Development of a district modeling approach for buildings using 3DEXPERIENCE and Dymola/Modelica environments

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Abstract

This paper presents a new set of modeling tools that can be used to design, to size and to operate district energy systems and the buildings that they serve. The models are based on the 3DEXPERIENCE platform and are developed in such way to evaluate thermal and energy behavior of buildings, systems and district heating and cooling networks.

Special algorithms are capable to extract, analyze, enrich and transform existent open-source GIS data which is used to build a 3D district model and to parameter automatically the Dymola/Modelica behavior models. Buildings defined KPIs or raw results (loads, temperatures, etc.) are visualized on the district 3D model.

Background and state of the art

It is well known that buildings and their energy infrastructures are the single largest contributor to climate change. For example, the European Union spends over 1 Billion euros every day on energy imports according to Canete (2015) which is representing over 53% of Europe's energy needs. Between 1990 and 2006 the proportion accounted by residential and commercial buildings rose from 35% to 38% according to European Commission (2015), making buildings the largest single energy consumer in Europe. Analyzing different projects and initiatives at a European level, it was observed a generalization of the awareness to rapidly create a framework for developing, applying and maximizing actions for optimizing the consumption patterns and the infrastructure planned for buildings and city districts.

Nowadays, if we are talking about urban expansion, building and city district densification in a context where energy transition prevails it is necessary to address, verify and optimize multidisciplinary questions and a high number of alternative interpretations at different steps during the building life, along with commitment and innovative thinking as well. Facing these complexities, it is necessary to treat city districts and their components in an integrated manner (segmenting, advanced modeling and evolution) since traditional methods and techniques of design appear outdated.

In this context, new approaches are needed to ensure the future success of cities. Lessons can be learned from industry whose resourcefulness and innovation has blazed trails that could lead toward truly 'smart' cities according to Dassault Systemes (2016). These findings are reinforced by Allegrini et al. (2015), Mastrucci et al. (2014), who consider that new generation set of tools (models and simulation) are required for the design, sizing and operation of urban energy systems and the buildings that they serve. Moreover, dynamic, complex systems such cities can benefit greatly from 3D collaborative technology to model, simulate, visualize and experience complete cities in a virtual environment. 3D can facilitate experiences which are necessary to open up new avenues for collaboration, discussion, planning and, ultimately, sustainable living according to Dassault Systemes (2016).

The aim of this article is to develop a collaborative city district modeling proof of concept (including buildings in a first phase and energy networks, equipment, acoustics, lighting in a second phase) in the 3DEXPERIENCE Platform and to investigate this approach on a real city district building data. Therefore, we present an approach for a 3D and Dymola/Modelica based decision-aid tool to enable modeling and simulation of buildings and energy systems of a city district. A Dymola /Modelica low-order building model is at the core of these developments. The low-order building model is connected with a geographical information system (GIS) to link spatial and geometrical data. Building envelop (opaque and transparent) characteristics, occupancy (number of persons) and internal gains (from occupancy, light, other appliances) loaded automatically from an external file enables thermal simulations and 'What If' scenario development on the whole city district. Special developed rules enable a fast and automated parameterization of the city district's low-order building models within RFLP (Requirement, Functional, Logical, Physical) functionalities of 3DEXPERIENCE. Additional developments will focus on the district heating and cooling networks. By linking them with the actual developments on the buildings behavior, district networks operators or buildings owners can have access to a set of tools allowing interventions at the pre-design, design and operation & maintenance phases.

The collaboration advantages induced by the use of such developments are related to the reuse of data (building geometry from the 3D to the behavioral model and the results from the behavioral model to the 3D, can be the best examples) between different project's stakeholders, to authoring (for example, multi discipline such as mechanical engineers (HVAC) and GIS specialists or architect can use the same tool for their project) and to the

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life-cycle (all the information is stored in a PLM (Product Life Cycle Management) database as objects which are managed in terms of version, life cycle throughout the life of the product/building). Moreover, another major advantage is that this type of technology can remove the frontiers between domains and their experts, 3D collaborative tools allowing them to communicate more easily.

