A comprehensive ontologies-based framework to support retrofitting design of energy-efficient districts

G. Costa & Á. Sicilia
ARC, La Salle Engineering and Architecture, Ramon Llull University, Barcelona, Spain

G.N. Lilis & D.V. Rovas
Department of Production Engineering and Management, Technical University of Crete, Chania, Greece

J. Izkara
Construction unit, Tecnalia Research & Innovation, Bizkaia, Spain

ABSTRACT: One of the challenges for the European construction sector as a part of the Europe 2020 strategy is to reduce the energy footprint and CO_2 emissions related to new and renovated buildings, an interest that is also fostered at district scale requiring new technological solutions to be more efficient in this design. In response to this challenge, a web-based platform for district energy-efficient retrofitting design projects has been proposed in the context of OptEEmAL research project. In order to provide data integration and interoperability between BIM/GIS models and energy simulation tools through this platform, a District Data Model (DDM) has been devised. This way, representations of CityGML and IFC schemes semantically enriched are related in this model to existing ontologies in the main fields for urban sustainable regeneration (energy, social, environment, comfort, urban morphology and economic). This paper discusses some approaches about how consistency integration of geometry and the semantic representation from IFC and CityGML files with different levels of detail can be achieved in a district data model.

1 INTRODUCTION

Energy efficiency is a fundamental part of Europe 2020 strategy to reduce the energy footprint and CO2 emissions related to new and renovated buildings. To help achieve this aim, the optimized, integrated and systemic design of energy efficient retrofitted buildings is also fostered at district scale. To be more efficient in this design, new technological solutions to carry out different types of simulations through comprehensive tools are necessary to assess the impact of different actions through a holistic approach. In this approach, these tools should be able to integrate the different data required to perform these simulations including GIS, BIM, energy, economic, weather, monitoring, social, targets, etc.

One way to assess the impact on energy efficiency of buildings is by applying energy conservation measures according to the needs of the project and compare the results. On the basis of this approach has been developed an "Optimised Energy Efficient Design Platform for refurbishment at district level" in the context of OptEEmAL project. This paper presents the project's vision, lines and general approach proposed to support the retrofitting design in the simulation terms described above.

The paper is structured as follows: after a brief justification of the need to apply energy efficient district retrofitting actions at district level in the current section, the OptEEmAL platform is introduced in Section 2, as a candidate solution addressing this need, which uses an ontology-based approach to facilitate district data integration and promote interoperability with multiple simulation tools. The three essential components of this platform: (a) Energy Conservation Measures Catalogue, (b) District Data Model, and the (c) Simulation Manager, are also introduced in Section 2. The role of ontologies to facilitate the integration of different data models and tools is reviewed in Section 3 in order to provide the theoretical base to explain how the DDM provides the intertwining of standard data models (e.g., CityGML, IFC) with ontologies in domains related with sustainable regeneration (energy, social, environment, comfort, urban morphology and economic), which is described in Section 4. Conclusions and discussion on ongoing research in the OptEEmAL project is provided in the last section of this paper.

1.1 *Energy efficient retrofitting at district level*

There are several factors which can play a role in the decision-making process and explain the reasons why a district can be retrofitted, for example, those related to improve the quality of the inhabitants, the use of spaces, the economic dynamism of the areas, or reduce pockets of poverty, among other causes. These factors are not only related to energy consumption, but also with social or economic aspects to be considered to reach cost-effective solutions and more sustainable developments. Based on these factors, different actions can be taken in the definition of a district retrofitting plan. However, this often requires stakeholders to make complex decisions through the use of different tools and where the objective parameters have to be brought to light and investigated through specific technical studies. To overcome these drawbacks and to better support the design of district retrofitting plans and strategies through a holistic approach, solutions able to integrate stakeholders, tools and all relevant information about retrofitting in a single framework; such solutions seem to be missing.

The management and conservation of urban districts requires an approach that considers each of the buildings and other city elements as forming part of an environment that should be conserved, brought up-to-date and showcased. This approach requires the integration of Geographic Information Systems (GIS) and Building Information Models (BIM), while at the same time bearing in mind the particular nature of urban districts (Döllner & Hagedorn 2007).

On the other hand, when the retrofitting is addressed at district scale the complexity of decision making grows exponentially due to the great number of factors to be considered (e.g. economic, social, technical), the interactions between them, and the number of stakeholders involved in the decision. Consequently, there is a need for an interactive and user-friendly decision support tool that enables analysis of the impact of the building energy oriented retrofitting project on the sustainability of the urban district in a holistic way, facilitating the necessary communication mechanisms that can forge agreement between the multiple stakeholders that are involved in this process (Romero et al. 2014).

