District-aware Building Energy Performance simulation model generation from GIS and BIM data

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Abstract

The assessment of district retrofit scenarios performed by the online platform OptEEmAL, requires an automatic and district-aware building energy performance simulation model generation operation, applied on certain buildings of interest. Such operation involves fusion of BIM, GIS and other data, under a common scheme suitable for building energy performance simulations and transformation of the fused data into appropriate simulation input data files. The above processes, which should conform to certain data quality conditions, are performed by data checking and semantic enrichment software tools, which are described in detail and demonstrated on specific building and district examples.

Introduction

The accuracy of a 3D zonal-type Building Energy Performance (BEP) simulation result is determined by its input data, mainly comprising the building geometry, internal loads, HVAC systems and components, weather data, operating strategies and schedules, and simulation specific parameters. These data can be further classified into static and dynamic data. Static data include the building geometry, construction materials, glazing information, systems used in the building, etc., while dynamic data consist of all time-dependent data such as user-actions (e.g. opening and closing the windows), occupancy schedules in each of the building zones, use of equipment, weather predictions, etc., commonly being in-building sensed measurements.

In current practice, to develop a 3D zonal-type BEP simulation model, modelers gather and combine 2D drawings such as Architectural and Mechanical Electrical Plumping (MEP) plan views, material data and other information, and manually transform them into the specific input data, required by the respective BEP simulation engine. BEP simulation model preparation consists of the following steps:

1. Determination of the building location and typical year weather data for that location (dynamic data).
2. Definition of the building geometry, constructions and spaces according to 2D architectural drawings (static data), taking into account shading surfaces of neighbour buildings.
3. Definition of space loads such as electric equipment, lighting, people etc. (static data).
4. Definition of the HVAC system and its components according to 2D Mechanical Electrical Pumping (MEP) drawings (static data).
5. Determination of other simulation parameters, such as numerical tolerances, start and end times of the simulation (dynamic data).
6. Determination of reference data for the building operation schedules (dynamic data).

This process has two strong weaknesses: a it is very time-consuming, often requiring more time than is available, due to project's tight deadlines; and b) it is a non-standardized process that produces BEP simulation models whose results can significantly vary from one modeler to another, according to their experience, even given the same initial building design information (Berkeley et al., 2014). Consequently, a standardized automatic creation of BEP simulation models could expedite the BEP simulation modeling process, making it less vulnerable to modeling errors. As a result, the automated data transformation from BIM and GIS data sources to input data of thermal simulation tools, which supports this automated BEP simulation model generation, has received considerable attention recently (Andriamamonjy et al., 2018; Reynders et al., 2017; Chen et al., 2017; Giannakis et al., 2015; Bazjanac, 2009).

This data transformation process has been adopted within OptEEmAL project, a project which aims at providing stakeholders with a web-based platform for district energy-efficient retrofitting design. OptEEmAL will introduce a platform which will make use of input data from a district of interest (geometrical, materials, renewable energy resources, existing energy systems, social aspects, economic data, barriers, specific targets, etc.). These data will pass through a four-stage process: diagnosis and formulation of scenarios; evaluation and optimization; best scenario selection and data exportation. A set of District Performance Indicators (DPIs), that are key performance indicators in the fields of energy, comfort, environmental, economic, social and urban aspects, are adopted to describe the pre- and post-retrofitting status of the district. Simulations will be then automatically launched to calculate these indicators.

BIM data source

As far as data sources are concerned, a Building Information Model, being an object-oriented digital representation of a building, is an information-rich source for setting up a BEP simulation model. A BIM model may conform to different data schemes, the more widely used being the Green Building XML schema (gbXML) and the Industry Foundation Classes (IFC) (ISO16739, 2013). The latter being more comprehensive, was selected for use within OptEEmAL. The IFC files contain a plethora of information, out of which only a subset is useful for the data transformation process from BIM/GIS to BEP simulation models, described previously. The need to extract this data subset from the IFC data pool, leads naturally to a model view definition (MVD) (Hietanen and Final, 2006) for BEP simulation purposes, as described next.

