SIMSTADT, A NEW WORKFLOW-DRIVEN URBAN ENERGY SIMULATION PLATFORM FOR CITYGML CITY MODELS

Nouvel, R.[1]; Brassel, K-H[1]; Bruse, M.[2]; Duminil, E.[1]; Coors, V.[2]; Eicker, U.[1]; Robinson, D.[3];

1: University of Applied Sciences Stuttgart / Energy Department, Germany

2: University of Applied Sciences Stuttgart / Geo-informatics Department, Germany

3: University of Nottingham, United Kingdom

ABSTRACT

In this paper, we introduce new urban energy simulation platform *SimStadt*, which has been developed to support public authorities and engineering companies in the planning of the energy transition at urban scale. SimStadt design is marked by two particular features: 1- it is based on the open 3D city model CityGML and, 2- its workflow-driven structure is highly modular and extensible. These particularities allow him for a potentially unlimited variety of urban analysis, benefiting from the big geo data possibilities. This first version contains the workflows Solar and PV potential analysis, Energy demand and CO2 emission calculation, and refurbishment scenarios generation and simulation. Other workflows and plug-ins are under way, in particular district network design and simulation.

This paper details these features and workflows, and presents an application on the administrative district of Ludwigsburg, a case study of half a million inhabitants spread over 34 municipalities.

Keywords: SimStadt, urban energy analysis, 3d city model, CityGML

INTRODUCTION

Used for modelling an ever growing number of cities (e.g. Berlin, Lyon), regions and even countries (Germany), virtual 3D city models represents an invaluable support for public authorities and engineering companies to tackle the urgently required energy transition.

They have recently shown huge possibilities in the fields City planning, Environment and Energy, enabling diverse urban studies (solar radiation exchange and shadowing, urban wind flows, district heating network etc.) and combining expert urban simulation algorithms with the richness of the Big Geo Data. Among the 3D city model formats, the open standard CityGML seems to stand out as the reference [1], providing an excellent and flexible spatio-semantic data structure for 3D geospatial visualization, multi-domain analysing, simulation and exploration tool. It is the basis of design of the new urban energy simulation platform *SimStadt*, commonly developed by the departments Energy and Geo-informatics of the University of Applied Sciences Stuttgart during the last 2 years.

This platform aims at supporting urban planners and city managers with defining and coordinating low-carbon energy strategies for their cities, with a variety of multi-scale energy analyses. It shall also allow scientists for developing and testing new simulation algorithms and exploring the potential of new data sources.

SIMSTADT APPROACH

To achieve the above goals, *SimStadt* must be able to integrate (a) large data sets of different kind and at different level, e.g. building geometries and features, heating networks, patterns of energy consumption, production and conversion, (b) third-party simulation systems, and (c) inhomogeneous hardware resources like database servers, simulation engines, web services, graphics cards, and workstations. Moreover, to be considered as a useful working tool, the platform must provide a modern graphical user interface, enable fast parallel computation and help to easily understand given workflows and add new ones.

When looking at these requirements, scientific workflow systems seem to be the natural choice of platform to use. [2] However, no standard for such systems exists yet. To avoid locking into a special software product, we decided to build upon Java and its rich ecosystem. Especially, new language idioms of Java 8 provide features common to scientific workflow systems like high-level support for parallel computing, domain specific languages, functional programming, and generic user interfaces. Last but not least, Java provides industry-proven support for XML processing that comes very handy for the kind of data we have to deal with.

A data structure based on the open city model standard CityGML

The OGC Standard CityGML [1] is the basis of design of the new urban energy simulation platform SimStadt. A considerable asset is its flexible object modelling in 4 different Levels of Details (LoDs), enabling the virtual city model to adapt to local building parameter availability and application requirements. The present release of SimStadt deals with the Level of Details LoD1 and LoD2, consideration of LoD3 is under way.

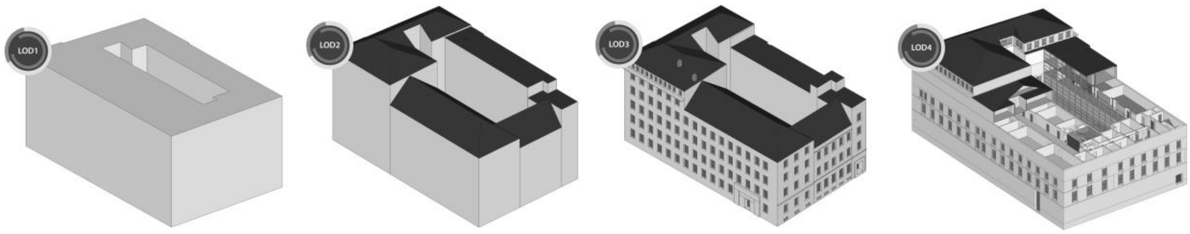

Fig. 1: The four Levels of Detail of CityGML applied to the Building 2 of the HfT Stuttgart.

