on modelling the behaviour of small generators, Combined Heat and Power (CHP), or large-scale storage systems frequently introduced in renovation projects at building level. The review highlighted the role of SAREF and extensions in the field of energy systems modeling. Nevertheless, additional modeling initiatives were evaluated as part of the review analysis and a non-exhaustive list of energy system models is presented in this section.

Energy Flexibility Interface (EFI) [35]

This a vertical abstraction of DER modeling to serve the deployment of DSM services. Over the years a lot of different Demand Side Management (DSM) approaches have been developed. Unfortunately, these DSM approaches are not interoperable. A similar issue can be identified on the appliance level. Appliances provide the flexibility that is being exploited by DSM. To begin with there are a lot of different appliances (washing machines, Combined Heat Power Systems, PV panels, fridges, etc.). They also use different protocols for communication (Zigbee, Z-wave, WiFi, PLC, etc.).
For that reason, **EF-Pi** aims to create an interoperable platform that is able to connect to a variety of appliances and support a host of DSM approaches. This way the EMS hardware does not need to be changed when a consumer switches from one service to another. At the same time the Energy Flexibility Platform & Interface makes it easier for service providers to introduce new services, since they do not have to provide the EMS hardware to their consumers to go with it. The high-level design of the EF-Pi is presented in the following figure.

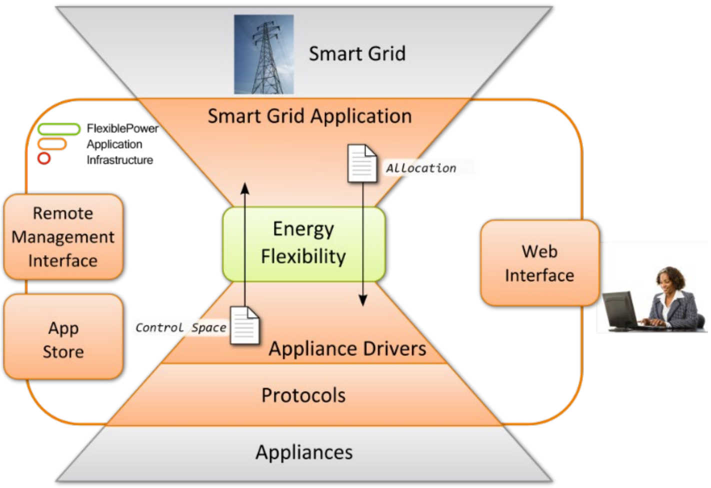

Figure 44: EF-Pi High-level design

The Energy Flexibility Platform & Interface is the connecting part between appliances at the home of the consumers at one side, and the (smart) energy grid on the other side. Appliances of different vendors can implement functionality which can be used to choose when and maybe how to start and use certain energy consuming or energy providing appliances.
The figure below provides an overview of all the communication classes in the Resource Abstraction Interface as the core layer of the EF-Pi model. All Energy Flexibility Interface messages have been derived from one of these communication classes.

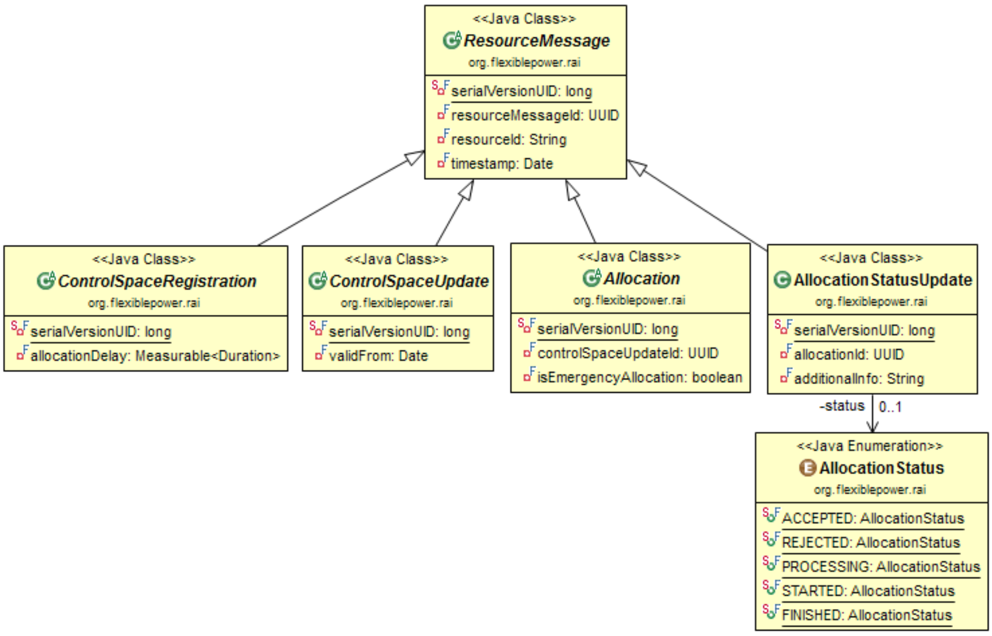

Figure 45: Energy Flexibility Platform & Interface Data Model

For more details about the EF-Pi model and the associated services defined, reference to the link: http://fpai-ci.sensorlab.tno.nl/builds/fpai-documentation/development/html/EF-Pi/EF-Pi.html

Other energy system related ontologies

There is a series of ontologies defined in research projects, specifying the details of the energy related assets in a building environment. A brief overview of the most relevant is provided.