The IFC model is expansive and may contain multifaceted information regarding the building (geometry, HVAC, quantities, processes, etc.). To facilitate specific exchanges between tools, only a subset of the information contained in the BIM schema is usually required, both in terms of content (instantiation of specific classes) and completeness representing different views of the BIM. The Model View Definition (MVD) specification (Hietanen and Final, 2006) allows to define, in a formal way, such views in the form of precise exchange requirements. Along with the introduction of IFC4, buildingSMART has published two general-purpose Model View Definitions: IFC4 Reference View (IFC RV) and IFC4 Design Transfer View (IFC DTV).

Within OptEEmAL, upon scrutiny of available IFC4 MVDs and the consideration of whether a new one is required, it was decided that the IFC4 DTV is suitable for the data exchanges. Most exporters already support the IFC4 DTV and therefore this selection allows for increased compatibility of the OptEEmAL platform with existing exporters.

Other data sources

Although IFC is an information-rich data model, it does not meet all the data requirements for automatic BEP simulation model generation: shading surfaces of neighbor buildings are not defined; and other simulation parameters, cannot be described following the IFC schema.

As far as the neighbor building shading surfaces are concerned, the geometric definition of all the buildings in a large sector of a geographical district is required; within OptEEmAL such information is provided in a CityGML data file format. These buildings include: the buildings of interest of OptEEmAL platform together with surrounding buildings affecting the energy balance of the buildings of interest indirectly by blocking sunlight.

Concerning the other simulation parameters, every building simulation process requires timing information to be performed as well as knowledge of the required output parameters. This type of information and can be grouped to a new data category called other simulation parameters. More precisely, other simulation parameters include: simulation start time (defined by: month, day, hour and minute), simulation end time (defined by: month, day, hour and minute) and simulation inter-sample time interval (in minutes), surface convection and heat balance algorithm options and others. Within OptEEmAL, values of these features are prefixed and have been selected carefully after numerous experiments, taking into account that these features require domain expertise for input specification and output assessment that cannot be addressed in automated transformation processes.

In order to collect all BEP simulation data requirements under a common data model, SimModel (O'Donnell, 2011) has been selected within OptEEmAL.

Main objective

The present work aims at presenting components of OptEEmAL's simulation model input generator module, a module used for the automatic generation of the input files used in the invocation of one of OptEEmAL's analysis tools (EnergyPlus). To support the module's operation, a tools-chain for the automatic generation of BEP simulation input data files from IFC and CityGML data, is developed and described analytically. The operations of this tools-chain involve functions like: data retrieval, data transformation, execution of the simulation tools, and computation of DPIs, which are performed by new, or modified existing, tools illustrated in Figure 1. These tools along with associated modeling guidelines, documented in the following sections, include:

- *Data Quality guidelines and tools*: BIM Design Guidelines; Modified IFC exporter; BIM checking tool; Geometric Error Detection Tool;
- *Semantic Enrichment for DPIs calculation components*: Common Boundary Intersection Projection tool (CBIP tool); District Neighbour Shading tool (DNS tool); Automatic Zoning tool; SimModel Enrichment tool; XML to RDF converter (Other supporting tools);
- *Simulation Input Files Generation components*: EnergyPlus Input File Generator; HVAC Input File Generator; NEST Input File Generator; Economic Input File Generator;
- *DPIs calculation*: EnergyPlus Computing Cluster.

