# Simulation model generation combining IFC and CityGML data

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ABSTRACT: The energy efficiency requirements at district scale, revealed the need for detailed building energy simulations with which, the overall district energy demand can be estimated with an acceptable degree of accuracy. In order to meet this need, an automated simulation model generation process is introduced at the context of the European project OptEEmAL, which includes: a query stage where data are gathered from IFC, CityGML files, and a transformation stage where a single IDF file is generated for a building in a district environment, suitable for EnergyPlus simulations. The queried data, are assumed to conform to certain correctness, completeness and consistency conditions across district and building scales. As a demonstration example, a simulation model is generated for a specific building. Future improvements of this work are discussed related to the integration of all the data requirements of the proposed process, in a District Data Model under an ontological framework.

## 1. INTRODUCTION

The recent building energy footprint reduction requirements highlighted the value and promoted the use of detailed building thermal energy simulations. Furthermore, since the thermal performance of buildings in a district environment is affected by phenomena caused by neighbor building topologies, treating buildings individually and neglecting their neighbor building topologies impact (e.g. shading effects and microclimate), results to reduced accuracy in their simulation results. The need for accurate thermal energy simulations is met by a plethora of simulation engines, developed for either building-scale simulations (e.g. EnergyPlus), where detailed building geometry information is required, or district-level simulations (e.g CitySim), where the geometry details of buildings are omitted. The input data to the above programs are formatted properly according to the specific program requirements.

From the input data availability perspective, two popular data schemas have been developed for different purposes: the first is a BIM scheme called IFC (ISO16739, 2013), designed for building-scale data and promoting interoperability among AEC industry programs; the other is a GIS schema, called CityGML (Kolbe, Gerhard, & Lutz, 2005), structured in order to render city scale data. These data sources cannot be used directly as inputs to thermal energy simulation programs as they require further processing related to the generation of the second-level space boundary geometric topology.

Incorporating the district's environmental impact in building-scale simulation programs improves the quality of their results. Attempts towards this direction have been reported via the use of co-simulation (Thomas, et. al. 2014). In order to perform detailed building thermal energy simulations including the building's district environmental impact, a simulation model generation process is introduced, as the main subject of the present work. Parts of this process will be used at the context of the European project OptEEmAL, which aims at automating the selection of the best energy conservation refurbishment scenario of a district, according to specific performance indicators. In order to include the district's environmental impact to the generated simulation models, input data from GIS and BIM sources are integrated. This idea of integrating data across building and district scales has appeared in past research efforts: SEMANCO project (Sicilia, et. al., 2014), GeoBIM extension (van Berlo & de Laat, 2010), ontology-based Unified Building Model (El-Mekawy & Östman, 2012), virtual 3D city model (Döllner & Hagedorn, 2007).

The rest of the paper is organized into two parts. In the first part, the current simulation model generation process is described which uses data from an IFC file of a building, combined with district data of surrounding buildings extracted from a CityGML file, in order to generate inputs suitable for the energy simulation program EnergyPlus. Initially, the data requirements of the process are highlighted, followed by the definition of data quality rules, these data have to satisfy, in order to be suitable for simulation model generation. Then, the algorithmic parts of the process are described, followed by an application example, on specific district data.

In the second part of the paper, it is discussed how the current simulation model generation process can be improved by moving some of its functional components and organizing its input data, in a single district data model, using an ontological framework. Such extensions will introduce interoperability possibilities to the process, by establishing semantic connections to other simulation tools.

## 2. DATA REQUIREMENTS

Building simulation data models require a variety of data, ranging from pure geometric descriptions, to operation characteristics of micro-climate control devices installed in building interiors. In order to organize such versatile data across building and district scales, an initial classification is attempted. According to this classification the required data for a simulation model generation in a district environment, can be classified into three categories (as illustrated in figure 1): BIM data, GIS data and Contextual data. The characteristics of each category are described in the following sections.