E-care@home Ontology

Consisting of the modeling of the IoT infrastructure, which provides information with an unambiguous, shared meaning across IoT devices, end-users, relatives, health and care professionals and organizations. The focus is on integrating measurements gathered from heterogeneous sources by using ontologies in order to enable semantic interpretation of events and context awareness. A snapshot of the ontology is presented in the following figure:

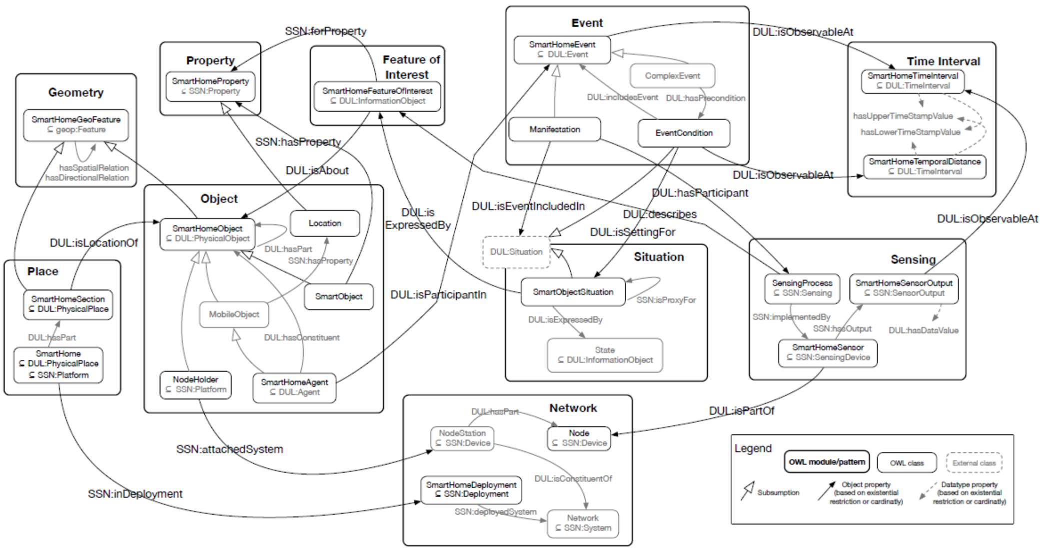

Figure 46: E-care@home Ontology

While the application domain may be different, the core principles may be adopted for the definition of the device level ontology in BIM4EEB project.

ThinkHome Ontology

With the main goal to minimize energy consumption while at the same time guaranteeing user comfort, the ontological framework is defined as knowledge base representation to fulfil all the demands of sustainable next-generation buildings. The main innovation and key aspect to be considered in the project is in the way to interlink energy systems with context related building elements. The ontology is available online through the link:
https://www.auto.tuwien.ac.at/downloads/thinkhome/ontology/
We have to point out that this ontology has been defined as a basis for extensions in the energy domain; a specific instantiation of the adapted model is presented in the following figure

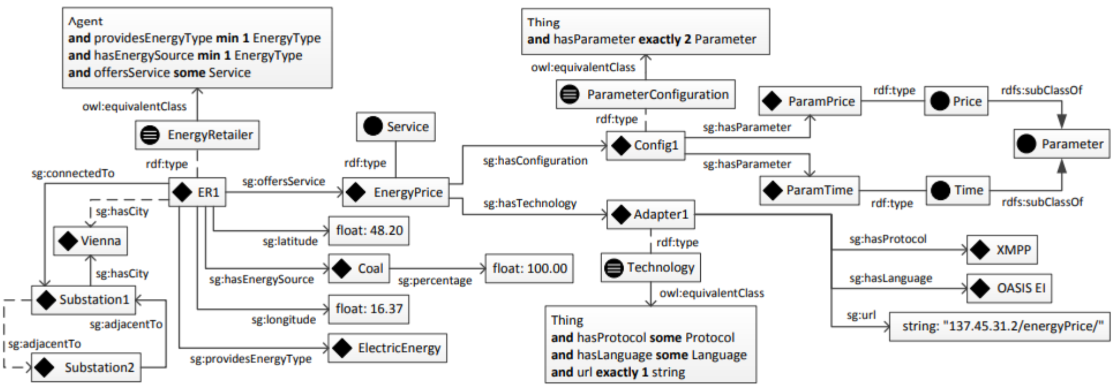

Figure 47: ThinkHome Ontology for Energy Applications

Along with the definition of the aforementioned ontologies, it is a main objective of this task to give "emphasis on modelling the behaviour of small generators, Combined Heat and Power (CHP), or large-scale storage systems frequently introduced in renovation projects at building level". For that reason, we have specified specific standards focusing on the information modeling of the associated energy entities