2 OPTEEMAL PROJECT

2.1 *Context and purpose*

In order to respond to the need for innovative design tools for refurbishment at building and district level, a development of a platform has been proposed in the context of OptEEmAL project with the aim of delivering an optimized, integrated and systematic design for building and district retrofitting projects. Based on given initial district conditions, the platform provides the necessary information to simulation tools according to multiple candidate energy conservation measures (ECM). This information includes buildings, urban areas, weather, sensors, etc., and project conditions (costs, barriers, targets, etc.). Through a comparison of the respective simulation results, the platform identifies the most suitable energy conservation measure, which achieves a desired reduction of the district energy demand and consumption under certain constraints. By selecting the best case, the design is updated according to the measures implemented to obtain an enhanced version which can be returned to the BIM authoring tools.

District and building scales have been addressed separately but they both are very much connected in the process of energy efficient retrofitting of districts. Strategic decisions — such as prioritization of areas to retrofit and implementation of district heating — are taken at district scale, while executive decisions are mainly addressed at building level. Urban scale and the influence and restrictions imposed by urban environment in the building retrofitting should be taken into consideration at initial stages of the retrofitting process (e.g. feasibility studies and conceptual design). In early stages of an energy retrofitting process, administrations and managers are mainly involved and the level of detail of the information required is low. In later stages of the process (e.g. design or implementation of the interventions) a detailed description of building components and their characteristics are required. Main stakeholders in these steps are architects and constructors, and decisions to be taken are focused on the building level, even more on component level. In this context, it is critical to identify solutions able to cover the need for the connection between the strategic scale (urban) and the executive scale (building), through the definition of a common, multi-scale and interoperable data model which contains geometric and semantic information required for the management and decision making in the district retrofitting.

2.2 *Platform components*

The OptEEmAL platform is composed of three main components in order to provide services for current situation diagnosis, retrofitting scenarios generation, evaluation and optimization and data export. These components are (1) an integrated ontology-based District Data Model (DDM) that is connected to a (2) catalogue of Energy Conservation Measures (ECMs) and which is accessed by a (3) simulation manager that is responsible to generate specific simulation models for each tool required (figure 1).

The DDM is the central component of the platform and has been conceived as a comprehensive ontologies-based framework for district information representation based on the intertwining of standard data models (e.g., CityGML, IFC) with ontologies in domains related with sustainable regeneration (energy, social, environment, comfort, urban morphology and economic). The DDM provides a semantically integrated data model (including information about the geometry, materials, equipment, and indicators, at the building and urban scales) that the platform needs to carry out retrofitting processes.

Energy conservation measures (ECM) both at the building and district level, are contained in an ECM catalogue. These measures contain key information to generate applicable scenarios, but also to overcoming the existing barriers in the district and being compliant with user objectives in terms of efficiency improvement, cost constraints, financial schemes, etc. The catalogue includes a wide range of measures to reduce the district energy demand and consumption through passive, active, local Renewable Energy Sources (RES) integration and control strategies measures.

The simulation manager implements different calculation methodologies that are necessary to generate simulation models. These models include the necessary information to be processed by external tools (e.g. EnergyPlus). From the results of the simulation tools, District Performance Indicators (DPIs) are computed. In summary, the simulation manager calculates the DPIs referring to (a) the baseline scenario to diagnose the current status of the district, and (b) from the retrofitting scenarios generated by applying different energy conservation measures. Once the DPIs are calculated according to possible optimized designs, they are compared with those calculated in the baseline design in order to assess the level of improvement in the energy performance.

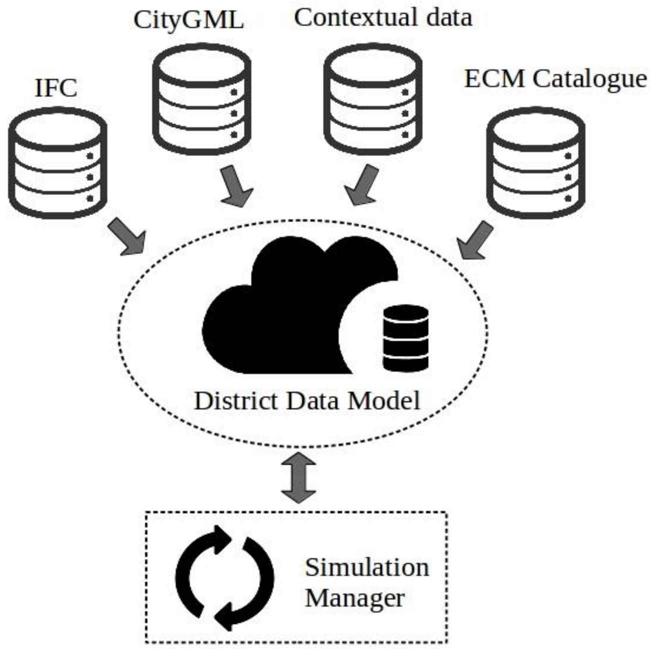

Figure 1. Overview of the architecture platform outlined in OptEEmAL project.