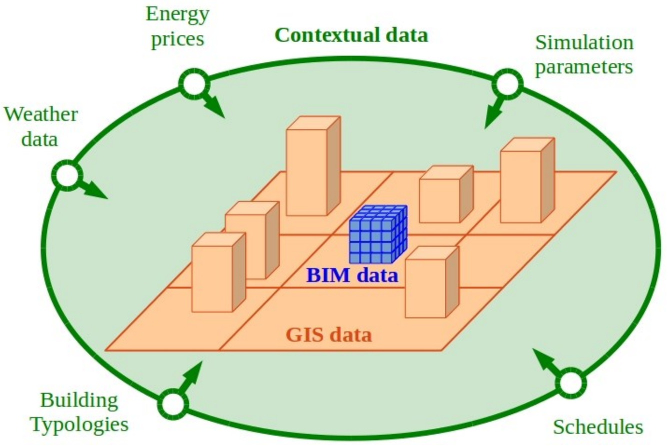


Figure 1: Data requirements of the simulation model generation process.

### 2.1 *BIM data*

The required BIM data for simulation model generation, are related to building geometric descriptions, material thermal properties, and the characteristics of the systems installed in the buildings. The required geometric BIM data contain either: the solid geometric representations of architectural elements (walls, slabs, roofs, coverings, openings and others, illustrated in figure 2A), or their respective boundary surface topology (illustrated in figure 2B).

The boundary surface topology is the only geometric prerequisite of a simulation model generation process. If it is missing, it can be obtained from the solid geometric representations of the architectural elements via geometric operations as illustrated in figure 2 (from a set of architectural element solid representations (part A), the respective boundary surface topology (part B) is produced). The boundary surface topology consists of data belonging to three categories: (a) second-level space boundaries, (b) virtual space partitions and (c) shading surfaces. The second-level space boundaries (Bajzanac, 2010), are boundary surface pairs, through which thermal energy flows either among building spaces (internal space boundaries, green surfaces of figure 2B) or between a building space and its environment air/ground (external space boundaries, orange surfaces of figure 2B). Virtual space partitions are also boundary surface pairs, which separate virtually internal building spaces, without the use of a building construction (blue surfaces of figure 2B). Finally, shading surfaces, are boundary surfaces which play an indirect role in a thermal simulation by blocking sunlight.

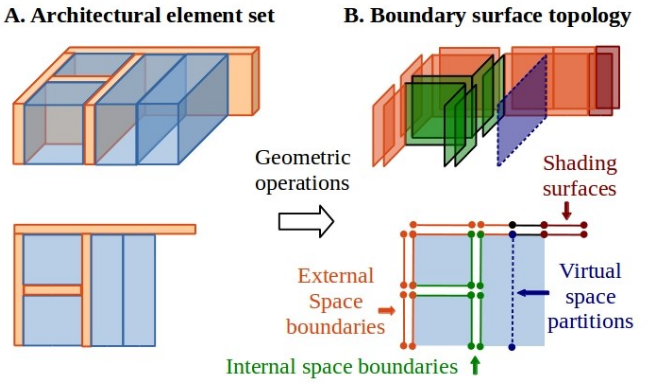


Figure 2: Boundary surface topology generation from its architectural element set.

The thermal properties of the material layers used in the building constructions, are also required for a simulation model generation, since they provides necessary information in order to determine thermal energy exchange among building spaces.

The properties of opaque constructions, refer to values of quantities related to every layer in the construction, such as: thickness, density, thermal conductivity and specific heat and others. If layer bedding information is not available, values of quantities referring to the whole construction, such as: total thermal mass and thermal resistance, have to be specified. For transparent constructions only quantity values referring to the overall construction, such as: the U-value and the solar transmission coefficient, are required to be specified as material properties.

Finally, the operation characteristics of energy consuming or self-sufficient devices installed in buildings which alter their internal thermal conditions, defined in a broad sense as systems, are BIM data, which are also required.