- IEC 61850-7-420 for model representation of DERs (focus on PVs, small generators, Batteries other DERs etc…) with the most focused Sunspec Alliance model instantiation for batteries/ PVs to be considered for the project.
- IEC 61400-25-2 for model representation of small wind turbines

Some details from each standard are provided in this section

IEC 61850-7-420: communications standard for distributed energy resources (DER)

defines IEC 61850 information models to be used in the exchange of information with distributed energy resources (DER), which comprise dispersed generation devices and dispersed storage devices, including reciprocating engines, fuel cells, microturbines, photovoltaics, combined heat and power, and energy storage. Utilizes existing IEC 61850-7-4 logical nodes where possible, but also defines DER-specific logical nodes where needed. An indicative schema, showing the different connections

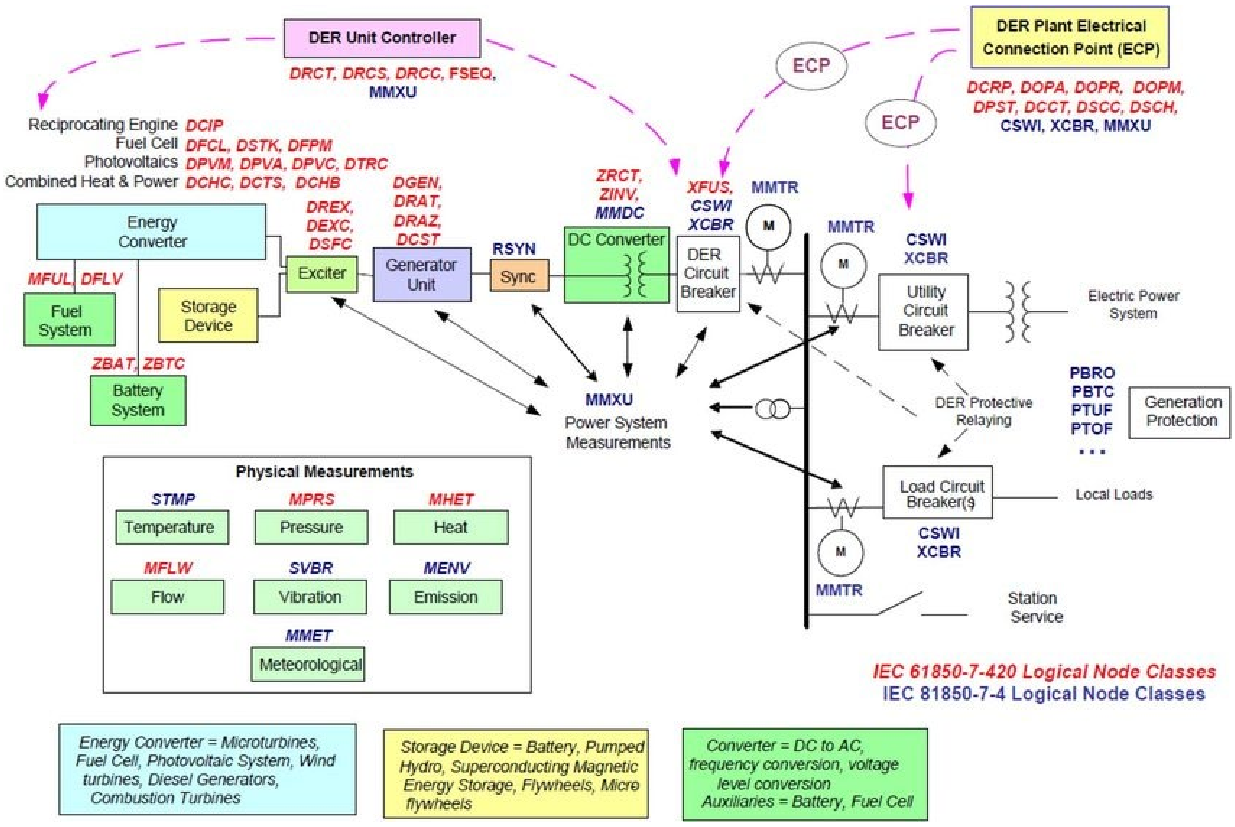

Figure 48: IEC 61850-7-420 based DER modeling

In the schema above it is clear that different types of data sources are handled in a common way, following the component-based approach for modeling the different entities that consist of the generation systems. The same approach applies for **SunSpec Alliance** which specifies interoperability specifications and information models that software developers, hardware manufacturers, and integrators use to achieve plug-and-play interoperability between Distributed Energy Resource (DER) components and smart grid applications. Link to the available information models through https://sunspec.org/download/