Methodology to handle city district data to supply building model

City district data handling

This section aim is to present a 4 step methodology, developed and used to build an experience from a city district 3D model (it is assumed the absence of this model) up to the simulation results analysis by the intermediate of the 3DEXPERIENCE Platform.

3DEXPERIENCE Platform is a collaborative platform developed by Dassault Systèmes which allows to integrate several heterogeneous sources of data (3D CAD information, GIS database, Dymola /Modelica models, City OpenData Documents, Requirements (Standard, Safety), simulations results, etc.). It enables several people from different organizations and different discipline to communicate around a single source of truth, using P&O (People&Organization) access to protect IP (Intellectual Property) of each user.

Figure 1: OpenStreetMap view of a city district in Rennes, France.

The first step of the methodology illustrated in this article consists in exporting GIS database or file geometrical information. OpenStreetMap database information was selected and thus from the OpenStreetMap Internet site, the city district (or the zone) to be analyzed can be manually chosen and the data exported in a *".osm"* file format.

From the *".osm"* captured file format, the second step is a pre-processing step and consists in developing inside a set of tools named *3DEXPERIENCE knowledgeware*, used to analyze and build the city district area presented in Figure 1. *3DEXPERIENCE knowledgeware* is a very powerful tool which allows to define parameters for instance on a CAD building and build automatically a model. It can be used as well to define rules in order to check and test model compliancy to norms/standards or its validity according to company user pre-defined set of rules.

3DEXPERIENCE knowledgeware allows also to define a *knowledgeware template* object, which allows to aggregate under a same objects some different facets of the building such as 3D CAD generic parametric model, a set of defined parameters, requirement and physical information. Thus, the template can store not only data but also methods/rules and formulas to re-compute the object and the associated parameters.

The 3D CAD generic parametric model integrates for instance a 3D building template which is composed in our case by a ground surface (with profile vertexes, set in Cartesian coordinates - dedicated scripts inside 3DEXPERIENCE were developed to convert extracted *".osm"* data file and to parse the information from latitude/longitude coordinates into X/Y Cartesian coordinates, using the appropriate projection system) and geometrical parameters such as the extruded heights (with 2 limits : roof and ground depending altitude information). The 3D model can be built from a more complex geometry definition or using dedicated 3DEXPERIENCE "apps". More complex 3D parametric model can be designed to integrate more geometrical detailed design information (for instance, floors, walls, rooms, etc.).

The set of defined parameters (not only geometrical parameters) will allow to the end user to "adapt" the 3D model to its technical need (domain). Thus, these parameters (Figure 2) will be accessed by the end user and will enrich the geometrical data (3D building). They can be valuated either manually, either automatically from input Excel/CSV files given by end user, by the intermediate of 3DEXPERIENCE *knowledgeware* scripts. These defined parameters can be classified in 2 categories (more categories can be defined by the user): *Imposed parameters*, for instance "Number of Occupants", envelope component "Heat transfer coefficient" "Air ventilation rate", etc. which will drive the Dymola/Modelica model (input parameters) and, *Computed parameters*, for instance the area of each surface computed on 4 main orientations (North, South, East, West). The *Computed parameters* are evaluated by scripts using dedicated API or by formula (inside *knowledgeware*) and stored in 3DEXPERIENCE. If the geometry is modified (for instance, height of the building), then all the areas are re-computed automatically.