The operation of the tools, presented in figure 1 can be described concisely as follows. During the data insertion (stage 2 in figure 1), BIM Design Guidelines provide the modeler with design rules to be fol-

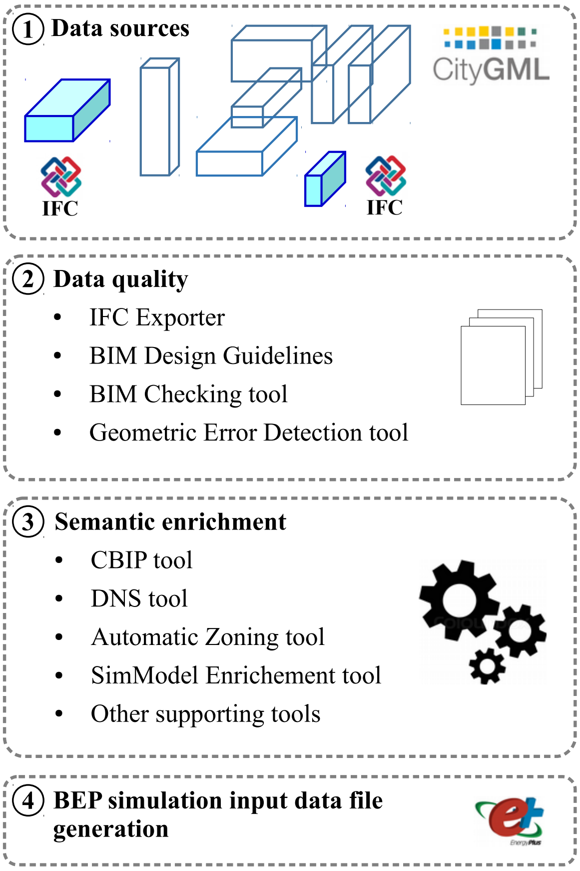

Figure 1: Overview of the tools chain of OptEEmAL's BEP simulation model generation process.

lowed to generate a consistent BIM model. A modified version of the Revit^{TM} IFC Exporter enables exportation of information which could not be exported by the original IFC exporter (e.g. material thermal properties). The BIM checking tool checks, using a static set of rules, whether required data are present in the IFC file, and the Geometry Error Detection tool checks for geometry errors that may affect the next tools in the chain (e.g. CBIP tool).

As far as the semantic enrichment tools are concerned (stage 3 in figure 1), CBIP tool enriches the IFC file with geometry information that is required for BEP simulation (namely, generates the building's 2^{nd}-level space boundary topology). The DNS tool retrieves information from the context and city repositories and generates a set of surfaces that have shading effect to the buildings under investigation (these buildings define the district). The automatic zoning tool aims at generating zoning information, if this is not available, from the supplied IFC file. Finally the SimModel Enrichment tool, retrieves the output of an IFC to SimModel XML process and enriches the energy data models with additional information required for energy simulations. Two other supporting, stand alone, tools have also been developed: the SimModel XML to RDF mapping tool which transforms a SimModel file to an ontology in RDF file format and the IFC-SimModel XML mapping tool which transforms directly IFC files in IFC4 file format to SimModel XML files.

Finally, the BEP simulation input data file generation stage (stage 4 in figure 1), contains tools of OptEEmaL's simulation input model generator module which retrieves data from the SimModel, generates input files for specific simulation tools (e.g. EnergyPlus), and submits these files to the Cluster Computing tool for simulation executions.

A brief introduction to the methodological background and a more detailed description of the aforementioned tools are contained in the following sections.

Data quality

Although both district and building data may be available for simulation input data files generation, there is no guarantee that these data are suitable for this purpose, since the quality of the data may not be at an acceptable level. Concerning building data, there are three stages of data quality checking operations to ensure a quality level suitable for a simulation model generation. These operations include consistency, correctness and completeness checks. Four individual tools for data quality insurance are developed to support the simulation model generation process: IFC Exporter; Design Guidelines; Geometry Error Detection tool; and BIM Checking tool. This section presents the validation of these tools.