IEC 61400-25-2 for wind turbine modeling: to define communication for monitoring and control of wind power plants. The modeling approach of the IEC 61400-25 series has been selected to provide abstract definitions of classes and services such that the specifications are independent of specific protocol stacks, implementations, and operating systems. The indicative structure for the wind model representation through this standard is provided in the following figure

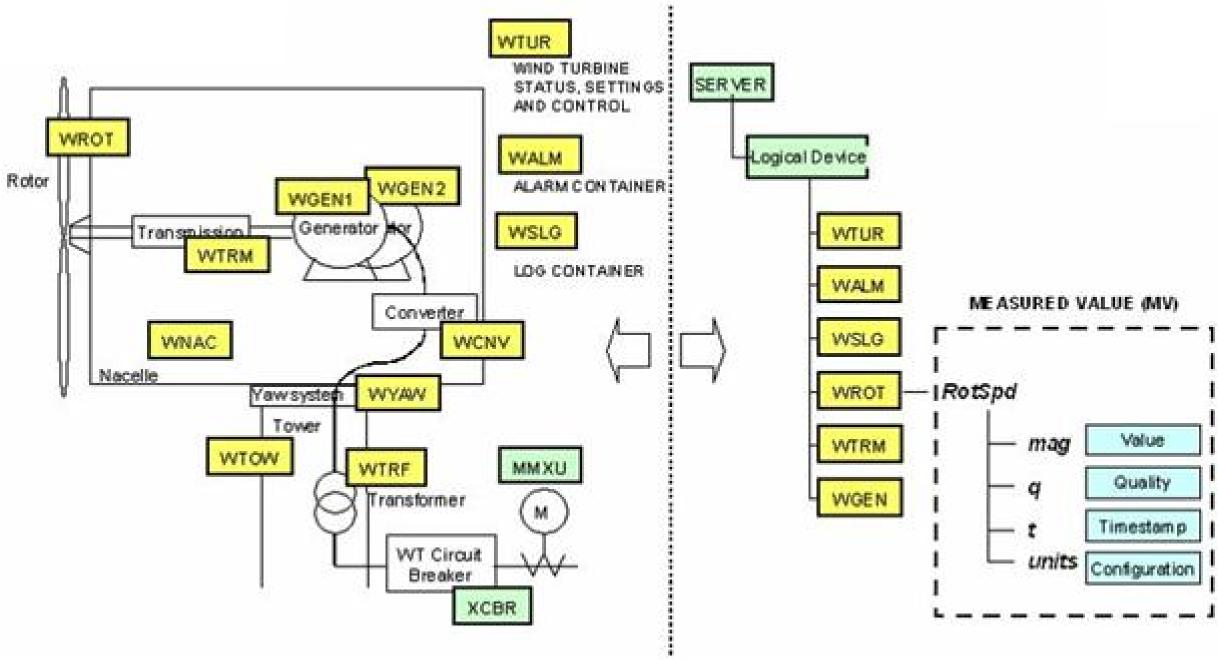

Figure 49: IEC 61400-25-2 based DER modeling

Annex III - List of IAQ parameters & models

In this section, an overview of the most typical IAQs parameters (properties) and the associated range values (range constraints) are presented. We have to point out that the constrain values are related to the standardization body defining the regulation.

The Environmental Protection Agency (EPA) list of VOCs is a comprehensive starting point to identify and reduce hazardous substances. This list of VOCs has been also been adopted from **ASHRAE** through the **2016 - 62.1 IAQ Standard.**

"Although threshold limit values for VOCs vary between countries and organizations, the EPA outlines several common VOCs and substances and their threshold limit values [44]:

- **PM2.5**: Particulate matter is one of the most dangerous forms of pollution as the size of the particles is so small that they can get into the lungs causing numerous adverse effects. PM2.5, in particular, are particles which are 2.5 μm or less in diameter. Their threshold limit value is 25 μg/m3, based on 24-hour data.
- **CO**: Being an odorless and colorless lethal gas, carbon monoxide (CO) is one of the most dangerous compounds in indoor environments. The American Conference of Governmental Industrial Hygienists (ACGIH) has given a threshold limit value of 25 ppm for an 8-hour workday, while the National Institute for Occupational Safety and Health (NIOSH) has estimated a recommended exposure limit of 35 ppm.
- **CO2**: CO2 is a natural compound in the air, with an average outdoor concentration of 300-400 ppm. Note that indoor levels are higher due to the confinement of indoor spaces. Human health effects can be observed at levels over 7,000 ppm. Therefore, the occupational limits set by ACGIH are 5,000 ppm TLV-TWA* and 30,000 ppm TLV-STEL.
- **Radon**: Radon is a radioactive gas formed by the decay of (natural) Uranium in the soil. As radon is carcinogenic, there are no safe levels of exposure. Yet, the EPA has set an action level of 4 pCi/L.
- **Formaldehyde**: One of the most common VOCs – formaldehyde – can be emitted from numerous sources, such as furniture, incense burning, and cooking. Note that its threshold limit value is 0.1 ppm TLV-TWA* and 0.3 ppm TLV-STEL.
- **Methylene chloride**: Methylene chloride or dichloromethane can be found in products like solvents. It has an odor threshold of 250 ppm. Note that a long-term exposure can lead to problems with the central nervous system.
- **NO2**: Due to the adverse effects associated with nitrogen dioxide (NO2), the EPA strengthened its health guidelines and set a 1-hour standard at the level of 100 ppb." [44]

A visual representation of IAQ boundaries is further presented in the following table.

indoor contaminants	allowable air concentration levels
carbon monoxide (CO)	< 9 ppm
carbon dioxide (CO2)	< 800 ppm
airborne mold and mildew	simultaneous indoor/outdoor readings
formaldehyde	< 20 μg/m ^{3} above outside air
total VOC	< 200 μg/m ^{3} above outside air
4 phenyl cyclohexene	< 3 μg/m ^{3}
total particulates	< 20 μg/m ^{3}
regulated pollutants	< national ambient-air quality standards
other pollutants	< 5% of TLV-TWA

Figure 50: IAQ upper levels - U.S. Environmental Protection Agency

A thorough research of several regulations was performed within the scope of Built2spec project and the summary results of the mail IAQ parameters and the associated levels are presented

Pollutant \ Country	N° CAS	France	Germany	NL*	UK**	Italy	Hungary	Mexico	Estonia	Belgium	Argentina	Austria	Denmark	Spain	Ireland	USA	Australia	New Zeland	Switzerland	Canada
Formaldehyde	50-00-0	0.6	0.37	0.15	2.5	-	0.6	-	0.6	-	-	0.6	0.4	0.37	2.5	1	1.2	0.6	0.37	0.36
Benzene	71-43-2	3.25	1.9	3.25	3.25	3.25	3	3.2	1.5	3.25	1.6	3.2	1.6	3.25	3	25	3.2	3.2	1.6	1.6
Naphtalene	91-20-3	50	0.5	50	-	-	-	50	50	53	52	50	50	53	50	50	52	52	50	52
Trichloroethylene	79-01-6	405	60	-	550	-	270	535	50	273	268	33	55	273	54	536	54	269	260	54
Tetrachloroethylene	127-18-4	138	138	-	345	-	50	670	70	172	170	345	70	172	170	680	340	335	345	170
Acetaldehyde	75-07-0	180	91	37	37	-	25	-	45	46	-	90	45	-	45	360	36	36	90	-
Toluene	108-88-3	76.8	190	150	191	192	190	188	192	192	188	190	94	192	192	753	191	188	190	75
Xylene	95-47-6 108-38-3 106-42-3	221	-	210	220	221	221	435	221	221	434	221	109	221	221	-	-	217	-	434
Styrene	100-42-5	100	86	-	430	-	50	215	90	216	85	85	105	86	85	425	213	213	85	-
1,2,4-trimethylbenzene	95-63-6	100	100	100	125	100	-	-	100	-	-	100	100	100	100	-	-	-	-	-
1,4-dichlorobenzene	106-46-7	4.5	6	150	153	122	122	450	122	61	60	122	60	122	122	450	150	153	122	60
Ethylbenzene	100-41-4	88.4	88	215	441	442	442	435	442	442	434	440	217	441	442	435	434	434	220	87
2-butoxyethanol	111-76-2	49	49	100	123	98	98	120	98	98	97	98	98	98	98	240	97	121	49	97
Acrolein	107-02-8	-	0.2	-	0.23	-	0.23	0.25	0.2	0.23	-	0.25	0.12	0.23	0.25	0.25	0.23	0.23	0.25	-
α-pinene	80-56-8	-	-	-	-	-	-	-	150	111	-	-	-	-	-	-	-	-	-	111
Limonene	5989-27-5 5989-54-8 138-86-3	-	-	-	-	-	-	-	-	-	-	-	390	-	-	-	-	-	40	-
Hexanal	66-25-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
delta-3-carene	13466-78-9	-	-	-	-	-	-	-	150	111	-	-	-	-	-	-	-	-	-	111
TVOC		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NO_2	10102-44-0	-	-	0.4	-	-	9	6	4	5.7	5.6	6	4	5.7	5	30	5.6	5.6	6	-
CO	630-08-0	55	-	29	35	-	33	55	40	29	29	33	29	29	23	9	34	27	35	29
PM 2.5	-	0.01	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PM10	-	0.02	-	-	-	-	-	-	-	-	-	-	-	-	-	0.05	-	-	-	-