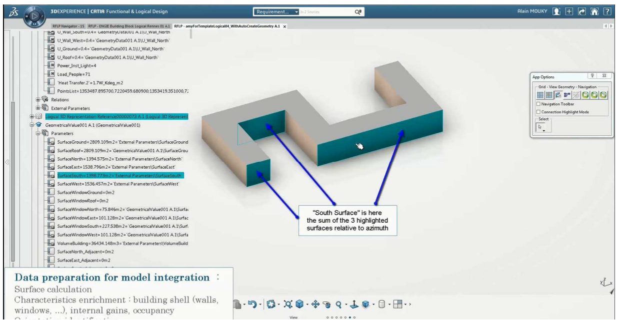


Figure 2 : 3DEXPERIENCE knowledgeware template

A *knowledgeware template* object can contain one or more Dymola/Modelica associated models. Thus, several behaviors models can be used for simulation, for instance one behavior for energy efficiency, one for thermal analysis, one for electrical or fluidic phenomena. A facet behavior can also be accessed as well as a FMI behavior.

Requirement information may be used, if needed, for traceability aspects. A requirement object can also be associated to several technical PLM Parameters stored in PLM. Some of these parameters can feed KPIs. Associating additional information such as Physical information, coming from external sources (for instance data for realistic building textures, or material structure definition like glazing for windows or concrete for walls), can bring to the 3D and behavior models, realistic attributes necessary for the visualization.

The third step consists in the template instantiation of the *knowledgeware template.* From the pre-processing files, it is possible to generate automatically all buildings from the 3DEXPERIENCE template, using *knowlegeware* dedicated scripts, which read input pre-processed files and parameter the buildings from the template object. When instantiating the template, all the parameters for each created building are set. At the end, the city district area is created and each building has after its own set of parameters which can be modified a posteriori (Figure 3).

Figure 3 : City district generated 3D model

The fourth step is the post-processing phase where the end user can modify parameters for a chosen created building. Thus, the end user can modify all the parameters manually by editing each value for the selected building or he can select to valuate only a set of parameters values (for instance heights, number of people) and for a number of buildings, in file-based tables. Thus, it is possible to modify automatically buildings parameters by launching *knowlegeware* dedicated scripts, which read and instantiate all the inputs from post-processed files and check at the end all valuated values for all buildings of the city district.

In conclusion, we create and connect a 3D city district geometrical model to a behavior building model by creating a data virtual model of the district in all its complexity. Thus, after the construction of the 3D model from the OpenStreetMap data, the 3DEXPERIENCE data structure obtained have a tree-based structure (Figure 4), where a district contains buildings, and each building contains geometry and zone components (walls, roofs, floors and schedules), which contain information about the physical characteristics. From there, we can understand and visualize (the results are linked it back to the 3D city district and building model) via simulated 'if-then' scenarios the potential effects of various systemic changes - such as how a certain change would decrease heating and cooling needs - before implementing them.

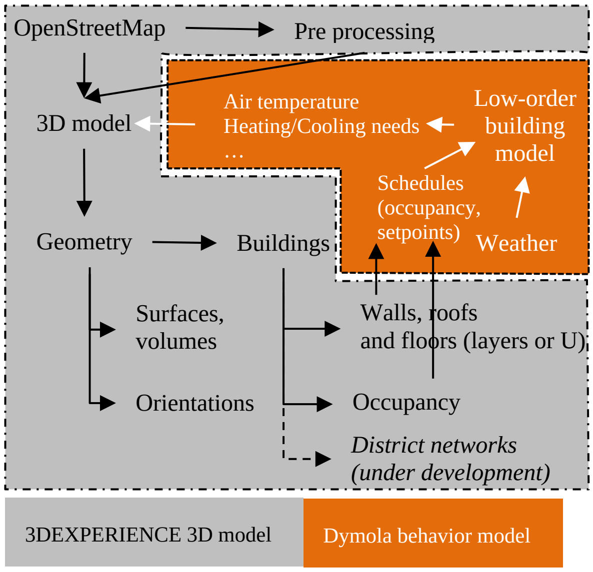


Figure 4: District data and building model connection.

Building model assumptions

The principle underlying the construction of the building model is one of "bottom-up" type, known as engineering designs. Thus, the buildings can be treated individually or classified into typologies to simplify the data collection, analysis and modeling process. This approach is generally required while dealing with districts with several hundreds or thousands of buildings. This enables to adapt to lower data availabilities (particularly for existing district), and keep simulation computational time acceptable and consistent with the global model precision.