Presently, the CityGML data model (version 2.0) does not contain any energy-related objects and attributes. To solve this issue, an application domain extension (ADE) for CityGML, called Energy ADE, has been designed and implemented with other European partner institutes. This extension enables the modelling of building thermal zones and boundary surfaces, construction and material properties, occupancy conditions of zone area, energy systems and consumptions. Having the energy-related data integrated into the city models eases the processing of this data through SimStadt.

SimStadt utilizes the library citygml4j [3] to load, process and store CityGML files with Java. This library provides a Java API and Java classes for all standard CityGML types so that a CityGML model can be instantiated in Java applications. Furthermore, citygml4j provides a JAXB-XJC binding compiler (ade-xjc) which conveniently generates Java classes from custom ADE XML schema definitions like the Energy ADE, so that the newly introduced energy-related attributes and types are now able to be loaded and stored together with a standard CityGML model by *SimStadt*.

Modular workflow-driven processing

The structure of computational tasks at hand is considerably simple, and best described as "hierarchical workflow". From a birds eye view, such workflows basically consist of chains of processing steps that create, transform and consume specific data objects step by step. Conforming to the disaggregation of model objects from high-level to low-level (e.g. city > district > building > building zone > wall) often a processing step at a higher level is realized by a chain of steps working on lower-level model objects, thus the term "hierarchical". In some cases, chains of processing steps at one level may be logically independent, and thus be executed concurrently. Note, that in this schema, circular processing of steps is not allowed. Fig. 2 depicts what it looks like to define a hierarchical workflow in SimStadt.

```
Workflow.start(new ImportCityGML("Stuttgart"))
  .next(new WeatherAndPreprocessing("Weather and Preprocessing")
         .par1(new WeatherProcessor("WeatherProcessor"))
         .par2(new Preprocessing("Preprocessing")
                .sub(Workflow.start(new BuildingFilter("Filter"))
                       .next(new GeomPreprocessor("Geometry"))
                       .next(new PhysicsPreprocessor("Building Physics"))
                       .next(new UsagePreprocessor("Building Usage"))
         )))
  .next(new RadiationProcessor("RadiationProcessor"))
  .next(new MonthlyEnergyBalance("DIN18599")));
```

Fig. 2: Definition of a hierarchical workflow to compute monthly energy balance.

While dealing with large-scale models based on different data sources, the risk of errors and incoherent results are generally very high. A Graphical User Interface (GUI) enables to navigate in the different workflows and workflow steps, allowing for the analysis of the intermediary results at each step of the workflow, through charts, tables and other output. The GUI also enables the user to modify the hypotheses and parameters of workflow steps and create scenarios accordingly.

FIRST BUNCH OF SIMSTADT FUNCTIONALITIES

At the redaction date of this paper, the SimStadt Platform integrates the workflows solar potential analysis, heating demand and CO2 emission calculator, based on the main WFS and functionalities detailed below. Due to its modular structure, SimStadt may be extended with new WFS and workflows corresponding to new urban energy analyses, provided that the required data are available in the 3D city model or processed previously by other WFS.

Data pre-processing and probabilistic disaggregation

Urban energy analyses and simulation algorithms are important consumers of geo data. Beside the geometric data, which can be extracted from the 3d city models, semantic data relative to the buildings physics and operation, occupants and local climate are also required. Nevertheless, the diversity of their availability and quality in existing urban areas represents a challenging issue. The use of the flexible city data model CityGML enables to adapt to the available data and their level of details, as described in the previous section. In addition, some data pre-processing modules integrated in the workflow enable to address gaps in information by estimating the missing data and transforming the available ones.

These data pre-processing modules use elementary algorithms to deduce missing parameters from available information (e.g. determination of the building types based on geometrical parameters), as well as different libraries of benchmarking values and archetypes:

- Building typology libraries, containing building physics archetypes referenced by building age and building type
- Building usage libraries, detailing occupancy and operation parameters representative of the different zone usage types (e.g. residential, retail, education).
- Energy System and fuel libraries.

Additionally, if some essential information data are neither available nor deducible at the building level, they can be probabilistically assessed from aggregated data. This method is particularly interesting to deal with energy systems or refurbishment states at urban scale. Although these information data are rarely accessible in private buildings, their distribution per neighbourhood or municipalities may be provided by European census data for instance.

Weather and radiation processing

Urban energy analyses such as the heating demand or solar potential analysis require local weather data, at hourly or monthly basis (e.g. ambient temperature, relative humidity, horizontal global and diffuse radiations). They are imported in the WFS WeatherProcessor from different online/software databases (*PVGIS*, *Insel*) or weather data files (*Meteonorm*), selected by the user, and if required pre-processed.