* Netherlands

**United Kingdom

Figure 51 Concentration values threshold for professional long-time exposure (mg/m3)

Pollutant \ Country	N° CAS	France	NL*	UK**	Italy	Hungary	Mexico	Estonia	Belgium	Argentina	Austria	Spain	Ireland	USA	Australia	New Zeland	Switzerland	Canada
Formaldehyde	50-00-0	1.2	0.5	2.5	-	0.6	3	1.2	0.38	0.4	0.6	-	2.5	2.5	2.5	1.2	0.74	1.2
Benzene	71-43-2	-	-	-	-	-	16	9	-	8	12.8	-	-	-	-	8	-	8
Naphtalene	91-20-3	-	80	-	-	-	75	-	80	79	-	80	75	-	79	79	-	79
Trichloroethylene	79-01-6	108	-	820	-	540	1080	140	545	536	132	-	134	1072	216	1070	520	134
Tetrachloroethylene	127-18-4	275	-	689	-	50	1340	170	695	679	1380	689	678	1360	1020	1005	690	679
Acetaldehyde	75-07-0	-	92	92	-	25	45	90	-	45	90	46	45	-	91	90	90	45
Toluene	108-88-3	384	384	384	-	380	-	384	384	-	380	384	384	1129	574	-	760	-
Xylene	95-47-6 108-38-3 106-42-3	442	442	441	442	442	635	442	442	650	442	442	442	-	-	-	-	650
Styrene	100-42-5	-	-	1080		50	425	200	432	170	340	172	170	851	426	426	170	-
1,2,4-trimethylbenzene	95-63-6	250	200	-	-	100	-	-	-	-	150	-	-	-	-	-	-	-
1,4-dichlorobenzene	106-46-7	306	300	306	300	306	675	306	306	-	306	306	306		300	306	-	-
Ethylbenzene	100-41-4	442	430	552	884	884	545	884	551	542	880	884	884	-	543	543	220	-
2-butoxyethanol	111-76-2	246	246	246	246	246	360	246	246	-	200	245	246	-	242	-	98	-
Acrolein	107-02-8	0.25	-	0.7	-	0.23	0.8	0.7	0.7	0.2	0.25	0.69	0.8	-	0.69	-	0.25	0.23
α-pinene	80-56-8	-	-	-	-	-	-	300	-	-	-	-	-	-	-	-	-	-
Limonene	5989-27-5 5989-54-8 138-86-3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	80	-
Hexanal	66-25-1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
delta-3-carene	13466-78-9	-	-	-	-	-	-	300	-	-	-	-	-	-	-	-	-	-
TVOC		-		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
NO_2	10102-44-0	6	1	-	-	9	10	10	9.5	9.4	12	9.6	9	-	9.4	9.4	6	1.9
CO	630-08-0	100	-	232	-	66	400	120	-	-	66	-	115	35	-	230	70	115
PM 2.5	-	0.025	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PM10	-	0.05	-	-	-	-	-	-	-	-	-	-	-	0.15	-	-	-	-

* Netherlands
** United Kingdom

Figure 52: Concentration values threshold for professional short-time exposure (mg/m3)

Along with the definition of metrics to set the IAQ framework, IAQ indicators have been defined in the literature (Also as part of the Annex 68 work). The most representative KPI formulas are presented in the assessment report of Annex 68 highlighting the main categories for IAQ indices.

- *Category I: One index per single pollutant*
- *Category II: Simple aggregation*
- *Category III: Aggregation according to the sources of pollutants and/or types of pollutants*
- *Category IV: Aggregation accounting for the IAQ in the building stock*
- *Category V: Aggregation of indices for deriving a multipollutant index*

Annex IV – Details of Building components and Material Ontology

As stated also in building component and material ontologies, same basic model principles are considerd to set the basis for the ontological modeling. These principles are preseted in this section.

Material Data in IFC schema/ifcowl: The IFC specifications are primarly considered for the ontology developement. This section discusses how the material definitions are considered in ifc-based openBIM, i.e. how material properties are defined, and what material data need to be modeled for building elements. In the ifc-based, openBIM meta-data model entities are related to their resources using the concept of objectified relationships. Material specifications of building elements are defined as a resource in the IFC-schema. They are related to the respective building elements through the objectified relationship called 'IfcRelAssociatesMaterial'. The detailed representation of this mechanism is denoted in Figure 53 below.