2.3 *Performance evaluation*

DPIs are defined in order to assess the impact of the measures contained in the ECM catalogue using different performance criteria, which include energy demand, consumption, cost and others. In this way the selected scenarios not only conform to a number of different performance constraints but also achieve desired performance values. Some of the DPIs require complex calculations while others are obtained by simple operations using other DPIs. DPIs requiring complex operations are evaluated through building simulations. In order to evaluate these DPIs in an automated manner and assess different retrofitting scenarios in a relatively short time, an automated simulation model generation process is established, using data across different time and space scales.

2.4 *Data requirements*

The required data of the OptEEmAL platform can be classified using space and time criteria. Using a spatial differentiation these data can be distinguished into (a) BIM and (b) district data. BIM data refer to each building individually and contain information regarding its geometric description, the materials of its constructions and the passive or active devices which may be present in its interior spaces. District data are related to building groups and include geometric description of multiple building envelopes, and district level systems, serving multiple buildings, such as district heating.

Using time criteria, the required data can be classified into: (a) static data, which remain unchanged during simulation executions such as building geometric data, and construction material data, and (b) dynamic data which change during simulation executions such as the operation schedules of building devices.

Managing the above plethora of different data appears to be a challenging issue for the automation of the simulation model generation process performed by the simulation manager. This automation involves careful selection of subsets of the above data sets based on the requirements and the characteristics of each individual simulation. Two general simulation cases can be distinguished: 1. District-scale simulations performed by CitySim where the district data are required, and 2. Building-scale simulations performed by EnergyPlus where both district and building-scale data must be taken into account. To cover both simulation types IFC, CityGML and Contextual data are required, as described next.

2.5 *Input data sources: IFC, CityGML and Contextual data*

Some of the data required for the population of DDM are coming from a variety of existing data structures such as the widely used IFC and CityGML schemas and some —not contained in the previous schemas— are inserted manually, characterized as contextual data. IFC is a popular data schema adopted by the AEC industry as a standard (ISO 16739 2013) to describe a variety of building entities including architectural, structural and mechanical components. In the context of the present work data from the architectural section of IFC are required to describe the geometry of the buildings and the properties of building materials and information from the mechanical part will be used to describe the installed systems in the buildings.

District-level data are collected from CityGML data structures. These include mostly geometric data of the building envelopes and also the geometric representation of other urban elements (e.g. green areas, roads, city furniture). These other urban element data, will play an indirect role in building simulations as shading surfaces and will not be a part of any retrofitting scenario. These data will either augment each individual building simulation models in order to perform better shading calculations by including additional neighbor shading objects or will provide the necessary geometric input of district-scale simulation models suitable for CitySim.

IFC and CityGML structures do not provide all the necessary data for simulation model generation. Missing data appear in both building and district contexts and are characterized as contextual data. These include: weather data, operation schedules of devices and inhabitants, simulation parameters, energy prices and building typologies (Vimmr et al. 2013).

Each individual data component before being inserted in the DDM should pass three checking stages: correctness, completeness and consistency. During the correction stage the inserted data are checked for compliance to certain correctness rules. Towards this direction, error detection and correction mechanisms, such as the ones developed for the geometric data of IFC files (Lilis et al. 2015), can be used in order to guarantee data correctness in DDM. Similarly, during the completeness stage, the data inserted in the DDM are checked against certain completeness rules. For example, completeness rules are defined by the minimum data requirements for simulation model generation. In case any of these requirements is not satisfied, a completeness error is reported. Finally, at the consistency stage, the inserted data structures are checked for compatibility to other existing DDM data structures. For example, an inserted IFC BIM model should be correctly placed (location/orientation) with respect to an existing three dimensional CityGML geometric context. Any inconsistency is also reported for correction.

3 USE OF ONTOLOGIES TO INTEGRATE DATA MODELS AND TOOLS

3.1 *Implementation scenarios for data integration*

Several European initiatives and guidelines consider data models of vital importance for improving the energy performance of buildings information (e.g. EeB[1], ECTP[2]) and try to establish a common geospatial information infrastructure at European Level (e.g. INSPIRE[3]), coming to the conclusion that a better understanding of the urban system is necessary in order to achieve sustainable development goals for cities (e.g. EPIC[4], SEMCITY[5]). Accurate 3D urban models are an important tool for a better understanding of urban systems and thus for sustainable urban development. The solution, based on 3D digital models, has grown in importance over recent years as it offers complete support which is easily brought up-to-date, allowing information storage and visualization on an urban scale (Mao & Ban 2011).