IFC Exporter

Many commercial authoring tools (e.g. Revit™, Allplan™, ArchiCad™) support exportation of IFC files. However, exportation is often not perfect: unlike what would be expected, the exported models can be of poor quality and therefore not directly usable. Revit™ (and its IFC4 DTV exporter) seems to be less prone to exportation errors. However, even the Revit™ IFC4 DTV exporter is far from perfect (see figure 2): although, IFC can incorporate information about thermal and optical properties of each building entitys construction material, internal gains (schedules and densities) and inverse relations in case of curtain walls, the current version of the exporter is not capable of exporting this information.

To overcome such limitations, and to guarantee correct exportation of such information, the Revit™ IFC exporter (which is an open source component) has been modified to create a bespoke OptEEmAL version that addresses these shortcomings. The OptEEmAL IFC Exporter supports the latest version of Revit (2018).

BIM Design Guidelines

Certain information contained within a BIM file can be visually inspected (e.g. geometry) and might appear correct. Still there might be hard-to-discern errors (for example object clashes) that may make these

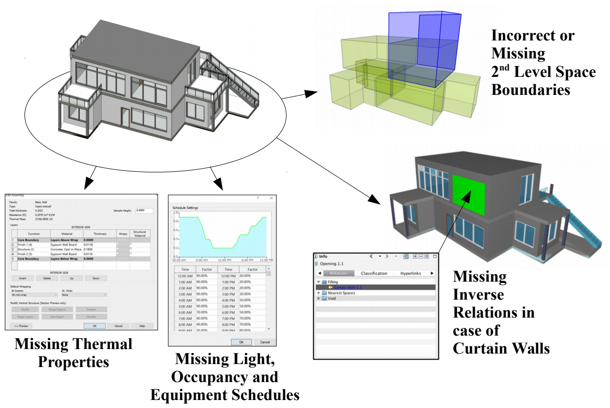

Figure 2: IFC exporter issues.

data less useful for receiving applications (e.g. for use to setup BEP simulation models). To eliminate (or reduce) such inconsistencies, a set of guidelines have been defined that should be followed by the designer of the BIM model (see figure 3), to ensure that the quality of the generated IFC model is suitable for use by the OptEEmAL platform.

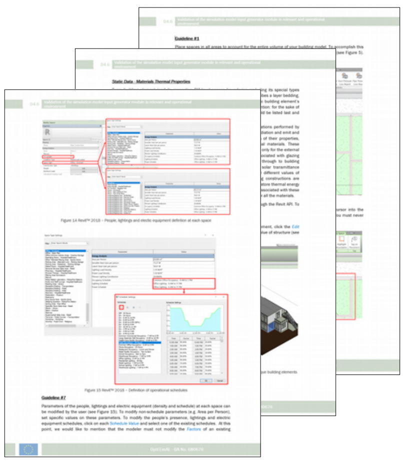

Figure 3: BIM design guidelines.

BIM Checking tool

Within OptEEmAL platform, there are several tools using BIM for various purposes. For instance, the CBIP tool receives IFC data, to generate 2^{nd}-level space boundary topology of each building. CBIP tool has well-defined data requirements, met by extracting BIM information from the Data Insertion Module; for its proper execution, the IFC file must contain (a) one building object; (b) one site object; (c) at least one space object (d) at least on building element object (wall, slab, etc); and some unit objects. Model View Definition (MVD) aims at describing such a subset of a schema (objects, relations, logical operations) that is needed to exchange the required data in specific exchange scenarios. Similarly, a subset of the IFC4 schema has been defined within OptEEmAL, while a BIM Checking tool has been developed that applies a set of static rules and methods to ensure the data availability for this subset.

Geometry Error Detection tool

Even if the modeler has installed the modified exporter, has followed the design guidelines to develop the BIM, and the exported IFC file has passed the data completeness check, there are still cases where IFC files geometric data might not be correct, which the modeler should correct manually.