The WFS RadiationProcessor allows for the computation of the incoming solar radiations on each building boundary surface. For this purpose, the user may select different radiation distribution models, depending on its precision requirements and allowed computational time:

- A radiation/orientation mapping, based on the Hay sky model. It considers each building as an insulated object without interaction with its surrounding. This model may be preferably used in urban area with low-density.
- A ray-casting algorithm, coupled with the Hay sky model. Programmed to benefit from the full computational power of GPU, it considers the obstruction of surrounding urban objects, but not the mutual reflections (instead, an urban albedo is considered).
- The Simplified Radiosity Algorithm [4], coupled with the Perez sky model. It considers both shadowing and reflexion effects of surrounding urban objects.

Energy demand calculation

The space heating, domestic hot water (DHW), and electrical demands are assessed in SimStadt, allowing for a global energy demand assessment, building per building.

The DHW and electrical demands, which depends mainly on the building usage and occupancy, are calculated by means of a statistical method at yearly basis. For the space heating demand calculation, a monthly energy balance (according to ISO 13790) is applied to each building, allowing for the pre-certification of the building energy-efficiency. In order to calculate additionally the hourly heating loads, the modular implementation of a simplified dynamic simulation is currently under development.

Based on these energy demand analysis and knowing the energy systems of the different buildings and their performances, the primary energy demand and CO2 emissions may be calculated.

Generation of scenarios

Based on the diagnosis of the actual energy state, alternative energy refurbishment and energy supply scenarios may be developed, compared, combined and optimized, with the purpose to plan and coordinate the best energy transition at urban scale.

The platform SimStadt offers a module to quickly generate such scenarios, by means of refurbishment rates (% of floor area per year), time horizon, and priority indexes (either oldest building first, or less-efficient buildings first, or a user-defined index, or randomly). Some reference refurbishment variants and energy-efficient systems to be implemented are predefined in the Building typology and Energy system libraries. The user may create further variants, so as to observe the impact of customized scenarios.

Software plug-ins

Plug-ins interfacing with third-party simulation softwares may be programmed inside WFS. This is the case of the actual workflow development "sizing and simulation of district heating network". Based on the geo-localized heat demand and loads calculated in *SimStadt*, an optimized network layout is automatically generated by means of graph algorithms, and its pipe sizes and heat losses calculated by the utility network calculation software *Stanet.*

EXAMPLE APPLICATION: ADMINISTRATIVE DISTRICT OF LUDWIGSBURG

The administrative district of Ludwigsburg covers a ground area of approx. 700 km² at the South-West Germany and counts 34 municipalities for a total population over half a million inhabitants.

In the framework of the project *Integriertes Klimaschutzkonzept Landkreis Ludwigsburg*, an Energy action plan was conducted to identify and plan CO2 emission savings, based on the available 3D city models (CityGML, Level of Details 1 and 2). For this purpose, different workflows of the urban energy simulation platform SimStadt have been used and combined to assess the actual heating demand and the related CO2 emissions per building, predict energy savings potential following different refurbishment scenarios, and identify the solar energy potential.

For the whole studied area, the total yearly heating demand reaches 3.9 TWh, with an average specific heating demand of 145 kWh/m².yr. Considering the heating system distribution available for each municipality (from census data survey), this corresponds to 0.92 Mega-tonnes equivalent CO_2 per year.

Fig. 3: Specific heating demand calculated with SimStadt, view in a Web browser (originally in color).

In a neighbourhood of Ludwigsburg (Grünbühl) where actual gas consumptions were available, comparison with the calculated consumptions showed deviations varying from 2% to 31% depending on the data availability and quality [5].

For the photovoltaic potential analysis, only roofs with a surface larger than 40 m² and receiving more than 1100 kWh/m².yr solar radiation have been selected. In total, the diffuse power central formed by all these roofs could generate 668 MWh/yr, which would cover 26% of the electric demand (for building electrical appliances) of the administrative district.

CONCLUSION AND PERPECPECTIVES

In the recent years, considerable progresses have been realized in both domains urban energy simulation and 3D Geographical Information System, however without notable cross-domain interactions. The new urban energy simulation platform SimStadt introduced in this paper holds in its DNA both domains, making the best common use of models and geo data.

The first *SimStadt* version integrates workflows, which allow for first city-scale energy demand diagnoses as well as low-carbon scenario simulations. Meanwhile, it remains a great deal of work to model energy flows more precisely, with higher Level of Details, shorter time resolutions (typically hourly loads) and taking into account the whole complexity of urban scale interactions. Integrating optimisation functions supporting decision takers in the definition of their energy strategies is also an exciting challenge.

In any case, based on its extensible modular structure and on the full potential of virtual city models, the new SimStadt platform may provide an adequate and powerful solution to plan and coordinate the energy transition, at the scale of neighbourhoods, cities or whole regions.

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