There are international standards for the management of data related with construction processes based on BIM (Building Information Modelling) and GIS (Geospatial Information System). At building level, data models based on XML facilitate the validation and exchange between Computer-Aided Design applications or energy assessment tools (gbXML, Architecture Engineering and Construction XML, Building Information Model XML, Industry Foundation Classes XML, etc.). At urban or city scale GML and KML are the most used data formats for 3D representation. However both can store geometry but are not designed to store semantic information. At building scale, the problems are similar, CAD tools used to work with lines and polygons and the semantic information available was almost zero. When the BIM concept appeared and Industry Foundation Classes (IFC) implemented the international open standard for BIM (Succar 2009), a significant step forward has been made in the semantization of the building scale model. A multi-scale data model that integrates both scales is CityGML. The aim of the development of CityGML was to reach a common definition and understanding of the basic entities, attributes, and relations within a 3D city model (Kolbe 2009). What is especially important, since it allows the reuse of the same data in different fields of application (Gröger & Plümer 2012). It has been designed to store both types of information, allows storing 3D information, considering both urban scale and building level. CityGML is a standard widely used in Europe (most of the German cities have a CityGML model at least at its lowest level of detail (LoD1), some of them with highest level. Berlin has one of the most advanced CityGML model, Dutch 3D standard IMGeo is a CityGML ADE, etc.).

Combining domain specific information with data models for the construction sector is a task being addressed through different approaches. Urban energy tool developers at city level (e.g. CitySim, NEST) have developed their own tailor made urban information. Extension of existing standard data models for construction sector (e.g. IFC, CityGML) in order

[1]http://ec.europa.eu/research/industrial_technologies/energy-efficient-buildings_en.html

[2]http://www.ectp.org

[3]http://inspire.ec.europa.eu

[4]http://www.semcity.net/cms

[5]http://www.epic-cities.eu

to complete them with domain specific information has been mainly addressed through the use of extension mechanism defined for existing data models (e.g. ADEs for CityGML). This approach allows storing relevant domain specific data in a common open city data model, used to perform domain specific simulation. However, the interoperability of the data model is reduced when the extension is implemented and the extension is tailored to the data model. The use of ontologies and vocabularies for the conceptualization of scenarios allows representing data from different domains in order to carry out holistic analysis. Multiple domains, scales, and levels of detail have to be modelled such as urban renovation projects (Crapo et al. 2011, Sicilia et al., 2014), this is particularly important in the necessary definition of scenarios.

3.2 *Semantic-based interoperability*

Semantic interoperability solutions are based on providing a shared understanding of the meaning associated to the data from different sources and domains in order to facilitate the exchange across networked information systems. The meaning can be provided through ontologies and making explicit the semantics of data through formal languages. Ontologies specified in OWL (Ontology Web Language) allow the specification of a description logic based formal structure to RDF graphs. If an ontology in OWL is instantiated in an RDF graph, generic queries and reasoning engines are able to easily reuse the data of this graph.

Semantic-based solutions can be applied to integrate data from different data models including IFC, CityGML and data from other sources such as cadastre, climate, consumption of buildings, and others. Semantic-based interoperability using Semantic Web technologies is a reasonable technological solution to integrate data from multiple heterogeneous sources and to ensure the communication between the integrated data and an open set of tools. The use of semantic technologies to enhance IFC and CityGML has already been explored in some research works (Laat & Berlo 2011, Amirebrahimi et al. 2015, and others).

3.3 *Data integration and transformation process in OptEEmAL*

The goal of the data integration and transformation process in the OptEEmAL platform is to populate the District Data Model with different input data models provided by an end-user (Figure 2). In the first step of the process, the data models are transformed into semantic data models by means of ontologies which define the particular domain of the input data. Then, in between the semantic data models and the simulation tools, there are the simulation data models which are ontology-based models to represent a simulation domain such as energy and economic. The simulation data models are generic enough and are representative in order to feed different simulation tools. From the simulation data models are derived the final simulation models which are particular from each simulation tool. For example, the simulation model of EnergyPlus is the input data files (IDF). For NEST (Neighborhood Evaluation for Sustainable Territories)[6], which is a tool for Life Cycle Assessment (LCA) calculation, the input data file is a proprietary format. For CitySIM[7], which is an urban performance simulation engine, the input data file is a XML.