There are certain geometric inaccuracies which affect the generation of a building energy performance simulation input data file, grouped into the following three categories: clashes; surface errors; and space incorrect definitions (Lilis et al., 2015). In general clashes among non-space entities, such as the one presented in the example of part I of figure 4 between a wall and a slab, do not affect the simulation model generation process. The clashes involving a building space volume or the building's site volume and other surrounding elements, as the space related clash presented in the example of part II of figure 4, affect the space boundary topology of the building and the simulation model generation process. The clashes among non-space entities affect the space boundary topology only if the intersection surfaces are attached to two different space objects or one space object and the external environment (air or ground site), leading to space boundary duplication, as illustrated by the Wall opening - Wall opening clash displayed in part III of figure 4. Consequently, all the clash types affecting the space boundary topology generation, are detected and reported to the user of the platform for correction.

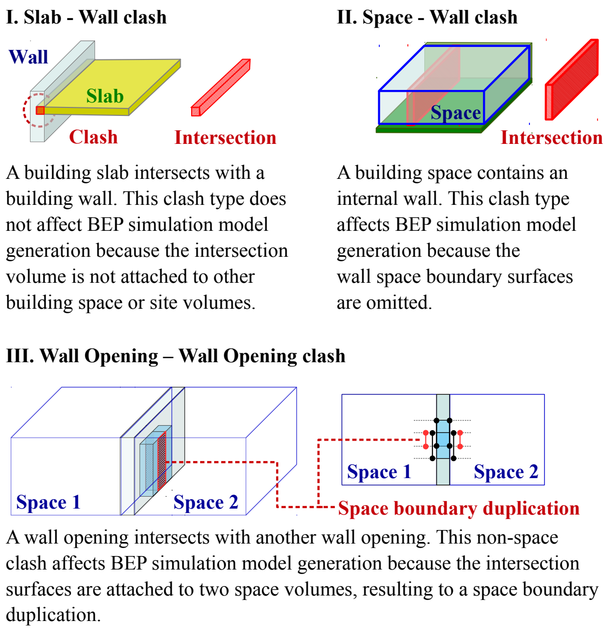

Figure 4: Examples of building clashes.

To help the modeler on providing an error-free IFC file in terms of geometry, the previous types of geometric inaccuracies are detected by OptEEmAL platform utilizing the Geometry Error Detection tool. This error detection is performed for every IFC file in the district. If errors exist, they are reported in an XML form, documenting the IFC global IDs of the involved entities, as well as the geometric definition of the related intersection surfaces, as illustrated by the following instance.


```
<ClashErrors>
    <Wall-Space>
        <ClashError id="1" , ...">
        <ClashError id="2" . ...">
        ...
    </Wall-Space>
</ClashErrors>
```

```
<ClashError id=1, ID_1=3, GID_1=..., ID_2=4,
GID_2=...>
    <boundaryRepresentation>
        <surface> ... </surface>
        ...
    </boundaryRepresentation>
</ClashError>
```


Semantic Enrichment for DPIs calculation

Even if the IFC files have passed the data consistency, completeness and correctness tests, SimModel data models populated by applying an IFC to SimModel XML data mapping process (see "Other Supporting tools" section) do not meet all the data requirements for a "district-aware" simulation input data file generation. To meet the remaining missing-data requirements, the following semantic enrichment software tools have been developed: CBIP, DNS, Automatic Zoning and SimModel Enrichment for EnergyPlus. The operations of these tools are described, in more detail, in the following sections.

CBIP tool

In terms of geometry, BEP simulations require information of the building polygonal surfaces through which the thermal energy is exchanged, either among the building internal spaces or between the internal building spaces and the building environment (air surrounding the obuilding, or the ground attached to the building). These surfaces are commonly known in the literature as 2nd-level space boundary surfaces (Bazjanac, 2010). Examples of 2^{nd}-level space boundary surfaces are displayed in the Solibri Model Viewer screenshot of figure 5.