### 2.2 *GIS data*

Building simulation models in district environment, require data referring to the overall district which are not included in the BIMs and are defined as GIS data. Similarly to the BIM data types, there are three GIS data types, characterized as, geometric, material property and system data types. GIS geometric data contain descriptions of the district building envelopes as polygon surface sets. These polygons are used in neighbor building shading calculations. GIS material property data contain the reflectivity coefficients of neighbor building surfaces, used for solar calculations. Finally, GIS system data refer to characteristics of district-scale systems which may be present in the district servicing multiple buildings.

### 2.3 *Contextual data*

Finally simulation models require data, which cannot be classified as BIM-related or GIS-related data and are defined as Contextual data. These data can be classified into the following five data types:

- *Weather data i*nclude the values of weather quantities required for building thermal simulations, such as: Outside dry-bulb temperature and pressure and others, which are contained in weather files.
- *Schedules a*re vectors formed by a time series which contains values describing the presence of users (occupancy) and the operation of passive and active devices installed in the buildings.
- *Simulation parameters* are values assigned to specific parameters required in order for a simulation to be initiated, such as: warm up time, starting and ending time instances, time step and others.
- *Energy Prices* refer to the cost in monetary units of the energy use in the district.
- *Building Typologies* contain data values fixed for all buildings, based on their geographical location, use and other classification parameters (Vimmr, et. al., 2013). In case building data are not available for specific buildings, they can be inferred using building typologies.

## 3. DATA QUALITY

The required data classified as BIM, District and Contextual data are obtained either from CityGML and IFC data sources, or inserted manually. These data pass three stages of data quality checking operations, in order to be suitable for a simulation model generation. These operations include consistency, correctness and completeness checks and are explained analytically, in the following sections.

### 3.1 *Data consistency*

The first checking operation ensures that an inserted IFC model is consistent with the underlying CityGML model. Although BIM geometric data obtained from an IFC file, might be visually correct, they may be inconsistent with the CityGML geometric data, which are described in world coordinates. Such inconsistencies occur when the geometric definition of a building in IFC model appear slightly rotated or translated with respect to the CityGML shell geometric definition of the same building. The inserted IFC model is considered CityGML-consistent if all IFC architectural elements are located inside a single CityGML shell. In any other case an inconsistency is declared and is communicated back for correction.

### 3.2 *Data correctness*

Both IFC and CityGML data should be checked for correctness, before being used as inputs to the simulation model generation process. Incorrect data have many causes and the respective errors have different characteristics, as discussed next.

#### 3.2.1 *Error causes*

There are three different sources of the errors appearing in IFC and CityGML data files, which can be ordered, depending on their causes, as follows:

- *Scanning errors*. Some of the CityGML geometric data are generated from point clouds obtained from terrestrial or airborne scanning devices, which contain errors related to malefaction of these devices or incorrect geo-referencing of the obtained points.
- *Design errors.* Oftentimes IFC and CityGML files contain errors caused by incorrect design, where the designer specifies incorrectly an architectural element, or material property or system.
- *Exporter errors*. Finally there are cases where either the IFC or the CityGML exporters generate errors by populating incorrectly the data classes in the respective IFC and CityGML files.

#### 3.2.2 *Error classification*

Errors appearing in IFC and CityGML files can be classified, with respect to their characteristics, into the following two categories:

- *Missing data.* There are cases where the data in IFC or CityGML files are not complete. For example, certain data might be omitted from the specification of the material layer properties of a construction. This errors is characterized as missing data error.

- *Incorrect data.* Apart from the missing data type of errors there are cases where IFC or CtyGML data are incorrect. For example a solid geometric representations of architectural element, might be misplaced with respect to other element representations.

A more detailed investigation of the geometric errors encountered in IFC files, and correction techniques, can be found in (Lilis, et. al. 2015).

