Integration of building material databases for IFC-based building performance analysis

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Abstract -

IFC-based building energy performance and life cycle analysis require structured data about thermal, ecological, and financial building material properties (e.g., thermal conductivity, global warming potential, construction cost). Dedicated databases to these domains exist, but share no common property sets, making the mapping process of all required properties to the materials in the IFC (Industry Foundation Classes) model, and subsequently to input data of energy performance engines or LCA/LCC software, labor intensive and error-prone. This study introduces (i) IFC property sets (psets) designed to fulfill the material input data requirements for EnergyPlus and the BIMERR LCA/LCC analysis module, (ii) third-party sources for providing the necessary input data, (iii) a building material classification system and ontology to integrate the identified data sources, (iv) a building material mapping approach to map similar building materials across different data sources, and (v) our validation results with three different building material databases and one real-world building.

Keywords -

Building Energy Performance and Renovation; IFC; Property sets; Ontology; Building material databases

1 Introduction

Identifying, evaluating and selecting building renovation measures require a quantitative assessment of their impact in terms of cost, energy savings, comfort improvement, etc. Within the H2020 EU-funded project BIMERR[1], RenoDSS has been developed. RenoDSS is a decision support system which automatically generates potential renovation scenarios based on the as-is Building Information Model (BIM) in IFC4 format of an existing building and rule sets on how to combine the various renovation measures. For each renovation scenario, RenoDSS calculates economic, energy, sustainability, and comfort Key Performance Indicators (KPIs) which are used to compare candidate renovation scenarios and enable the user to select the one that meets their preferences.

The KPI calculation relies on the availability of data for building materials which are used or replaced during the renovation. These data include among others thermal parameters (e.g., thermal conductivity and specific heat), cost parameters (e.g., purchase costs for the various materials, installation costs or depreciation), and LCA-related parameters (e.g., embodied energy, lifetime expectations or recyclability of the materials).

Although such data can be extracted from existing libraries and databases, often, the required information is not provided by a single source (e.g., the IFC file or a third-party material database). Hence, it is necessary to obtain it from distributed sources (building material databases, vendor information, IFC file, user information, etc.) and map it to the building materials within the BIM-model. The main challenge at integrating different data sources is to correctly map their property sets and to convert property units (e.g., from kg to m^3) if necessary. To this direction, we rely on semantic technologies, more precisely ontologies, which are formal and explicit conceptualisations of shared knowledge [1] and allow for heterogeneous data integration providing explicit semantic information by means of well-known standard languages. In this work, we present our contributions to support this information gathering and mapping process:

- development of IFC property sets (Psets) which fulfill the material data requirements of EnergyPlus [2] and the BIMERR LCA/LCC module for calculating the building performance KPIs - see Appendix A,
- identification of third-party data sources which provide the input data required for economic, energy, sustainability, and comfort KPIs calculation - see Section 3,
- development of a building material classification system and ontology which integrate the identified data

[1]https://www.bimerr.eu

sources (including harmonization of measurement units) - see Section 4,

- development of a building material mapping approach which can be used to collaboratively and semi-automatically map similar building materials across different data sources - see Section 5, and

- validation with three different building material databases (baubook, ökobaudat, ASHRAE) at one real-world building - see Section 6.

The developed approach enables the user to efficiently map building material data across various data sources, re-use mappings which have been created by other users, enrich the IFC-model with the selected building material data, and finally use it for automated performance analysis with EnergyPlus and the BIMERR LCA/LCC module.

2 Related work

This section reviews related work and existing models in the building material domain. In a recent study [3], a BIM-LCA framework that integrates LCA data from the ÖKOBAUDAT database using IFC has been proposed. The authors developed a Model View Definition (MVD), which defines the software subset of an IFC data model to meet the exchange requirements (ER) for a whole building LCA. The research results enable the identification of information exchange requirements to perform life cycle analysis within a BIM-based environment.

The Digital Construction Building Materials ontology [4] is a semantic building material model and aims at describing building elements, construction details, materials and their respective properties. The models follows the IFC material set definition pattern which states that a building element can be decomposed using three types of material definitions: a layer set, a constituent set, and a profile set. Each of these material definitions has one or many materials, each one linked with material properties that describe them. However, no classification of materials is provided.

Another example is the Green Building Material Type and Green Building Material Name ontologies [5]. The main purpose of these ontologies in to manage green building materials information. The Green Building Material Type Ontology (GBMTO) consists of elements that define the material properties, whereas the Green Building Material Name Ontology (GBMNO) describes the material classification system. Although the model allows the classification of materials and the description of some properties, it is not intended to represent building elements in detail.

The Materials Design Ontology [6] forms an effort to represent material science knowledge, mostly from the solid state physics domain.

Finally, the European Materials & Modelling Ontology (EMMO) [7] is a top level ontology which aims at the development of a standard representational ontology framework based on current materials modelling and characterization knowledge. It has been developed from the very bottom level, using the actual picture of the physical world coming from applied sciences, and in particular from physics and material sciences. Although, EMMO and its extensions cover several sub domains, none of them tackle the building materials, energy or LCC/LCA performance simulation domains.