However, there are not quite a few the cases where, in the IFC files, such information is missing or is incorrect, as illustrated in the upper right part of 2. To deal with such data insufficiency, the Common Boundary Intersection Projection tool (CBIP) (Lilis et al., 2016) has been developed.

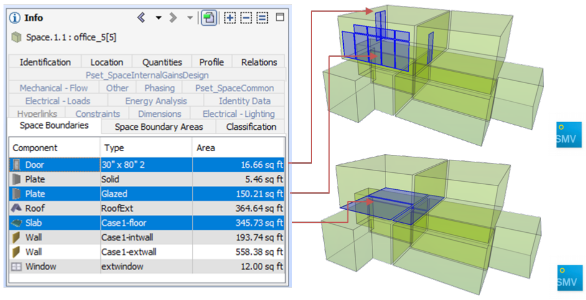

Figure 5: Results of CBIP tool on a demonstration building (Solibri Model Viewer™ screenshot).

CBIP tool calculates the 2^{nd}-level space boundary surfaces using the algorithm described in (Lilis et al., 2017b). The algorithm is applied on the geometrical description of the buildings' architectural elements (walls, spaces, slabs, openings, etc.), which is contained in the tools' input IFC BIM files. Finally, CBIP tool enriches the input IFC files, with the data of the calculated 2^{nd}-level space boundary surface topology, by populating appropriate data classes. Unlike other graph-based methods (Rose and Bazjanac, 2015), (van Treeck and Rank, 2007), CBIP is a graphless method and requires the complete geometric descriptions of the internal building space volumes.

DNS tool

All required simulations within OptEEmAL should be district-aware, which partially means that the effect of surrounding district environment should be considered. To this direction, a District Neighbour Shading (DNS) tool has been developed which uses the algorithm described in (Lilis et al., 2017a), to determine the set of surfaces of neighbor buildings that block solar energy from entering the simulated buildings. This neighbor building shading effect has a direct impact on the thermal energy balance of the buildings of interest; hence, it should be included in the input data of the BEP simulation. In short, DNS tool receives as input the CityGML file, the IDs of the buildings of interest and the citys longitude and latitude, and reports the geometry of the shading surfaces of neighbour buildings, in an XML form. The shading surfaces, obtained by the DNS tool, of an imaginary building envelope, placed at the center of a district in the city of Santiago de Compostella in Spain, are displayed in figure 6.

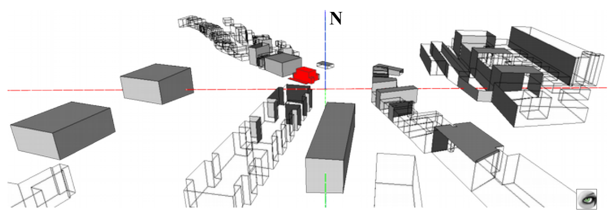

Figure 6: Results of DNS tool on a demonstration district (MeshLab screenshot).

Automatic Zoning tool

Within OptEEmAL, aiming at discovering the best retrofitting scenario, an optimization process is adopted, where repeated evaluation of different candidate scenarios is performed. For each scenario evaluation, a respective, accurate building simulation model is developed and executed, making the overall decision-making (optimization) process a quite laborious and time-consuming task.

The major factor affecting the overall computational time of this repeated evaluation process, is the simulation execution time. Since high complexity and prohibitive simulation execution time are predominantly due to the full-scale, and detailed, geometry representation of the buildings, geometry simplification methodologies can be applied to reduce these effects. The effectiveness of such methodologies relies on the modeler's experience and the building's shape, hence an automatic process to generate speedup models, by applying geometry reduction methodologies, is unfeasible.