### 3.3 *Data completeness*

Finally the inserted IFC models are checked for completeness. More specifically, IFC data have to satisfy certain minimum data requirements expressed as a set of conditions, in order to be suitable for simulation model generation, which are:

- *Boundary conditions.* The boundary surfaces at which the buildings of the district are attached to the outside air and ground should be explicitly defined for every building.
- *Conditioned spaces.* The inserted IFC file should have at least one conditioned space volume, i.e. a building space which is going to be studied thermally.
- *Material properties and space boundaries*. Every second level space boundary surface pair, of the boundary surface topology of a building, related to either a thermal or an opening element should be connected semantically with a building construction characterized by a set of thermal properties.

Provided that the above conditions are satisfied, the simulation model generation process can be performed, as described in the following section.

## 4. SIMULATION MODEL GENERATION

The purpose of the simulation model generation process is the creation of an Energy Plus compatible input data file <*.idf$_b$>, referring to a building b, in a district setting, from its IFC file (IFC$_b$) and a CityGML file describing the geometry of the district. Both IFC$_b$ and CityGML data files are assumed to conform to the data quality rules described in previous sections.

Algorithmically, the simulation model generation process can be divided into three stages: (a) Data query from IFC$_b$ and CityGML data files, (b) Boundary Surface topology generation process where the boundary surface topology of building b, is generated and augmented with shading surfaces from neighbor buildings and (c) Input Data File generation where the augmented space boundary topology combined with the construction material property data, are used in order to produce a single input data file suitable for Energy Plus simulations. These stages are illustrated in figure 3 and explained in detail in the following sections.

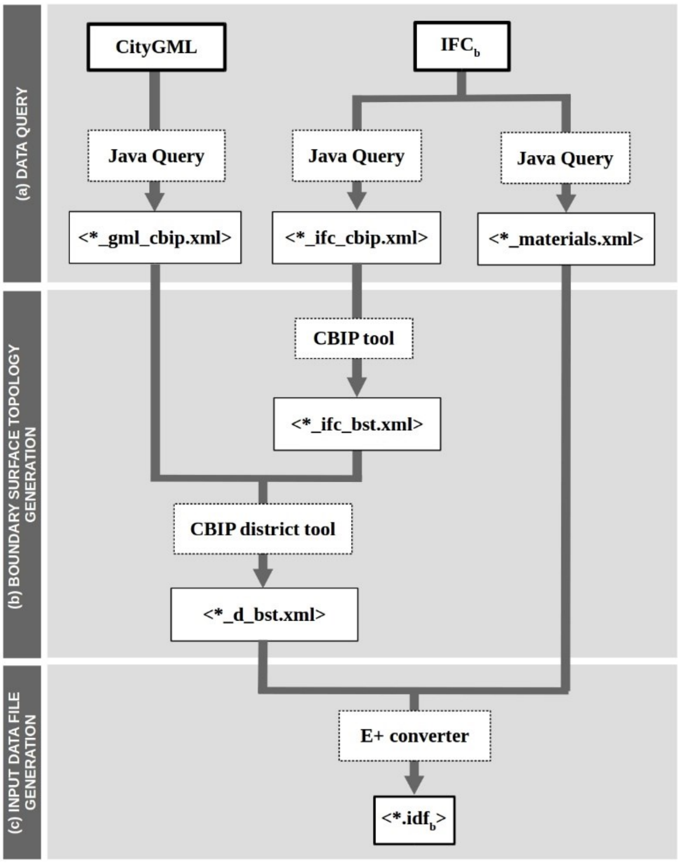


Figure 3: Overview of the simulation model generation process

### 4.1 *Data query*

The required data for the simulation model generation, of a single building in a district, are obtained from two different meta-models, which both are defined in a textual format, which are usually object-oriented and tend to be large. The most popular BIM meta-model is the IFC, which is based on the EXPRESS data model language and its schema is available in a STEP file. Additionally, the most common GIS meta-model is the CityGML, which is based on a XML data model language and its schema is defined by a set of XSD files. Because the proposed query components have been written in Java, which is an object-oriented language, it is useful to have on-memory the populated Java objects. In order to achieve this functionality, third-party frameworks have been chosen: for the conversion of the IFC schema the Eclipse Modeling Framework (EMF) was used and for the CityGML schema, the Java Architecture for XML Binding (JAXB) was chosen. Specifically, in the case of IFC schema the BuildingSMART library, which is a part of the BIM Server project, has been used for the automated generation of certain Java classes. On the other hand, in the case of CityGML schema the Reference Implementation (RI) of JAXB, which is a part of the GlassFish project has been used. As mentioned before, these classes are used to store on-memory BIM and GIS models and pass them to the proposed components for further manipulation. Both IFC query and CityGML data queries are described next.