3 Building material databases

In this section, databases that provide the required thermal, ecological, and financial building material data are introduced. The required data is defined by the input data requirements of the energy performance (EnergyPlus) and the BIMERR LCA/LCC calculation module which are used to calculate the economic, energy, sustainability, and comfort KPIs of each renovation scenario. Please see Appendix A for the Psets which are required for each building material.

3.1 Thermal data

In Baubook [8] the building materials are declared according to thermal and ecological parameters and other product group-dependent properties. The information is supplemented with a product description, pictures, safety data sheets and technical data sheets as well as manufacturer and, if applicable, dealer data. The data is entered by the manufacturer and quality-assured by Baubook. The Baubook XML file provides building physics and ecology reference values for (i) generic building materials, (ii) concrete products, and (iii) combined building structures (walls, roofs, etc.). Table 1 shows the data properties provided by Baubook for 1.198 building materials. We use Baubook data to initialize the developed Building Material & Component database with thermal and ecological building material data.

EnergyPlus requrires the following entities and properties to simulate the materials' thermal behaviour: material (roughness, thickness, conductivity, density, specific heat), material no mass (roughness, thermal resistance), air gap (thermal resistance), and glazing (thickness, solar transmittance, front side solar reflectance, back side solar reflectance, visible transmittance, front side visible reflectance, back side visible reflectance, infrared transmittance, front side infrared hemispherical emissivity, back side infrared hemispherical emissivity, and conductivity).

Property name
Title
Description
Category
Group
Manufacturer
Component structure for composite products
Lambda
Heat transfer coefficient (Ud)
Diffusion resistance (My)
Specific heat capacity
Resistance to water vapour diffusion (sd)
Bulk density
Thickness
Area weight
PENRT Non-renewable primary energy, total
PENRM Non renewable primary energy, as raw material
PENRE Non renewable primary energy, as energy source
PERT Renewable primary energy, total
PERM Renewable primary energy, as raw material
PERE Renewable primary energy, as energy source
GWP100 Total global warming potential
GWP100 C content Global warming potential
GWP100 Process Global Warming Potential
AP Acidification potential of soil and water
ODP depletion potential of the stratospheric ozone layer
POCP Formation potential for tropospheric ozone
EP Eutrophication potential

Table 1. Baubook data properties

Such data can be extracted from the ASHRAE 2005 Handbook of Fundamentals; relevant materials and thermal properties data come with the installation of EnergyPlus. We enrich the Building Material & Component database with ASHRAE data to meet the EnergyPlus data input requirements.

Property name
Name
Category
Type
Reference size
Unit of reference
Bulk density (kg/m3)
Surface weight (kg/m2)
Bulk density (kg/m3)
Layer thickness (m)
Yield (m2)
Length weight (kg/m)
Conversion factor to 1kg
Module
Global warming potential (GWP) - total
Depletion potential of the stratospheric ozone layer (ODP)
Formation potential for tropospheric ozone (POCP)
Acidification potential (AP)
Eutrophication potential (EP)
Potential for abiotic depletion of non-fossil resources (ADPE)
Potential for abiotic depletion of fossil fuels (ADPF)
Renewable primary energy as energy source (PERE)
Renewable primary energy for material use (PERM)
Total renewable primary energy (PERT)
Non-renewable primary energy as energy source (PENRE)
Non-renewable primary energy for material use (PENRM)
Total non-renewable primary energy (PENRT)
Use of secondary materials (SM)
Renewable secondary fuels (RSF)
Non-renewable secondary fuels (NRSF)
Use of freshwater resources (FW)
Hazardous waste to landfill (HWD)
Non-hazardous waste disposed of (NHWD)
Radioactive waste disposed of (RWD)
Components for reuse (CRU)
Materials for recycling (MFR)
Materials for energy recovery (MER)
Exported electrical energy (EEE)
Exported thermal energy (EET)

Table 2. ÖKOBAUDAT data properties

3.2 Ecological data

The ÖKOBAUDAT [9] database provides life cycle assessment (LCA) data sets on building materials, construction, transport, energy and disposal processes. Currently more than 1.200 data sets are provided for the different building products - since 2013 conforming to DIN EN 15804, making ÖKOBAUDAT the first life cycle assessment database to completely follow this standard. The data of the ÖKOBAUDAT-database are based on the background databases 'GaBi' and 'ecoinvent'. Table 2 shows the data properties provided by ÖKOBAUDAT. All values are provided per life phase according to EN 15804 (e.g., A1-A3: production). We enrich the Building Material & Component database with ÖKOBAUDAT data to meet the LCA/LCC calculation data input requirements.

3.3 Financial data

The availability of open building material price databases is very limited. Those which are available provide price data only for a certain geographical region or a limited set of building materials. One example is the US National Residential Efficiency Measures Database [10] which provides data on residential building retrofit measures and associated costs. The database offers retrofit measures in the field of: (i) appliances, (ii) domestic hot water, (iii) enclosure, (iv) heating, ventilation, and air conditioning (HVAC), and (v) lighting. Each retrofit measure is described by properties such as lifetime, physical description, performance data, costs, etc. As costs vary across regions and building projects, a range of costs for the US market is provided. Cost data refers to the sole implementation of the retrofit measure.