A common assumption and characteristic of the full-scale thermal simulation models, which are outputs of introduced automatic BEP simulation model generation process, is the one to one mapping between each building space and a its respective thermal zone. This assumption increases significantly the simulation runtime, since computational effort is more than proportional to the number of zones, as increased number of zones corresponds to increased number of ordinary differential equations to be solved. Towards reducing the overall computation time, by reducing the number of thermal zones in an automated manner, two zoning reduction methodologies have been introduced (Giannakis et al., 2017). The first one utilizes the Hierarchical Clustering theory (Maimon and Rokach, 2005), while the second one adopts the Koopman modes theory (Georgescu and Mezić, 2015). Both methodologies have been included in the Automatic Zoning tool, a software tool which is incorporated under the OptEEmAL framework.

SimModel Enrichement for EnergyPlus tool

In terms of BEP simulation, for energy demand estimation, the data reported in (Maile et al., 2013), are required. Investigation of the SimModel capability to meet these requirements without any extension of its current schema has been performed, leading to a list of existing SimModel classes that could be used. However, SimModel files generated by the IFC to SimModel XML process are IFC-oriented and therefore some required non-IFC oriented SimModel instances are missing in these files. Hence, it is necessary to apply certain rules to enrich these files with additional data for correct EnergyPlus input data file generation. These rules have been implemented in a new tool, named SimModel Enrichment for EnergyPlus tool.

Other Supporting tools

In order to increase the interoperability and the automation of the input data file generation process of BEP simulation models within OptEEmAL, several other supporting tools and libraries have been developed. The selected schema of OptEEmAL's core data model (SimModel), is based on a set of XSD files, which are updated in a regular basis to match the evolution of the Input Data Dictionary (IDD) of the newest version of EnergyPlus. Using the SimModel schema as input the supporting tools can generate: a) The SimModel ontology in TTL format; b) The Java class library and API of the SimModel XML data.

Based on the produced files further tools have been developed to provide additional functionalities into the Simulation Module and the Semantic Enrichment services. The TTL files of the SimModel OWL are applied for the generation of the transformation rules between the SimModel XML and SimModel RDF data. On the other hand, the SimModel Library is used mainly for loading the SimModel XML in-memory, while the API is used for manipulating the loaded objects more efficiently. The following subsections describe in detail the functionality of each tool as well as the acheived goals.

SimModel XML to RDF Mapping tool

A standalone mapping tool has been developed to perform bi-directional transformations between the SimModel XML and SimModel RDF data. To do this, it uses the Jena API and the SimModel API to load in-memory the objects and then applies a sequence of rules to transform the data types and the instances to the requested output format. Additionally, it requires the SimModel XSD schema as well as the SimModel OWL to retrieve meta-data information about the definitions of the SimModel classes, abstractions, data types etc.

IFC - SimModel XML Mapping tool

A standalone tool for the automatic mappings from the IFC4-SPF to SimModel XML has been developed. Utilizing this tool, each BIM model is transformed using a mapping framework directly to the SimModel representations in one step. The mapping framework collects meta-data of the IFC4 and SimModel classes to generate mapping objects which can be used together to copy data from one object graph to another, recursively. Then, the SimModel XML output can be transformed in RDF using the SimModel XML to RDF Mapping Tool which has been described previously.

The produced SimModel XML is fully compatible with the SimModel XSD schema, since the mapping tool is using internally the SimModel Library and API.

Simulation Input Data Files Generation

Data retrieved from SimMdodel Data Models comply with certain groups of transformation rules to generate the required simulation input files: input data file (IDF) for every building of interest, to be used as input to EnergyPlus.

EnergyPlus IDF is an ASCII file which contains information about the building and the HVAC system to be simulated. The EnergyPlus input data are structured into classes. For each class, fields are defined, which describe the characteristics of the class objects. Objects are the instances of a class. All the available classes are listed into the Input Data Dictionary file (IDD).

To generate the IDF file of a specific building, a set of mapping rules have been defined that transform data of the respective, enriched SimModel file (result of applying the SimModel Enrichment for EnergyPlus tool) to IDD classes objects and writes a text file according to the IDD specifications. This set of rules forms the EnergyPlus Simulation Input Data File Generation tool. An example of the IDF generation tool's output is demonstrated and validated visually, by the Google SketchUp™ screenshots of Figure 7.