In the DDM, the semantic data models and simulation data models must be represented by ontologies that define the particular domain of the models. This is needed (1) to carry out the transformation of input data to a specific semantic domain, and (2) to provide a representation in RDF format in order to facilitate their querying through SPARQL. Queries in this language enable to retrieve data to generate simulation models in a flexible way.

Since ontologies are required to represent the input data (IFC, CityGML and contextual data) in RDF in order to facilitate their integration into simulation data models such as the EDM (Energy Data Model).

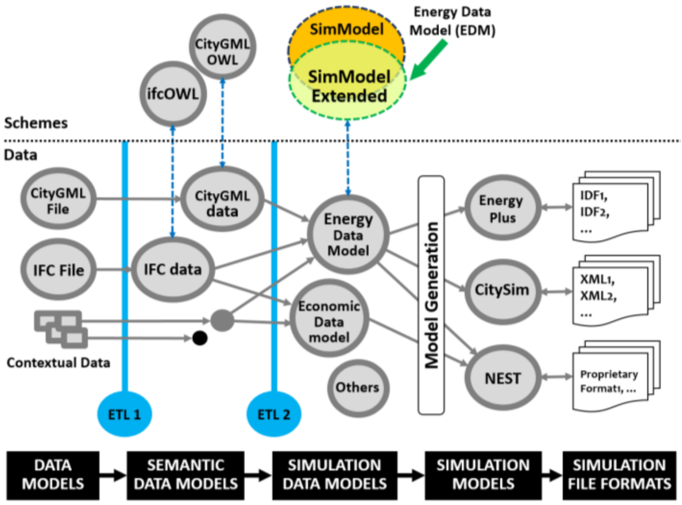

Figure 2. Overview of the data integration and transformation process in OptEEmAL platform. In this figure the process is exemplified for the case of EDM, EnergyPlus and CitySim tools.

Different prototypes of ontologies in these domains have been developed in the last decade in order to provide their representation as semantic data. For example, Katranuschkov et al. (2003) created an ontological framework as part of an extensible and open architecture to access data in IFC format. More recently, and as a result of some research projects (Schevers & Drogemuller 2005, Beetz 2009, Pauwels & Terkaj 2016), IFC is now available as an ontology (ifcOWL) with the support of the Build-

[6] http://www.nobatek-nest.com

[7] http://citysim.epfl.ch

ingSMART. The ifcOWL ontology enables extensions towards other structured data sets using semantic web technologies (buildingSMART 2015). Regarding CityGML, Métral et al. (2010) presented various approaches based on the use of ontologies to improve the interoperability between 3D urban models. This helped to demonstrate that ontologies can overcome the semantic limitations in CityGML data models.

In the energy domain, SimModel is the prime example of simulation data model (O'Donnell 2011). It is an xml-based data scheme designed to support building-scale simulation models which has an OWL version (Pauwels, 2014). SimModel does not contain district-related data structures. Therefore, to integrate district data an extension can be developed. Since, simulation data models — such as SimModel — are represented by means of ontologies, they can be easily extended.

The data integration and transformation process in OptEEmAL is based on three steps:

- ETL1: between data models and semantic data models. This is a transformation from raw data sources stored in CSV files, relational databases, XML, Json, etc., to RDF. In the Semantic Web community exists several technological solutions to deal with this kind of sources such as relational-to-RDF translators (e.g., morph-RDB) and mapping languages (e.g., R2RML).
- ETL2: between semantic data models and simulation data models. This is a transformation from a RDF graph to another RDF graph with a different structure defined by simulation data models (e.g., SimModel).
- Model generation: between simulation data models and simulation models. This transformation has to be created ad-hoc for each simulation tool using SPARQL queries.

4 DISTRICT DATA MODEL (DDM)

4.1 *Data integration process to generate simulation models*

The approach adopted in the OptEEmAL platform in order to assess the performance of district retrofitting scenarios, through calculation of different types of DPIs, is divided into four stages: (1) input data quality checking, (2) transformation of input data to OWL/RDF input data (structured according to semantic data models: CityGML OWL, IFC OWL, Contextual Data OWL and ECM data OWL), (3) conversion of OWL/RDF input data to OWL/RDF simulation data models (structured according to semantic data models: SimModel Extended OWL and Other Simulation Domains OWL), and (4) generation of simulation models, as illustrated in Figure 3. This section shows the role played by the DDM in this process to ensure the interoperability between simulation data models and tools, and showing its relation with the rest of the platform components previously introduced.

The process starts with the entry of project data by users of the platform (a CityGML model and different IFC models (noted as IFC_b), but also other data such as socio-economic, sensors monitoring, energy prices and weather). Input data is checked in this first part of the process to verify its correctness, completeness and consistency checking, as described in section 2.5. Since the information provided in the IFC files cannot be used directly as inputs to energy simulation programs as they require further processing related to the generation of the second-level space boundary geometric topology, a converter is used to made this transformation of these IFC files into a Boundary Surface Topology (BST) (Lilis et al. 2016).