As it was not possible to centrally obtain financial data required by the LCA/LCC module (material cost, installation cost, maintenance cost, disposal cost) for all possible renovation scenario configurations (location, project size, building type, etc.), we decided to let the user input project-specific cost for material and installation with regards to the used building materials and components. It is worth mentioning though that the LCA/LCC module provides default cost values based on cost data of similar projects which are stored in RenoDSS.

4 Building material classification and ontology

This section details the materials data model used to harmonize the different aforementioned data sources. The model is implemented as an ontology using the W3C OWL language [11] and has been developed following the LOT methodology [12]. The ontology is published according to the W3C best practices [13] under the URI "http://bimerr.iot.linkeddata.es/def/material-properties#", which will be compacted as "mat:" along this section. Figure 1 presents an overview of the classes (coloured boxes), relations (arrows) and attributes (dashed boxes) included in the materials ontology.

The main purpose of the materials data model is the description of building elements, their materials, and their corresponding properties. The ontology is focused on the building components that follow the material set definition stated in the IFC 4 standard. Examples of these elements include walls, slabs and roofs. The material set definition indicates that an element may have a construction of type `mat:MaterialLayerSet`, `mat:MaterialProfileSet`, or `mat:MaterialConstituentSet`. These construction types can be further decomposed into `mat:MaterialLayer`, `mat:MaterialProfile`, and `mat:MaterialConstituent` respectively, where each of these entities has a set of related materials (`mat:Material`).

The materials can be further described by a set of properties. For this purpose, the model reuses the artefacts provided by the SAREF ontology v3.1.1 [14] . As we can see in Figure 1, the `mat:Material` class is related to the concept `mat:PropertySet`, which group together similar properties or properties that have a common denominator such as "properties for a wall". The properties are related to specific measurements (`mat:Measurement`), connected at the same time to different units of measure (`mat:UnitOfMeasure`).

Additionally, a classification schema is constructed under the `mat:Material` concept to enable the user to efficiently find a given material and map different building material data sources. Figure 2 illustrates the building material classification schema which was derived from the used data sources Baubook, ÖKBAUDAT, and ASHRAE. In its current version, materials of the third-party data sources Baubook, Ökobaudat and ASHRAE have been linked to the material categories. The developed mapping methodology is described within Section 5.

4.1 Data model instantiation example

Figure 3 showcases how we can use this ontology to describe the materials of a wall. The element described in this example is the wall `data:Wall01` with IFC identifier "WallIFCGuid" that has a construction represented by the concept `data:MaterialLayerSet01`. This wall is composed by several layers, one of them is the layer `data:MaterialLayer01` that has a thickness of 10 centimeters and is in the second position within the structure of the wall, where the ordering starts from the layer that interfaces with the internal spaces of the building.

This layer is made of brick masonry (`data:BrickMasonry01`) as the main material, which

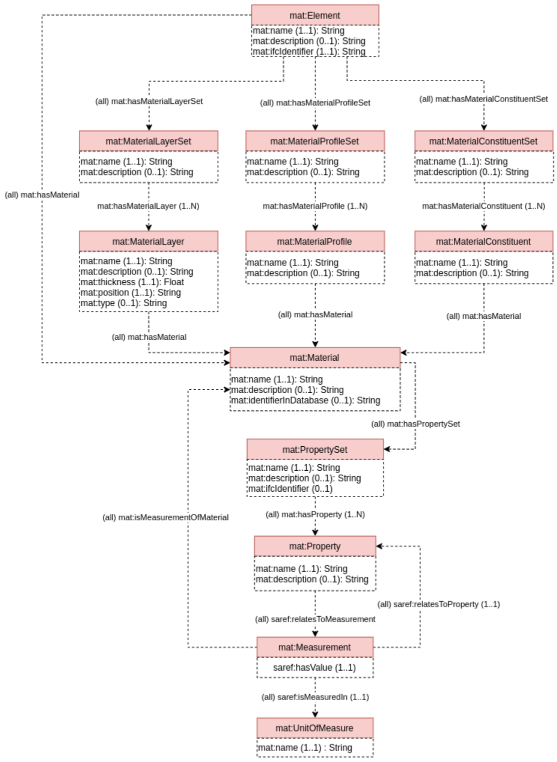

Figure 1. Building materials ontology

has a set of properties that are organized in property sets (`data:PropertySet01`). One of the properties considered in this set is the Density (`mat:Density`), which for this specific material has a value equal to 1922 Kg-per-m3.

5 Category/product matching

In a first step we manually mapped the categories of the building material databases Baubook, ÖKOBAUDAT, and ASHRAE. This enabled us to group all materials of these databases to a unified classification structure (see Figure 2). The materials properties information is structured according to the materials ontology presented in Section 4. The materials from each database are instances of the mat:Material class; the properties for these materials are instances of the `mat:Property` class which are grouped into property sets; and the values and units of measures for those properties are instances of the `mat:Measurement` and `mat:UnitOfMeasure` classes, respectively.