As far as the CityGML query process is concerned, only geometric surface descriptions contained in the CityGML file, which refer to the district building envelopes, are queried while any appearance related data structures are omitted. Additionally, elements not related to building envelope surfaces (transportation objects, vegetation objects and others), were not taken into account. The coordinates of the points of the building envelope surfaces, were gathered and used to populate appropriate data structures in the <*_gml_cbip.xml> data file (figure 3). Apart from the geometric content of the envelope surfaces, the semantics of these surfaces classifying them as either: wall, ground or roof surface, were gathered as well in order to be used for future reference.

Regarding IFC data, two data types are queried: geometric data and material property data. The geometric data refer to characteristics of geometric solid representations of architectural elements contained in the IFC file, such as the extruded area solid, the manifold and the faceted boundary representation. Each architectural element and the characteristics of its solid geometric representation, are written in the output <*_ifc_cbip.xml> file, which is used as an input file to the boundary surface topology generation process described in section 4.2. Regarding the material property data, certain thermal property values contained in the IFC file are queried, referring to building constructions and their respective layer bedding, as mentioned in section 2.1. These properties are written in file <*_materials.xml>, which according to the process diagram of figure 3, is used as input, to the input data file generation process described in section 4.3.

### 4.2 *Boundary surface topology generation*

Sometimes, although IFC files contain the necessary structures to support the geometric data requirements of a simulation model generation process, the geometric data of IFC files referring to the boundary surface topology of buildings, are incorrect, or they are missing. In such cases the generation of the boundary surface topology of building is required, and is performed using the Common Boundary Intersection Projection Algorithm (CBIP) (Lilis, G. N., et. al., 2014). In a nutshell, CBIP receives as input the geometric solid descriptions of architectural building elements and performs the necessary geometric operations, illustrated in figure 2, in order to generate the boundary surface set of a building described in section 2.1. Additionally, apart from the boundary surface topology geometric data requirements referring to a single building, shading surfaces of neighbor buildings must also be determined. CBIP process is extended in order to include such surfaces, as described next.

Algorithmically, the boundary surface topology generation process in a district environment (illustrated by the process block (b) in figure 3), includes two stages. In the first stage CBIP is used in order to transform the queried IFC architectural geometric data of the building, contained in xml file <*_ifc_cbip.xml>, into an intermediate xml data file containing the boundary surface topology data of the building <*_ifc_bst.xml>. In the second stage the district component of CBIP augments the generated <*_ifc_bst.xml> file from the first step, by including the neighbor shading building surfaces from the data queried from the CityGML file, contained in <*_gml_cbip.xml>, and generates a new xml data file containing the boundary surface topology of the building in the district environment <*_d_bst.xml>.

### 4.3 *Input data file generation*

In EnergyPlus, input data are defined by two ASCII (text) files: the Input DataDictionary (IDD) and the Input Data File (IDF). The IDD file contains, all possible EnergyPlus classes and descriptions of their properties. Each version of EnergyPlus has a different IDD file. The IDF file consists of all the necessary data to properly define a thermal simulation model of a certain building, described using appropriate IDD classes.