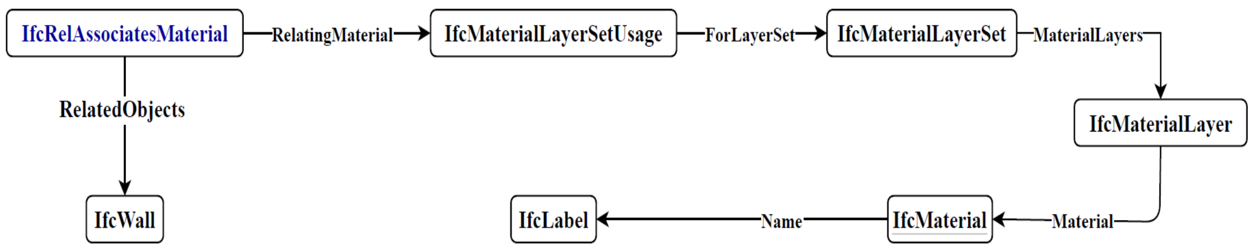

Figure 53: Material assignment to the wall element through layers in IFC

In comparison, Figure 54 represents the concept in an ontological format named ifcOWL. ifcOWL uses a methodology and tools to translate IFC-Express into an RDF format initially developed by[9]. In this case, modelling of material and assignment to building elements uses a similar method, but modeling languages are different. Limitations in terms of extendibility, reasoning, vocabulary, and inference are disticnt.

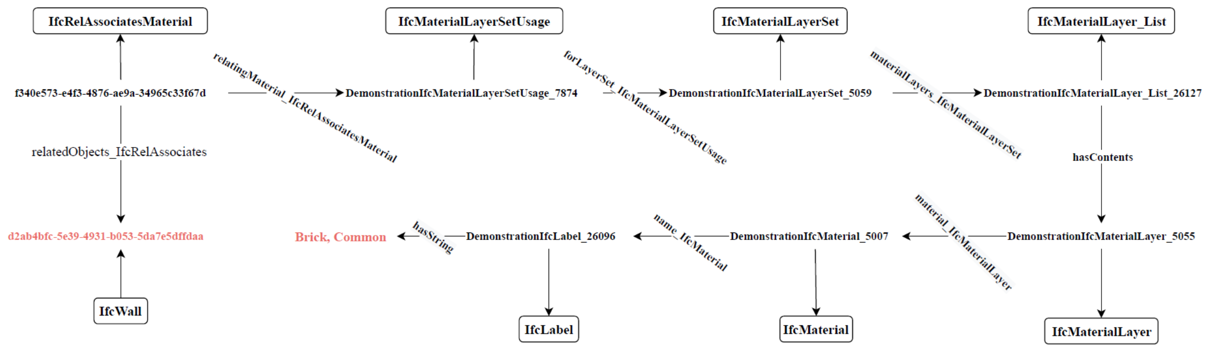

Figure 54: Assignment of material to the wall object using layer system in ifcOWL

The order and position of layers in building elements in relation to other elements are inefficiently modelled. Figure 55 represents the layer sequence in the ifcOWL ontology using the object properties express:hasNext, express:hasContents [10]. The IfcMaterialLayer_List specifies a sequence of Object Properties (OP) using express:hasNext feature to link an IfcMaterialLayer to specific material using express:hasContents. The ifcOWL ontology represents the sequence but it did not explain the relation with its element and other adjacent elements. The DICM ontology proposed in this deliverable will address these constraints by introducing new concepts and roles.

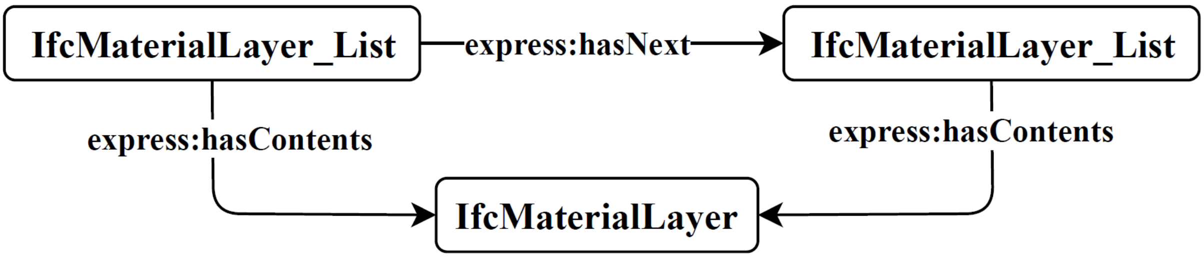

Figure 55: Material Layer sequence in the ifcowl ontology

Apart from the IFC/ifcOWL, BOT ontology also considered in the development ontology. Since BOT defines the terms related to the building elements and their inter connection, few concepts are considered in the materials ontology.