In a second step, the input data from CityGML and IFC files are transformed into data described in OWL and RDF languages, according to ontologies that correspond with versions of these standards, and ontologies from other domains related with sustainable regeneration (energy, social, environment, comfort, urban morphology and economic). Through a mapping between ontologies it is possible to perform ETL (Extract, Transform and Load) processes in which the data defined in each of the input domains are transformed to different simulation data models. When the data are defined in the domain of a simulation data model, measures from the ECM Catalogue can be applied as new data aggregated, for example, in as new properties of elements and materials. Information described in the simulation data models (e.g. EDM) is queried through SPARQL queries to generate the simulation models in the last step of this process, which are generated according to each specific tool (EnergyPlus, SimCity, NEST, etc.).

The two following sections show in more detail how the simulation models are generated and how the type of definition of the input data provided is related to different levels of accuracy for the calculation of the DPIs using a methodology.

4.2 *Simulation data models*

The simulation programs which will be used for DPI evaluation (EnergyPlus, CitySim, NEST) require different forms of input data populating different simulation data models. Furthermore, depending on the data availability, different calculation methodologies can be established using the same simulation tool. As a result, multiple simulation data models can be formed, using different queries as part of the ETL process mentioned earlier, depending on the selected simulation tool and calculation methodology (as highlighted in figure 3, step 3).