The input data file generation process aims at creating an IDF file from boundary surface topology data of a building in a district setting, contained in <*_d_bst.xml> file and material thermal property data, contained in <*_materials.xml> file, as illustrated in the process block (c) in figure 3. This process is developed using MATLAB programing environment and includes two stages: in the first stage, a MATLAB script has been developed that identifies the version of the IDF file (<*.idf> file), parses the appropriate IDD file (<*.idd> file) and creates a library (MatlabIDDxx, where xx is the EnergyPlus version) of MATLAB classes, corresponding to EnergyPlus classes; in the second stage, the generated MATLAB classes are populated based on the geometric and material data contained in <*_d_bst.xml> and <*_materials.xml> files, and exported into a final input data file (<*.idf> file).

This input data file generation process, referring to a single building, conforms to certain transformation rules described thoroughly in (Giannakis, 2015). In summary, certain IDD classes are populated from data obtained from: (a) CBIP’s xml geometric output and contained in <*_ifc_bst.xml> file (figure 3) and (b) material properties queried from the IFC file contained in <*_materials.xml> file (figure 3). From CBIP’s geometric output the classes Zone, Building

Surface:Detailed and FenestrationSurface:Detailed are populated, while the classes Construction, Material and WindowMaterial:SimpleGlazing System are populated from the material property file.

Geometric data referring to neighbor buildings, which are queried from the CityGML file and added to the <*_ifc_bst.xml> file, via the CBIP's district tool, generating the final boundary surface topology file <*_d_bst.xml> of the building in a district environment (illustrated in figure 3). These geometric data, are used to populate the IDD class Shading:Building:Detailed in the final IDF file.

## 5. EXAMPLE

The proposed simulation model generation process is demonstrated on a residential district, which is a part of Santiago de Compostela city in Spain, displayed in Figure 4A. The chosen LoD2 CityGML model of the district consists of 65 building envelopes out of which one was selected (indicated in Figure 4B), in order to be replaced by a more detailed IFC building model geometric representation.

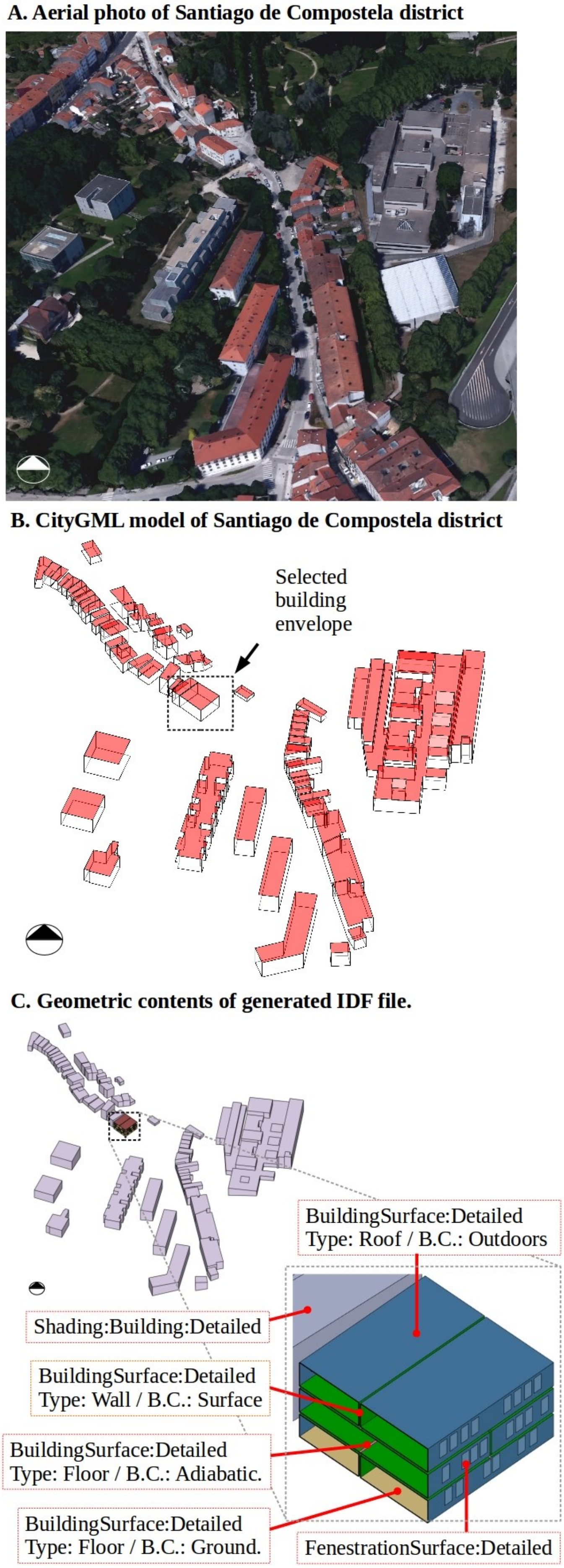
A single IDF file was obtained following the stages of the described simulation model generation process. The geometric content of the generated IDF is displayed in figure 4C, where different colors are used, in order to highlight the characteristics of the different surfaces contained in the IDF file (blue color is used to display external space boundaries. green color is used for internal space boundaries, purple for neighbor building shading surfaces and yellow for site boundaries). Although all neighbor district building shading surfaces were considered here as a proof of concept, algorithms selecting the ones which have considerable impact to the building simulation, using proximity criteria, will developed in the future.