Experience in modeling and dynamic simulation of buildings and energy systems has shown that detailed thermal modeling (viewed as a detailed thermal balance for a known data set: surfaces, volumes, building envelop characteristics and energy systems, occupancy, etc.) is difficult to adopt a high number of buildings. This is due to the fact that detailed modeling is impossible to execute for a set of important input data (several hundred buildings where information may be limited or even non-existent).

A commonly used alternative to avoid such difficulties and simultaneously obtain reliable and solid results consists of developing and using low-order building models. The idea is to apply the principle of analogy between two different physical domains that can be described by the same mathematical equations. Existing in several configurations depending on the required precision according to Hazyuk et al. (2012) and Berthou et al. (2014), these analogies allow a sufficiently detailed modeling to evaluate precisely the dynamic behavior of buildings.

Low-order building model used in this paper is derived from linear network representations with lumped parameters developed by Berthou et al. (2014). By analogy between two different physical domains, a linear electrical circuit represents the building. The equivalent circuit of the building is obtained by assembling models of the walls, windows, internal mass, etc. Building envelope (walls, roof and floor) is represented by resistances and capacities (R-C). Internal thermal mass (C) is usually represented by capacities. Windows, ventilation and infiltrations are represented as simple resistances (Figure 5).

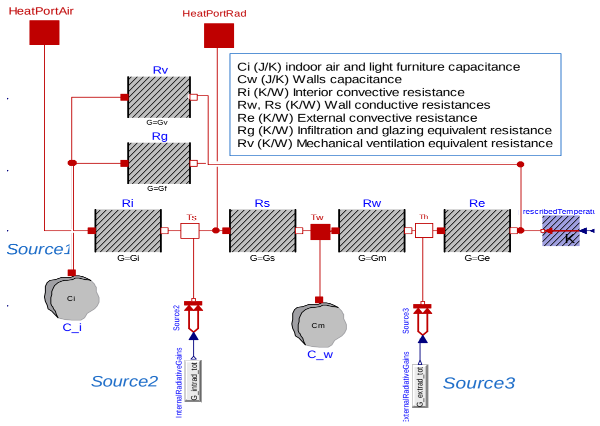


Figure 5: ENGIE Lab's low-order building model electrical analogy Dymola representation.

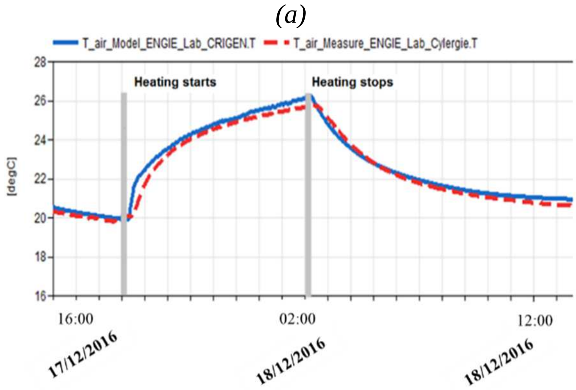
Berthou et al. (2014) recommends the use of second degree configuration (R6C2 – six resistances: external convective resistance, wall conductive resistances, infiltration and windows equivalent resistance, mechanical ventilation equivalent resistance and 2 capacities : internal air and walls internal mass) in order to better take into account the solar gains (Figure 5). The integration of two specific nodes (Ts: indoor surface wall node and Th: outdoor surface wall node) allows to take into account the solar radiation ($Source2$ and $Source3$). Thus, the solar flux transmitted through the windows reaches directly the wall capacitance and the air capacitance. This repartition is determined by the value of R_i and R_s. The solar flux coming on light furniture which has a fast impact on the indoor air temperature compared to solar flux coming on heavy walls. For the solar flux on the external walls ($Source3$), one part hits the wall capacitance through insulation and the other part is directly discharged into the atmosphere (through R_e) by convection. With the R6C2 configuration, the model takes into account the mechanical ventilation (variable resistance R_v (which is proportional to the airflow rate). In Figure 1, $Source1$ represents the internal convective gain (variable, function of the occupancy type and intensity, and the heating/cooling power added to the building), $Source2$ the internal radiative gains (variable, function of the occupancy type and intensity, and the internal solar gains) and $Source3$ the external radiative gains (variable, function of external solar gains).