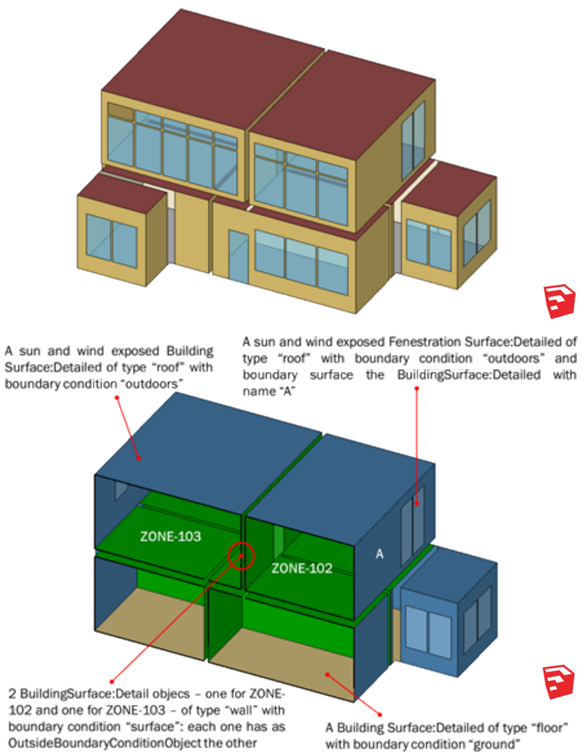

Figure 7: Illustrative examples of the enriched SimModel to IDF mapping rules correctness, rendered by surface type (top) and by boundary condition type (bottom) using Openstudio plugin for SketchUp

Conclusions

In the present work, a tools-chain performing an automatic and "district-aware" BEP simulation input data file generation (SimModel XML and IDF files for EnergyPlus), from GIS (CityGML) and BIM (IFC4) data files, used within the OptEEmAL framework, was presented. The analysis concentrated on documenting the overall architecture, where several new (or modification of existing) supporting tools and guidelines were introduced. These tools perform the required data retrieval and data transformation operations which ensure the correct execution of OptEEmAL's Simulation Model Input Generator Module processes. These introduced tools can be classified into two main categories: the data quality checking tools and the semantic enrichment tools.

Initially, and from a data quality viewpoint, in order to ensure the generation of flawless IFC data files, specific BIM design guidelines were documented and a modified IFC exporter was introduced. Then, two data quality checking tools were described: the BIM checking tool, which examines the data completeness of the input IFC files and the Geometric Error Detection tool, which checks the geometric data correctness of the input IFC files.

As far as semantic enrichment is concerned, the introduced tools included: the CBIP tool which enriches the IFC file with geometry information that is required from the BEP simulation viewpoint (2^{nd}-level space boundaries), the DNS tool which retrieves information from OptEEmAL's context and the city repositories (containing the CityGML data) and generates a set of surfaces that have shading effects to the buildings under investigation (simulated buildings), the Automatic zoning tool which aims at generating reduced simulation models with smaller simulation runtime than full-scale models, the SimModel Enrichment tool which retrieves the output of an IFC to SimModel XML mapping process and enriches the resulted SimModel XML with information required from the EneryPlus perspective and finally, the simulation input data file generation process which produces the final IDF file suitable for EnergyPlus simulations. Additional supporting tools improving the interoperability and the automation of the introduced input data file generation process, were also presented.

To achieve IDF file accuracy, the input IFC and CityGML data must be consistent (the building in the IFC context should be correctly defined with respect to its neighbor building envelopes defined in the CityGML context) and the IFC file should be complete and error free. The IFC-CityGML geometric consistency, checking rules which ensure acceptable data quality of the input IFC/CityGML data and the inclusion of active building energy systems to the presented BEP simulation model generation process, are subjects of further investigation.

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