In a second step our goal was to identify similar or equivalent products stemming from different databases within each category. As outlined before, each database has a different focus (e.g., thermal or ecological data) and none of them provides the full thermal, ecological, and financial data set.

The developed building material mapping methodology

- Adhesive and filler
- Air
  - Heat flow horizontal
  - Heat flow upwards
  - Heat flow downwards
- Building board
  - Fibre-cement board (interior)
  - Plasterboard
  - Wood and wood-based panel
  - Clay building board
  - Sheets of bonded lightweight aggregate
  - Cement-bound lightweight concrete slab
- Building technology
  - Electrical installation
  - Heating system
    - Biomass boiler
    - Fossil boiler
    - Radiators/radiator
    - Heating pipe
    - Heat pump
  - Hot water tank
  - Photovoltaic system
  - Pipe material
  - Sanitary installation
  - Solar system
  - Ventilation system
    - Ventilation unit
    - Ventilation pipe
    - Accessories
- Ceiling and roof element
- Coating and impregnation
- Concrete
  - Concrete in WU quality
  - Concrete with pumice aggregate
  - Concrete with expanded shale aggregate
  - Concrete with expanded clay or brick chippings aggregate
  - Concrete with EPS aggregate
  - Concrete with slag pumice aggregate
  - Concrete with sulphate slag cement
  - Normal concrete
  - Reinforced concrete / normal concrete with reinforcement
- Constructive (solid) wood
- Door
- Facade cladding
- Fills and aggregate
- Floor covering and skirting board
  - Elastic floor covering
  - Solid floor covering of wood and other natural raw materials
  - Mineral floor covering
  - Textile floor covering
  - Underlays and back coating of floor covering
- Gas
- Sealing sheet, vapour barrier, foil
  - Waterproofing membrane
  - Vapour barriers and brake
  - Film protection material
- Wall element
  - Chipboard concrete wall element
  - Wall element made of lightweight concrete
  - Wall element made of cellular concrete
- Wall paint and covering
- Water
- Window and window component
  - Window (total)
  - Window frame
  - Glazing
  - Linear thermal bridge coefficient (PSI value)
- Insulation
  - Insulating material from renewable raw material
    - Cotton insulation material
    - Flax insulating material
    - Grass fibre insulation board
    - Hemp insulating material
    - Wood fibre insulating material
    - Wood shaving (loose), sawdust
    - Coconut fibre insulating material
    - Cork insulating material
    - Sheep wool insulation
    - Reed insulation panel
    - Straw insulation material
    - Cellulose fibre insulation material
  - Mineral insulation material
    - Glass wool insulating material
    - Wood chip insulation board
    - Wood wool insulation board
    - Wood-wool multi-layer insulation board
    - Mineral foam insulation board
    - Perlite insulation board
    - Foam glass insulation board
    - Rock wool insulation material
    - Vacuum insulation panel
  - Synthetic insulating material
    - EPS insulating material
    - Phenolic resin foam board
    - Polyester fibre insulating material
    - Polyethylene (PE) insulating material
    - PUR/PIR insulation board
    - XPS insulation board
    - Cement-bound EPS board
- Masonry
  - Concrete masonry
  - Sand-lime brickwork
  - Adobe masonry (unfired)
  - Natural stone masonry
  - Aerated concrete masonry
  - Brick masonry
    - Filling brick
    - High perforated brick masonry
    - Slotted brick masonry
- Mounting accessories / individual building material
- Natural stone
- Outdoor surfacing
  - Asphalt pavement
  - Floor covering capable of infiltration
- Plaster and mortar
  - External plaster
  - Adhesive bridges and pre-spray
  - Interior plaster
  - Mortar
  - Plaster base
- Roof covering
- Screed
- Sealant, adhesive, and filler
  - Bitumen coating
  - Bitumen adhesive, sealant, and filler
  - Bitumen grouting compound
  - Sealing tape and thermal bridge interrupter
  - Sealant
  - Liquid foil

Figure 2. Building material classification system

enables users to efficiently plug-in additional building material data and map missing data points for the LCA/LCC and energy performance calculation. After loading the renovation project and the corresponding IFC file in RenoDSS, the completeness checking of the building material data (thermal properties, LCA/LCC properties, etc.) will be performed.

If building material data is missing from the loaded IFC file, RenoDSS supports the user at completing the data by the following building material mapping approach (initiated by clicking on the green button as shown in Figure 4 and 5):

- For each data point (MRU, GWP, AP, etc.) RenoDSS checks for existing mappings to similar building materials.

- For each data point without an existing mapping, RenoDSS provides the user a list of potential mapping candidates. Each building material which belongs to the same category and provides the missing data point will be shown as a potential mapping candidate. The candidates are sorted by the attribute (e.g., density in case of insulation materials) which has been defined in the admin view for the specific category. The sorting properties are used to order the list of similar materials so that more similar materials are shown first to the user. This helps the user to find a matching material more easily. Each category/subcategory can have its own sorting property.