## 6. FUTURE WORK

### 6.1 *Energy Data Model*

Although the simulation generation process mentioned earlier, is automated for geometry and material thermal property input data, building system characteristics have not yet included in this process as input data. The versatility of such input data, highlights the need for integrating all these diverse data sources under a common data model.

A suitable data model towards this direction, which provides the necessary input data structures for the Energy Plus simulation program, is the SimModel (O'Donnell, 2011). SimModel is an xml-based data scheme, which although is designed to support building-scale simulation models, it does not contain district-related data structures.


**A. Aerial photo of Santiago de Compostela district**

**B. CityGML model of Santiago de Compostela district**

**C. Geometric contents of generated IDF file.**

Figure 4: (A) Aerial photo of Santiago de Compostela district (B) CityGML model geometric representation, (C) Geometric content of the generated IDF file (B.C.: Boundary Condition).

Consequently, in order to integrate the input data of a district environment, an extension to the current SimModel schema, is viewed as a potential future work path. This extension will be used to populate a new Energy Data Model, as illustrated in figure 6 with a dashed rectangle. Furthermore, according to figure 6, the Energy Data Model (EDM), is visualized as a subset of a District Data Model (DDM), which will be a central functional component of OptEEmAL platform (Izkara, J. L., et al. 2016), designed to provide the necessary data to support, one (for the whole district), or multiple (for every building) simulations. Additionally, in order to provide interoperability links to other simulation programs an ontology based structure of the DDM is visualized, as described in the following section.

## 6.2 Ontology-based district data model design

Data integration based on ontologies can be useful to effectively combine data from multiple heterogeneous data sources (Wache, 2001). This way, by means of ontologies it is possible to integrate data from different sources when there is an ontology that represent them. When these data sources are based on open standards, such as CityGML and IFC, is easier to carry out this integration since there are ontologies already implemented that can be reused. In this context, ontologies are useful to facilitate data linking between different data models.

The use of ontologies to integrate information to an energy domain is not new. For example, this approach was applied in SEMANCO project at the urban level, multi-scale analysis of carbon reduction problems and integration of GIS (Sicilia, et. al., 2014). In the case of OptEEmAL platform, input data from IFC, CityGML files and contextual data can be transformed into RDF according to existing domain ontologies such as ifcOWL. Thereby, the District Data Model can be redefined as an ontology-based framework where the role of ontologies is to facilitate the integration of these three input data sources. In this framework, the EDM is based on a version of the SimModel in OWL (SimModelOWL). The EDM is populated through an ETL process taking data from the different ontologies of the DDM, as illustrated in Figure 6.

To carry out this ETL process, the DDM ontologies has to be aligned to SimModelOWL using ontology matching methods. For example, ifcOWL is aligned with SimModelOWL. Then, the RDF data derived from the input sources can be transformed according to the EDM structure. Since the data in the DDM is already in RDF, it becomes a problem of RDF reshaping.