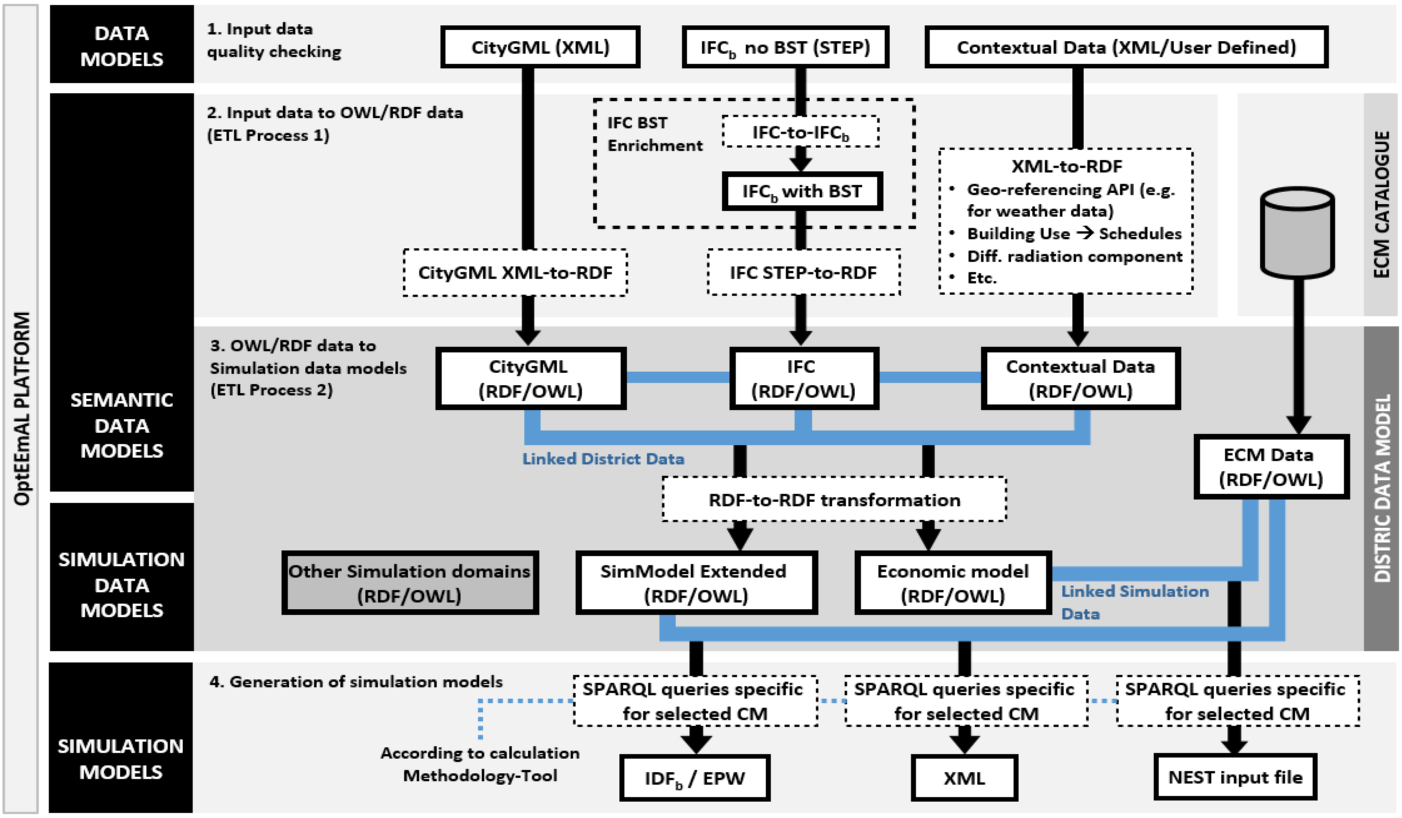

Figure 3. Data flow of the process to generate simulation models.

In EnergyPlus input data must be structured using different classes defined, depending on the version of the program, in an input data dictionary file (*.idd file). Based on the data class descriptions contained in the IDD file, a single input data file (*.idf file) will be generated by the simulation manager for each selected retrofitting scenario and calculation methodology.

Similarly in CitySim, inputs are structured in an xml file format according to a predefined XSD schema. Again here, this XML file will be populated based on the selected scenario of and calculation methodology.

Finally, the interface of OptEEmAL platform with the NEST tool and the related NEST input file data format, remains as a future work.is a future work direction.

4.3 *Calculation methodologies*

Sophisticated simulation tools such as EnergyPlus, accept different representations in multiple input data types (DTs). For example the building construction, input data type, may have two descriptions, a detailed multi-layer description where the properties of each material layer are defined, or an equivalent single layer description. Such variability in the accuracy of the description of the input DTs, generate multiple simulation execution possibilities, defined as calculation methodologies (CMs), for every simulation tool (ST). The expected accuracy of the DPI evaluation of each CM, varies as well, as illustrated in figure 3. Consequently for each refurbishment scenario and simulation tool, a finite number of calculation methodologies (CM) can be established, depending on the number of possible combinations of the input data type descriptions. Each CM is defined by a unique combination of input data type descriptions, highlighted by the solid arrow in figure 4.

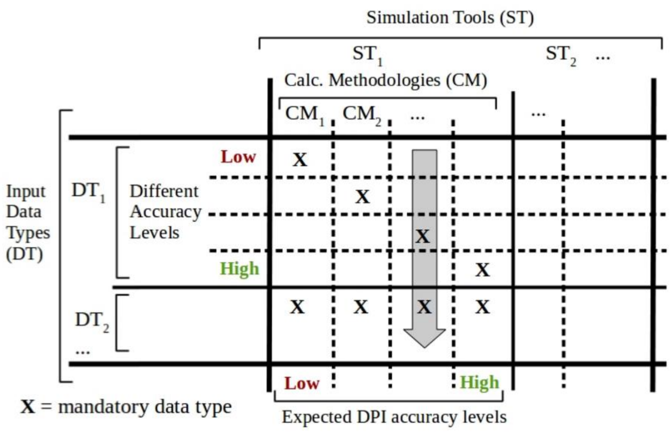

Figure 4. Expected DPI accuracy variation depended on the selected calculation methodology.

5 CONCLUSIONS

This paper has introduced a District Data Model devised for the OptEEmAL platform as a framework to support retrofitting designs in districts. Its implementation as an ontology-based approach has been discussed in this paper as a possible solution to integrate different design information (BIM, GIS and contextual data) necessary to perform simulations using different tools.

The use of simulation data model in the context of the DDM is presented as a plausible approach to solve the interoperability issues between data models (e.g, IFC, CityGML) and different simulation tools. In the case of the energy domain, SimModel is a simulation data model which is tailored towards energy-related data required by most popular energy simulation tools. In other domains, such as the economic one, it is still not clear that there is such representative model.

One of the conclusions that can be highlighted in the research outlined in this paper is that even with more flexibility to generate the simulation models from the data models to perform simulations for each tools, ad-hoc adapters need to be developed to provide this interoperability.

The next steps in this research are to further develop the ontology-based solution adopted in the DDM to carry out fully-automated energy simulations with EnergyPlus and CitySIM.

6 ACKNOWLEDGEMENTS

Part of the work presented in this paper is based on research conducted within the project "Optimised Energy Efficient Design Platform for Refurbishment at District Level", which has received funding from the European Union Horizon 2020 Framework Programme (H2020/2014-2020) under grant agreement n° 680676.

7 REFERENCES

Amirebrahimi, S., Rajabifard, A., Mendis, P., & Ngo, T. (2015). A Data Model for Integrating GIS and BIM for Assessment and 3D Visualisation of Flood Damage to Building. *Locate*, 15, 10-12.