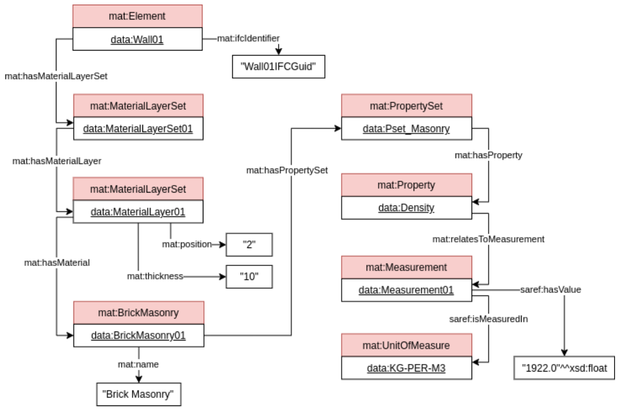

Figure 3. Example of use of the materials ontology

- When the user selects an alternative material, the value for which this material was selected is automatically updated with the value of the selected material. If the materials reference units do not match, a unit conversion is done to the selected unit of reference. It is also possible to overwrite existing values with values from other materials or by manually providing the data. A checkbox is provided so the user can decide if they want to keep the original value or replace it with the new one.

Once the mapping is done all mappings are globally stored and thereby accessible to other users to minimize future mapping efforts. Figure 6 shows the completed building material data after the mapping.

6 Validation

We validated our methodology using the IFC file of an existing two-storey residential building, located in Thessaloniki, Greece. The IFC file did not contain any building material properties which are required as input for the EnergyPlus and the BIMERR LCA/LCC module simulations. Listing 1 and 3 show instances of a wallboard and an outdoor air conditioning unit respectively, extracted from the input IFC file. Applying the developed approach, building material and components in the IFC file were enriched with links to the described psets, whereas the developed user interface was used to complete the property values. Listing 2 and 4 present the output of the developed approach applied on the exemplary wallboard and air conditioning unit of Listing 1 and Listing 3, respectively.

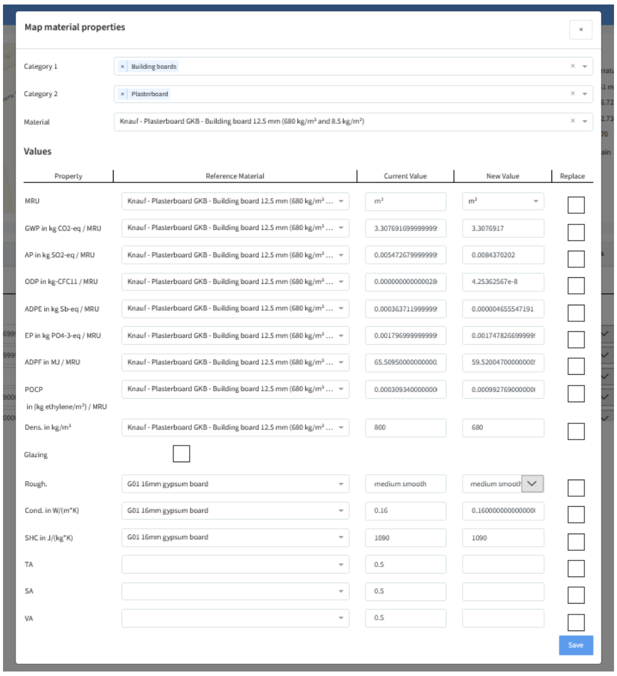

Figure 4. building material mapping modal

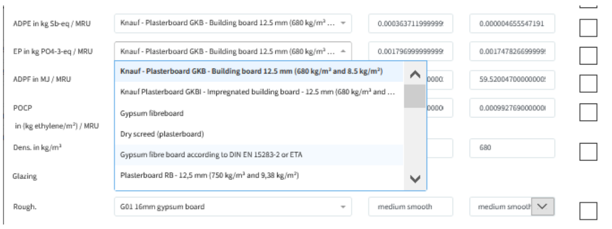

Figure 5. alternative material selection

Listing 1. Input wallboard

```
#2366=IFCMATERIALLAYER(#2317,0.0216,$,'Gypsum Wall
      Board','SpecificHeat: 840, ThermalConductivity:
      2.13254593175853, MassDensity: 1100, Emissivity:
      0.9, Compressibility: 0','Generic',$);
#2317=IFCMATERIAL('Gypsum Wall Board','SpecificHeat:
      840, ThermalConductivity: 2.13254593175853,
      MassDensity: 1100, Emissivity: 0.9,
      Compressibility: 0','Generic');
```

Listing 2. Output wallboard

```
#2366=IFCMATERIALLAYER(#2317,0.0216,$,'Gypsum Wall
      Board','SpecificHeat: 840, ThermalConductivity:
      2.13254593175853, MassDensity: 1100, Emissivity:
      0.9, Compressibility: 0','Generic',$);
#2317=IFCMATERIAL('Gypsum Wall Board','SpecificHeat:
      840, ThermalConductivity: 2.13254593175853,
      MassDensity: 1100, Emissivity: 0.9,
      Compressibility: 0','Generic');
#61829=IFCMATERIALPROPERTIES('OpaqueMaterialProperties
      ',$
      ,(#61833,#61834,#61835,#61836,#61837,#61838,#61839)
      ,#2317);
#61833=IFCPROPERTYSINGLEVALUE('Density',$,
      IFCMASSDENSITYMEASURE(1250.),$);
#61834=IFCPROPERTYSINGLEVALUE('Roughness',$,IFCTEXT('
      MediumSmooth'),$);
#61835=IFCPROPERTYSINGLEVALUE('Conductivity',$,
      IFCTHERMALCONDUCTIVITYMEASURE(2.85433070866142),$
      );
#61836=IFCPROPERTYSINGLEVALUE('SpecificHeat',$,
      IFCSPECIFICHEATCAPACITYMEASURE(960.),$);
```