This ontological approach also facilitates that integration of new simulation tools. The generation of energy simulation models for such tools is a matter of aligning the EDM –which contains all the parameters needed to carry out a detailed energy simulation– with the input model of such tool. This approach would also be extrapolated to other data model for other kinds of simulations such as cost analysis.

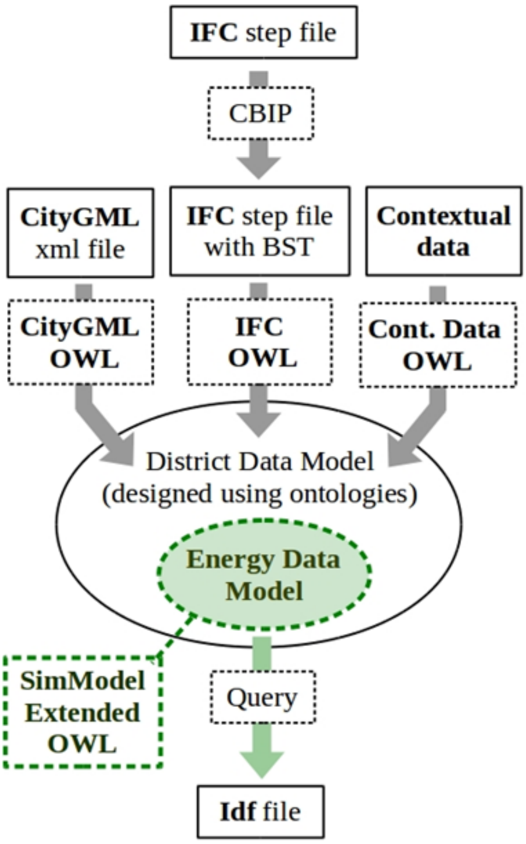


Figure 5: Illustration of the inclusion of an ontology-based District Data Model into the current simulation generation process (BST: Boundary Surface Topology).

## 6.3 CBIP as an IFC data completeness tool

The ontological structure of the energy data model, described earlier, will enable CBIP to be used as an IFC data completeness tool and not as a part of the simulation model generation process. Such use is supported by the fact that CBIP's output, the boundary surface topology (second-level space boundaries, virtual space partitions, shading surfaces), can be adequately described by *IfcRelSpaceBoundary2ndLevel* and *IfcShading Device*, IFC data classes. Therefore CBIP's operation can be a part of the IFC data completeness process before the DDM formation. During this process IFC data are enriched by the boundary surface topology, obtained by CBIP. After the IFC data being enriched, they can be transformed to RDF using the ifcOWL ontologies and become a part of the DDM. A visualization of CBIP's independent operation as data completeness tool is displayed in figure 6.

## 7. CONCLUSIONS

A semi-automated simulation model generation process capable of forming input data files suitable for Energy Plus calculations in a district environment, combining data from IFC and CityGML files, was presented. This process is a part of the European research project OptEEmAL, which aims at selecting the best according to certain performance measures, district retrofitting solution. Consistency, correctness and completeness data quality rules, for both IFC and CityGML input data files, were also discussed. Provided that these data quality conditions are met, the three stages of the proposed simulation model generation process, were described in detail. The overall process was demonstrated successfully, on a selected building defined by an IFC file, in a demo district described by a CityGML file.

Future improvements of the process related to the organization of its input data using ontologies into an energy data model, and to the use of the process' boundary surface topology generation tool, as an IFC data completeness tool, were also discussed.

Conclusively, there are certain key concepts and challenges which have to be addressed, arising from the proposed process, which include: the need for establishing data quality validation processes, which will ensure consistency, correctness and completeness of the available input data; the use of mechanisms for automating the query of input data from other sources (apart from BIM and GIS), such as weather data should also be included; and finally the possibility of creating links of CBIP's geometric output to other simulation tools, should also be examined.

## 8. ACKNOWLEDGEMENTS

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