The low-order building model is integrated in a high-level model where the boundary conditions, the schedules, the energy systems and the KPIs (loads and specific heating & cooling needs, temperatures, etc.) are modeled. Buildings Library TMY3 reader block is used to feed the low-order building model with outdoor dry bulb temperature and solar radiation. Thus, the global, direct and diffuse solar radiation inputs are connected and treated inside the low-order building model in order to have both solar gains on the walls and through the windows function of orientation, geometrical information and time of the day. A schedule block is outputs whether the building is currently occupied, and how long it will take until the next time when the building will be occupied or non-occupied. This block is used to output signals for heating, cooling, ventilation and occupancy, and calculate internal gains ($Source1$ and $Source2$) for the low-order building model. The energy systems models are integrated here in a simplified way (dual-setpoint for heating, cooling, ventilation controlled by a PI controller and injection of the associated power in the convective and radiative nodes). Further developments will be allow to take into account energy systems performances in order to calculate the energy consumptions for each building. Function of the use of the platform (pre-design, feasibility, etc. project phase) and the size of the district, the developed platform is capable to take into account simplified and detailed models.

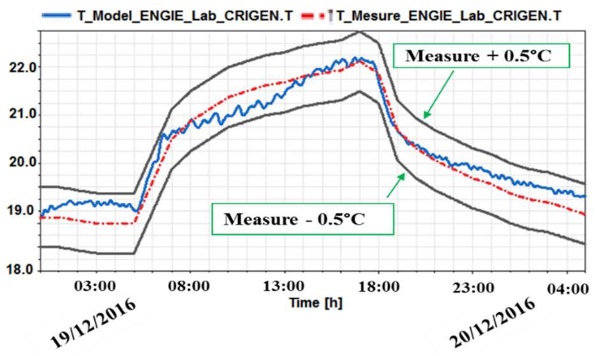
The KPIs evaluated at this stage by the high-level model are represented by : heating, cooling needs (expressed in [kWh] and [kWh/m²]), power (instantaneous and maximum over the year in [W]), indoor air temperature (instantaneous, maximum and minimum in [°C]), internal gains (expressed in [kWh] and [kWh/m²]), ventilation, windows and walls thermal losses (expressed in [kWh]).

The actual developments of the proposed R6C2 building model in Dymola were tested for heating and free-floating controlled periods for a 1260 m² existent, average energy performance school building and under real weather in Lyon, France (Figure 6).

(a)



(b)



(c)

Figure 6: ENGIE Lab's building model comparison with real data. (a) School building; (b) Building model results for a heating power step (c) Building model results for normal operation

The low-order building model was parameterized with data (surfaces, orientations, envelop performance, gains, …) from the real building and exposed to identical boundary conditions. The indoor air temperatures and the heating power calculated by the model were compared with real data measured on site.

Figure 6 (b) illustrates the building model and the real building temperature response to a heating power step. The principle consists of a dynamic experiment where the inside of the building is submitted to a constant thermal load in two phases. Both phases had the same duration but different heating power and were performed during the night without occupancy in order to avoid any additional power sources. Figure 6 (b) illustrates the building model and the real building temperature response normal operation. The model shows good results for temperature and seems to be a good compromise between precision, available data needed to parameter the model and computational time. At the time of writing this article, the proposed model is under testing and validation for an additional commercial and two residential buildings.