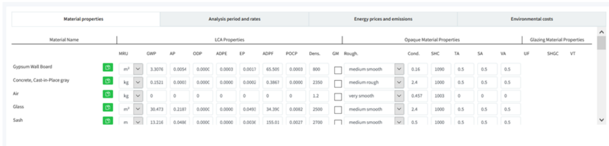

Figure 6. completed building material data

```
#61837=IFCPROPERTYSINGLEVALUE('ThermalAbsorptance',$,
      IFCREAL(0.9),$);
#61838=IFCPROPERTYSINGLEVALUE('SolarAbsorptance',$,
      IFCREAL(1.),$);
#61839=IFCPROPERTYSINGLEVALUE('VisibleAbsorptance',$,
      IFCREAL(1.),$);
#61840=IFCMATERIALPROPERTIES('SustainabilityProperties
      ',$
      ,(#61841,#61842,#61843,#61844,#61845,#61846,#61847)
      ,#2317);
#61841=IFCPROPERTYSINGLEVALUE('GWP',$,IFCREAL(1.),$);
#61842=IFCPROPERTYSINGLEVALUE('AP',$,IFCREAL
      (0.0136032000000000001),$);
#61843=IFCPROPERTYSINGLEVALUE('ODP',$,IFCREAL(5.31143E
      -10),$);
#61844=IFCPROPERTYSINGLEVALUE('ADPE',$,IFCREAL
      (3.70409999999999973E-06),$);
#61845=IFCPROPERTYSINGLEVALUE('EP',$,IFCREAL
      (0.00093749),$);
#61846=IFCPROPERTYSINGLEVALUE('ADPF',$,IFCREAL
      (107.2727),$);
#61847=IFCPROPERTYSINGLEVALUE('POCP',$,IFCREAL
      (0.0118382),$);
#61894=IFCPROPERTYSINGLEVALUE('Lifetime',$,IFCREAL
      (30.),$);
#61888=IFCMATERIALPROPERTIES('Pset_CostProperties',$
      ,(#61889,#61890,#61891,#61892,#61893),#2366);
#61889=IFCPROPERTYSINGLEVALUE('InstallationCost',$,
      IFCREAL(1.),$);
#61890=IFCPROPERTYSINGLEVALUE('DisposalCost',$,IFCREAL
      (1.),$);
#61891=IFCPROPERTYSINGLEVALUE('MaintenanceCost',$,
      IFCREAL(5.),$);
#61892=IFCPROPERTYSINGLEVALUE('MaterialCost',$,IFCREAL
      (1.),$);
#61893=IFCPROPERTYSINGLEVALUE('InstallationYear',$,
      IFCREAL(1970.),$);
```

Listing 3. Input AC unit

```
#69763=IFCUNITARYEQUIPMENT('0WfKv63y9AXxoSruVWpscy
      ',#42,'Outdoor LG simple box KRIPIS v1:
      ARUN080LTE4:1442645','Outdoor LG simple box
      KRIPIS v1:ARUN080LTE4',#69762,#69756,'1442645',.
      AIRCONDITIONINGUNIT.);
```