On the other, and following the Building components and Material Ontology classes presentation in Section 4.2, we briefly list the object and data properties of the model. The detailed description of these properties is provided in the online documentation in https://w3id.org/digitalconstruction/0.5/Materials.

Following the DNAs principles, OccupantBehaviour is associated with the following classes defined:

- In addition to the actuation over a specific device, the **userPreference** class is The **occupantComfort** class is defined to represent the model parameters of the data driven comfort profiling framework defined in the project. Different types of comfort profiles are defined in the project, specified by the subclasses **(thermal, visual, acoustics)**., preferred value **(environmentalPreferences)** over a specific **environmentalProperty** (which is a subclass of the generic observableProperty; indicative values for these properties are temperature, luminance, noise etc..)

a. Object Properties

This section explains brief details about the object properties in DICM ontology. The following table shows the list of object properties in DICM.

Object Property	Domain	Range	InverseProperty
Dicm:hasAdjacentElementLayer			
Dicm: hasAdjacentLayer	Dicm:Layer	Dicm:Layer	
Dicm:adjacentElement		Dice:BuildingObject	
Dicm:hasMaterial		Dicm:Material	
Dicm:hasMaterialBatch	Dice:Process	Dicm:MaterialBatch	Dicm:isMaterialBatchIn
Dicm:hasLayerSet		Dicm:LayerSet	
Dicm:hasLayer		Dicm:Layer	
Dicm:hasOuterLayer		Dicm:Layer	Dicm:isOuterLayerOf
Dicm:hasInnerLayer		Dicm:Layer	Dicm:isInnerLayerOf
Dicm:isMaterialBatchIn	Dicm:MaterialBatch	Dice:Process	Dicm:hasMaterialBatch

Dicm:isOuterLayerOf	Dicm:Layer		Dicm:hasOuterLayer
Dicm:isInnerLayerOf	Dicm:Layer		Dicm:hasInnerLayer
Dicm:hasProfileSet		Dicm:ProfileSet	
Dicm:hasProfile		Dicm:Profile	
Dicm:hasConstituentSet		Dicm:ConstituentSet	
Dicm:hasConstituent		Dicm:Constituent	

Table 13: Object properties used in the DICM ontology

b. Data Properties

The dicm:hasValue is the main data property defined in the DICM ontology. dicm:hasValue is used to define the property values for the different material properties. dicm:hasValue has domain opm:Property and range will be xsd:double. Value may be defined, measured and estimated. To address this specific types, three sub properties created for dicm:hasValue. They are dicm:hasDefinedValue, dicm:hasMeasuredValue, dicm:hasEstimatedValue. dicm:hasReference describes the source of a value and unit for the property. For example, different standards defines different values for the materials, in such case dicm:hasReference address the standard name. Also, material data properties are defined in the DICM ontology and they are objectified.The following table list the data properties used in the DICM ontology.

Data Property	SubDataProperty
hasAcidityConcentration	
hasAlkalinityConcentration	
hasBoilingPoint	
hasCarbonContent	
hasCO2Content	
hasCOContent	
hasCombustionTemperature	
hasDynamicViscosity	
hasFreezingPoint	
hasGasPressure	
hasHardness	
hasHigherHeatingValue	
hasIsothermalMoistureCapacity	
hasLowerHeatingValue	
hasLowerVaporResistanceFactor	
hasMassDensity	
hasMoistureCapacityThermalGradient	
hasMoistureDiffusivity	
hasMolecularWeight	
hasN20Content	
hasPHLevel	

hasPoissonRatio	
hasPorosity	
hasShearModulus	
hasSolarReflectanceBack	
hasSolarReflectanceFront	
hasSolarRefractionIndex	
hasSolarTransmittance	
hasSpecificHeatCapacity	
hasSpecificHeatTemperatureDerivative	
hasThermalCapacity	
hasThermalConductivity	
hasThermalConductivityTemperatureDerivative	
hasThermalExpansionCoefficient	
hasThermalIrEmissivityBack	
hasThermalIrEmissivityFront	
hasThermalIrTransmittance	
hasThermalResistivity	
hasUpperVaporResistanceFactor	
hasVaporPermeability	
hasViscosityTemperatureDerivative	
hasVisibleReflectanceBack	
hasVisibleReflectanceFront	
hasVisibleRefractionIndex	
hasVisibleTransmittance	
hasYoungModulus	
hasReference	
NumberOfLayers	
hasValue	hasDefinedValue
	hasEstimatedValue
	hasMeasuredValue

Table 14: Data properties used in the DICM ontology