Beetz, J., Van Leeuwen, J., & De Vries, B. (2009). IfcOWL: A case of transforming EXPRESS schemas into ontologies. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 23(01), 89-101.

Bontas, E. P., Mochol, M., & Tolksdorf, R. (2005). Case studies on ontology reuse. In *Proceedings of the IKNOW05 International Conference on Knowledge Management* (Vol. 74).

BuildingSMART. (2015). IFC4 Release Summary. http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-release

Crapo, Andrew, Ray Piasecki, and Xiaofeng Wang. (2011). The smart grid as a semantically enabled internet of things. In *Implementing Interoperability Advancing Smart Grid Standards, Architecture and Community: Information Interoperability Track, Grid-Interop Forum* (Vol. 2011).

Döllner, J., & Hagedorn, B. (2007). Integrating urban GIS, CAD, and BIM data by service based virtual 3D city models. R. et al.(Ed.), *Urban and Regional Data Management-Annual*, 157-160.

Gröger, G., & Plümer, L. (2012). CityGML–Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing*, 71, 12-33.

Gröger G, Kolbe T H, Nagel C, Häfele K H. (2012). OGC City Geography Markup Language (CityGML) Encoding Standard Version 2.0. http://www.opengis.net/spec/citygml/2.0

ISO 16739. (2013) Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries.

Kolbe, T. H. (2009). Representing and exchanging 3D city models with CityGML. In *3D geo-information sciences* (pp. 15-31). Springer Berlin Heidelberg.

Laat, R., and Berlo, L. (2011). Integration of BIM and GIS: The Development of the CityGML GeoBIM Extension. In *Advances in 3D Geo-Information Sciences*, Berlin, Germany, 211-225.

Lilis, G. N., Giannakis, G., & Rovas, D. (2015). Detection and Semi-automatic correction of geometric inaccuracies in IFC files. IBSPA Conference, Hyderabad, India.

Lilis, G.N., Giannakis, G.I., Katsigarakis, K., Rovas, D.V., Costa, G., Sicilia, A., & Garcia, M.A. (2016). Simulation model generation combining IFC and CityGML data. In *Proceedings of the 11th European Conference on Product & Process Modelling*. Limassol, Cyprus, pp. XXX-XXX.

Mao, B., & Ban, Y. (2011). Online Visualization of 3D City Model Using CityGML and X3DOM. *Cartographica: The International Journal for Geographic Information and Geovisualization*, 46(2), 109-114.

Métral, C., Billen, R., Cutting-Decelle, A. F., & Van Ruymbeke, M. (2010). Ontology-based approaches for improving the interoperability between 3D urban models. *Journal of Information Technology in Construction*, 15, 169-184.

O'Donnell, J., See, R., Rose, C., Maile, T., Bazjanac, V., & Haves, P. (2011). SimModel: A domain data model for whole building energy simulation. *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, Sydney.

Paslaru, E. (2005). Using context information to improve ontology reuse. *In Doctoral Workshop at the 17th Conference on Advanced Information Systems Engineering CAiSE* (Vol. 5).

Pauwels, P., Corry, E., & O'Donnell, J. (2014). Representing SimModel in the web ontology language. In *American Society of Civil Engineers* (pp. 2271-2278).

Pauwels, P., & Terkaj, W. (2016). EXPRESS to OWL for construction industry: towards a recommendable and usable ifcOWL ontology. *Automation in Construction*, 63, 100-133.

Romero, A.; Egusquiza, A.; Izkara, J.L. (2014). Integrated decision support tool in energy retrofitting projects for sustainable urban districts. In *proceedings of the SB14 World Sustainable Buildings*. Barcelona. October 2014.

Schevers, H., & Drogemuller, R. (2005, November). Converting the industry foundation classes to the web ontology language. In *Semantics, Knowledge and Grid, 2005. SKG'05. First International Conference on* (pp. 73-73). IEEE

Sicilia, A., Madrazo, L., & Pleguezuelos J. (2014). Integrating multiple data sources, domains and tools in urban energy models using semantic technologies. In *Proceedings of the 10th European Conference on Product & Process Modelling*. Vienna, Austria, pp. 837-844.

Simperl, E. (2009). Reusing ontologies on the Semantic Web: A feasibility study. *Data & Knowledge Engineering*, 68(10), 905-925.

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction*, 18(3), 357-375.

Vimmr, T., Loga, T., Diefenbach, N., Brita, S., & Lucie, B. (2013). Tabula - Residential Building Typologies. In *12th European Countries - Good practice example from the Czech republic*. CESB13 Prague, Czech Republic.