Listing 4. Output AC unit

```
#69763=IFCUNITARYEQUIPMENT('0WfKv63y9AXxoSruVWpscy
      ',#42,'Outdoor LG simple box KRIPIS v1:
      ARUN080LTE4:1442645',$,'Outdoor LG simple box
      KRIPIS v1:ARUN080LTE4',#69762,#69756,'1442645',.
      AIRCONDITIONINGUNIT.);
#117305=IFCRELDEFINESBYPROPERTIES('1
      yrbumZfX2k9X0gWmLP8Kj',#117299,$,$,(#69763)
      ,#117306);
#117306=IFCPROPERTYSET('169bcZ9rv8ChphMX$sdtoi
      ',#117390,'Pset_SustainabilityProperties',$
      ,(#117369,#117374,#117375,#117376,#117377,#117389,
      #117394));
#117307=IFCRELDEFINESBYPROPERTIES('0
      blbQARfr078mWLvt6mZV9',#117299,$,$,(#69763)
      ,#117308);
#117308=IFCPROPERTYSET('138h010xf1JfzJHzWyCXc1
      ',#117370,'Pset_VRFSupplyProperties',$
      ,(#117378,#117379,#117380,#117381,#117382,#117383,
      #117384,#117385,#117386,#117387,#117388));
#117369=IFCPROPERTYSINGLEVALUE('GWP',$,IFCREAL
      (582.91728),$);
#117374=IFCPROPERTYSINGLEVALUE('AP',$,IFCREAL
      (3.176493),$);
#117375=IFCPROPERTYSINGLEVALUE('ODP',$,IFCREAL(4.194E
      -05),$);
#117376=IFCPROPERTYSINGLEVALUE('EP',$,IFCREAL
      (1.79562178),$);
#117377=IFCPROPERTYSINGLEVALUE('POCP',$,IFCREAL
      (0.26948552),$);
#117378=IFCPROPERTYSINGLEVALUE('Name',$,IFCTEXT('
      ARUN080LTE4'),$);
#117379=IFCPROPERTYSINGLEVALUE('EER',$,IFCREAL(5.11),$
      );
#117380=IFCPROPERTYSINGLEVALUE('COP',$,IFCREAL(5.5),$)
      ;
```

```
#117381=IFCPROPERTYSINGLEVALUE('
    ConsumptionCoolingCapacity',$,IFCPOWERMEASURE
    (4380.),$);
#117382=IFCPROPERTYSINGLEVALUE('
    ConsumptionHeatingCapacity',$,IFCPOWERMEASURE
    (4580.),$);
#117383=IFCPROPERTYSINGLEVALUE('
    EfficiencyCoolingCapacity',$,IFCPOWERMEASURE
    (22400.),$);
#117384=IFCPROPERTYSINGLEVALUE('
    EfficiencyHeatingCapacity',$,IFCPOWERMEASURE
    (25200.),$);
#117385=IFCPROPERTYSINGLEVALUE('
    MaxOutdoorTemperatureCooling',$,
    IFCTHERMODYNAMICTEMPERATUREMEASURE(43.),$);
#117386=IFCPROPERTYSINGLEVALUE('
    MinOutdoorTemperatureCooling',$,
    IFCTHERMODYNAMICTEMPERATUREMEASURE(-10.),$);
#117387=IFCPROPERTYSINGLEVALUE('
    MaxOutdoorTemperatureHeating',$,
    IFCTHERMODYNAMICTEMPERATUREMEASURE(18.),$);
#117388=IFCPROPERTYSINGLEVALUE('
    MinOutdoorTemperatureHeating',$,
    IFCTHERMODYNAMICTEMPERATUREMEASURE(-25.),$);
#117389=IFCPROPERTYSINGLEVALUE('ADPE',$,IFCREAL
    (0.0148703),$);
#117394=IFCPROPERTYSINGLEVALUE('ADPF',$,IFCREAL
    (2324.34),$);
```

7 Conclusion

Within the validation we have shown how the research results can be used to enrich an existing IFC file with the property sets and input data required to run automated and IFC-based energy performance simulations with EnergyPlus and LCA/LCC analysis with the BIMERR LCA/LCC module. The research results enable the user to efficiently gather the required input data by using predefined building material mappings or define new ones based on the developed building material classification system and ontology. The following limitations exist and it is planned to address them in future research: project-specific costs for material and installation must be provided by the user, as it was not possible to centrally obtain this data for all possible project configurations (location, project size, building type, etc.). Currently, the BIMERR LCA/LCC module provides default cost values based on cost data of similar projects which are stored in RenoDSS.

8 Acknowledgement

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A Appendix

Pset name	Property name	Template	Type	Unit
OpaqueMaterial-Properties	Roughness	IfcProperty-SingleValue	IfcText	-
	Conductivity	IfcProperty-SingleValue	IfcThermalCond-uctivityMeasure	W/mK
	Density	IfcProperty-SingleValue	IfcMassDensity-Measure	kg/m^3
	SpecificHeat	IfcProperty-SingleValue	IfcSpecificHeat-CapacityMeasure	J/kg K
	ThermalAbsorptance	IfcProperty-SingleValue	IfcReal	-
	SolarAbsorptance	IfcProperty-SingleValue	IfcReal	-
	VisibleAbsorptance	IfcProperty-SingleValue	IfcReal	-
Pset_Glazing-Material-Properties	Ufactor	IfcProperty-SingleValue	IfcThermal-Transmittance-Measure	W/m^2 K
	SolarHeatGainCoefficient	IfcProperty-SingleValue	IfcReal	-
	VisibleTransmittance	IfcProperty-SingleValue	IfcReal	-
for materials: Sustainability-Material-Properties	GWP	IfcProperty-SingleValue	IfcReal	-
	AP	IfcProperty-SingleValue	IfcReal	-
	ODP	IfcProperty-SingleValue	IfcReal	-
for objects: Pset_Sustainability-Properties	POCP	IfcProperty-SingleValue	IfcReal	-
	ADPE	IfcProperty-SingleValue	IfcReal	-
	EP	IfcProperty-SingleValue	IfcReal	-
	ADPF	IfcProperty-SingleValue	IfcReal	-
Pset_Cost-Properties	MaterialCost	IfcProperty-SingleValue	IfcReal	-
	InstallationCost	IfcProperty-SingleValue	IfcReal	-
	MaintenanceCost	IfcProperty-SingleValue	IfcReal	-
	DisposalCost	IfcProperty-SingleValue	IfcReal	-