Results and discussion

Using the previously described methodology, we present in what follows the abilities of the developed tools to integrate the geometrical information to the 3DEXPERIENCE platform, and to perform further annual simulations. A city district of 13 hectares in the town Rennes, France, was chosen and a 3D model developed in order to test the proposed approach and the information treatment process. The city district is composed by 39 residential buildings (apartment blocks) with footprints varying from 160 to 5000 m². The buildings were erected during different periods and thus they have different thermal characteristics (envelop heat loss coefficient, windows area, etc.). The main building envelope characteristics used to parameter the 3D model (Figure 3) are illustrated in Table 1.

Table 1:Use Case building stock characteristics

Construction date	**Weight in the stock**	**Heat loss coefficient [W/m²K]**		**Total area of the walls [m²]**					**Total area of the windows [m²]**			
		Walls	**Windows**	**Ground**	**N**	**E**	**S**	**W**	**N**	**E**	**S**	**W**
1920	15%	2	2	5374	3228	3278	3215	3257	149	211	448	199
1930	10%	2	2	3127	3927	5081	3918	5159	125	106	269	125
1960	10%	2	1.7	3049	2070	1420	2067	1421	91	91	274	152
1970	13%	1	1.7	6029	3873	2795	3889	2915	181	241	603	181
1980	18%	0.7	1.7	2540	1762	1428	1765	1431	94	89	220	105
1990	13%	0.45	1.7	3855	3437	3895	3418	3788	104	139	312	139
2000	5%	0.4	0.8	7780	6699	7425	6703	7422	210	280	630	280
2005	3%	0.36	0.8	1896	16	33	16	33	51	68	154	68
2010	8%	0.2	0.8	4466	3785	1765	3786	1768	107	143	322	143
2012	5%	0.15	0.8	1966	1165	1440	1119	1020	47	63	142	63

After the parameterization of all the buildings, the city district logical model was simulated regarding different scenarios (a reference scenario with initial characteristics, as presented in Table 1, and building envelope new characteristics corresponding to building renovation actions packages such insulation of a part of the buildings' walls, replacement of windows, ventilation improvement and combination of actions) using different set of parameters**.**

In 3DEXPERIENCE, a dedicated object named *Simulation object* can aggregate scenarios and results from the same logical model. Thus, raw data (identical Dymola/Modelica data structure and content i.e. all the non-protected variables) from the simulations is stored and visualization can be performed. For example, buildings KPIs (heating and cooling demands, indoor air temperatures and losses (walls, ventilation, windows) are visualized directly on the district 3D mockup.

Figure 7 shows the heating demand for the entire city district. Dynamic coloring can be visualized above the 3D mockup accordingly to thermal behavior of each building. The coloring is based on a French (European) widespread energy label (A – high efficient building colored green while G or I is a low efficient building colored red or black). The coloring is linked to simulation period and thus the end user can select a specific time (corresponding to a date for example) and visualize the simulation data and results at this specific time.

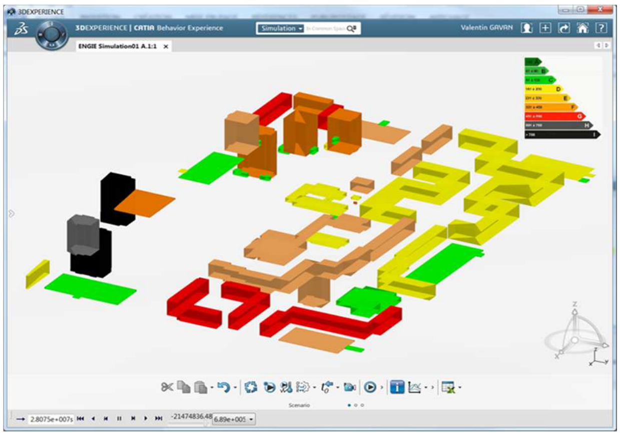


Figure 7: Annual heating demand of the city district, expressed in kWh/m².

Figure 8: Instantaneous information combined with annual heating demand of the city district.