Table 3. Required psets and properties for opaque and glazing materials

Pset name	Property name	Template	Type	Unit
Pset_Radiator-Properties	AvailabilitySchedule	IfcProperty-ReferenceValue	IfcIrregular-TimeSeries	-
	HeatingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	-
	HeatingType	IfcProperty-SingleValue	IfcLabel (HotWater, Electric)	-
Pset_Boiler-Properties	BoilerType	IfcProperty-SingleValue	IfcLabel (DistrictHotWater, Hot-WaterBoiler, CondensingHotWa-terBoiler)	-
	Capacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	Efficiency	IfcProperty-SingleValue	IfcReal	-
	FuelType	IfcProperty-SingleValue	IfcLabel (Electricity, NaturalGas, Diesel)	-
	MinimumPartLoadRatio	IfcProperty-SingleValue	IfcRatioMeasure	-
	MaximumPartLoadRatio	IfcProperty-SingleValue	IfcRatioMeasure	-
	OptimumPartLoadRatio	IfcProperty-SingleValue	IfcRatioMeasure	-
	WaterOutletUpper-TemperatureLimit	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
Pset_VRFSupply-Properties	Name	IfcProperty-SingleValue	IfcText	-
	EER	IfcProperty-SingleValue	IfcReal	-
	COP	IfcProperty-SingleValue	IfcReal	-
	ConsumptionCoolingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	ConsumptionHeatingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	EfficiencyCoolingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	EfficiencyHeatingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	MaxOutdoorTemperature-Cooling	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	MinOutdoorTemperature-Cooling	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	MaxOutdoorTemperature-Heating	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	MinOutdoorTemperature-Heating	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
Pset_VRFDemand-Properties	SupplySideSystemName	IfcProperty-SingleValue	IfcText	-
	CoolingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	HeatingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
Pset_Thermostat	Name	IfcProperty-SingleValue	IfcText	-
	HeatingSetpoint	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	CoolingSetpoint	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
Pset_Residential-ACunits	ConsumptionCoolingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	ConsumptionHeatingCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	EER	IfcProperty-SingleValue	IfcReal	-
	COP	IfcProperty-SingleValue	IfcReal	-
	CoolingDesignSupplyAirTemperature	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	HeatingDesignSupplyAirTemperature	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	SupplyFanTotalEfficiency	IfcProperty-SingleValue	IfcReal	-
	SupplyFanDeltaPressure	IfcProperty-SingleValue	IfcPressureMeasure	Pa
	SupplyFanMotorEfficiency	IfcProperty-SingleValue	IfcReal	-

Table 4. Required psets and properties for HVAC components

Pset name	Property name	Template	Type	Unit
Pset_SolarCollectors	MaximumFlowRate	IfcProperty-ReferenceValue	IfcVolumetric-FlowRateMeasure	m^3/s
	SurfaceName	IfcProperty-SingleValue	IfcText	-
	GrossArea	IfcProperty-SingleValue	IfcAreaMeasure	m^2
	TestFlowRate	IfcProperty-SingleValue	IfcVolumetric-FlowRateMeasure	m^3/s
	Coefficient1of-EfficiencyEquation	IfcProperty-SingleValue	IfcReal	-
	Coefficient2of-EfficiencyEquation	IfcProperty-SingleValue	IfcReal	-
	Coefficient3of-EfficiencyEquation	IfcProperty-SingleValue	IfcReal	-
	Coefficient2of-IncidentAngleModifier	IfcProperty-SingleValue	IfcReal	-
	Coefficient3of-IncidentAngleModifier	IfcProperty-SingleValue	IfcReal	-
Pset_WaterHeater/ Storage	TankVolume	IfcProperty-SingleValue	IfcVolumeMeasure	m^3
	HotWaterSetpointTemperature	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	DeadbandTemperatureDifference	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	MaximumTemperatureLimit	IfcProperty-SingleValue	IfcThermodynamic-TemperatureMeasure	C
	HeaterMaximumCapacity	IfcProperty-SingleValue	IfcPowerMeasure	W
	HeaterFuelType	IfcProperty-SingleValue	IfcLabel (Electricity, NaturalGas, Diesel, DistrictHeating)	-
	HeaterThermalEfficiency	IfcProperty-SingleValue	IfcReal	-
	UseSideDesignFlowRate	IfcProperty-SingleValue	IfcVolumetric-FlowRateMeasure	m^3/s
	SourceSideDesignFlowRate	IfcProperty-SingleValue	IfcVolumetric-FlowRateMeasure	m^3/s
Pset_Photovoltaics	SurfaceName	IfcProperty-SingleValue	IfcText	-
	RatedElectricPowerOutput	IfcProperty-SingleValue	IfcPowerMeasure	W
	NumberOfSeries-StringsInParallel	IfcProperty-SingleValue	IfcCountMeasure	-
	NumberOfModulesinSeries	IfcProperty-SingleValue	IfcCountMeasure	-
	FractionOfSurface-WithActiveSolarCells	IfcProperty-SingleValue	IfcRatioMeasure	-
	CellEfficiency	IfcProperty-SingleValue	IfcReal	-

Table 5. Required psets and properties for solar collectors, water heater, and photovoltaics