Furthermore, for visualization purposes, a specific Dymola/Modelica library has been developed in order to display dynamic numerical information (annual heating demand expressed in kWh/m², instantaneous temperature expressed in °C, annual heating and cooling demand expressed in kWh) on the 3D on each roof of the building (Figure 8). Other variables can be added to the library and visualized by the end user.

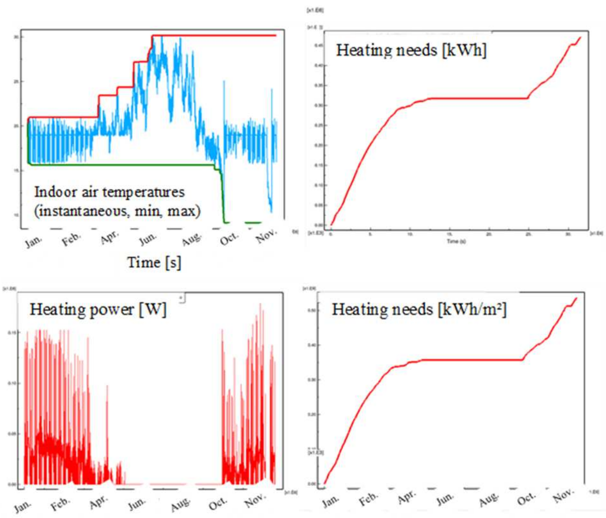


Figure 9: Results visualization with plots for buildings behavior (annual basis).

Combined with the dynamic coloring and "play" functionality (scan the entire simulation period), the end user can qualitatively and quantitatively visualize and detect abnormal behavior. Results can be visualized and analyzed as well through plot results (Figure 9) for dedicated Dymola/Modelica selected variables. The end user can have access at all non-protected variables delivered from the behavioral (Dymola/Modelica) models.

Conclusion

Several simulation tools quantify the energy and thermal behavior of buildings, from the urban to the building scale and with different precision level. Few tools are capable to cover the complicated cycle of linking the existing data (not always available or adapted) to the energy analysis at a city district scale.

An automated city district 3D model generation combined with a low-order building model integration and parameterization proof of concept tool chain was developed and presented in this paper. Its advantages are the reduction of resources and complexity related to building modeling and simulation.

Consequently, the use of energy performance modeling and simulation at a city district level by aggregating all its buildings behaviors is made more feasible. These development will allow end users to create building models and run simulations faster on large scale for buildings, city districts and even full cities.

A city district in Rennes, France is presented as case study, demonstrating the capacities of 3DEXPERIENCE platform to handle (extract, analyze, enrich and transform existent data) and evaluate by simulation the thermal behavior for each building. 3DEXPERIENCE city district model can be simulated, stored and shared. This character of the platform combined with technical functionalities (connection between GIS open-source data, 3D modeling and behavior simulation) represent an innovative approach for the urban energy analysis. The results show the feasibility of the data treatment approach, further tests with additional buildings should be performed to better evaluate it. The usage of physical behavioral models concepts for district modeling and analysis seems promising, especially in combination with GIS tools and open-data databases, which enables visualization and modification of city objects and their attributes. Experiences show that the proposed methodology can be sufficient for a preliminary analysis of city districts as well as for the generation of building models for dynamic simulations.

Ongoing development of this research topic is focusing on developing in the same platform the tools which will deal with the modeling and simulation of district heating and cooling networks. The developed methodology will be updated in order to integrate automatically in the city district model the existent GIS information at networks operators. Thus, the network model will be able to generate data (length, diameter, altitude between points, materials, etc.) which will parameter a Modelica/Dymola thermo-hydraulic model. The thermo-hydraulic model will be automatically linked to the building model for the entire city district area. Thus, the building behavior and energy management influence can be evaluated at the district network level where the operation, and further the production, can be adapted. With these new developments, the 3DEXPERIENCE platform can participate at the optimization of the city district energy behavior.

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