

URBAN ENERGY SIMULATION BASED ON A NEW DATA MODEL PARADIGM: THE CITYGML APPLICATION DOMAIN EXTENSION ENERGY. A CASE STUDY IN THE EPFL CAMPUS OF LAUSANNE

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ABSTRACT

The rapid urbanisation and the increase of world population underline the need of a new approach in the urban design, based on the energy efficiency and the sustainability of the built environment. When focusing on City Energy Modelling, unlike Building Energy Modelling, each urban simulation engine generally has its own tailor-made data-model: municipalities and other urban information data administrators use their own data base structure to collect and manage urban information data, without the possibility to store and share urban models. To address this issue, since May 2014, an international consortium of urban energy simulation developers and users is establishing an Urban Energy Information standard, as Application Domain Extension (ADE) of the CityGML urban information model. This paper presents a methodology to establish a gateway between one of the urban simulation tools CitySim and the CityGML Energy ADE data format. The future EPFL campus in Lausanne is presented as case study, demonstrating the storage possibility of the CityGML Energy ADE of geometrical properties and annual heating and cooling demands for each building. The connection between CitySim and CityGML Energy ADE represents an innovative approach for the urban energy analysis: city model can be simulated, stored and exchanged between both format creating a common database of knowledge, in which researchers and municipalities could share their results.

Keywords: CityGML, Urban Energy Simulation, urban data model, CitySim

INTRODUCTION

Due to a rapid urbanization throughout the planet, planners and decision makers from municipalities are facing important challenges in controlling the growth of the number of shelters and their associated energy consumption. Furthermore, the densification of actual city centres goes through inevitable planning choices that need to be addressed from the city scale point of view in order to mitigate traffic and building energy consumption but also to increase renewable energy

sources. To address these urban scale elements, specific algorithms and software solutions have been recently developed by international research centres and private sector actors.

When focusing on City Energy Modelling, unlike Building Energy Modelling where few well-established building information model standards exist (IFC, gbXML, etc.) and serve as exchange support between different tools and experts, each urban simulation engine generally has its own tailor-made data-model. The situation gets even more complicated as municipalities and other urban information data administrators use their own data base structure to collect and manage urban information data. This leads to multiple import and export features for the different tools that may complicate the life of the practitioners and feel like an everlasting starting over.

To address this issue, since May 2014, an international consortium of urban energy simulation developers and users (11 European organisations¹ representing 5 urban energy platform developments²) is establishing an Urban Energy Information standard, as Application Domain Extension (ADE) of the CityGML urban information model. CityGML is a XML-based open data model for the storage and exchange of virtual 3D city models, issued by the Open Geospatial Consortium (OGC) (Gröger et al. 2012). CityGML is organised around a CityGML core model, prolonged by Application Domain Extensions (ADE) for different purposes such as : geometry, construction, occupancy and energy systems. With the Energy ADE under development, the set of ADE will allow to add Energy related information to existing CityGML models. The CityGML core is already well established for the

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² CitySim, SimStadt, Energy Atlas, Modelica library AixLib, Sunshine platform.

modelling of whole agglomerations (Berlin, Lyon) (Eicker et al. 2012) (Nouvel et al. 2013), regions and countries (Germany) (OGC), it offers possibilities for numerous and varied spatial analyses at the city scale such as noise mapping, urban wind flow studies, photovoltaic potential or flood risk analysis. A considerable asset of CityGML is its flexible object modelling in different Levels of Details (LOD) (Biljecki et al. 2014), enabling the virtual city model to adapt to local building parameter availability and application requirements. CityGML works in five discrete LODs (LOD0–4) characterized by further increase of details, from LOD0 that represents the digital ground without buildings, to LOD4 that adds the internal geometry of buildings (Biljecki et al. 2014). LODs enable the virtual city model to adapt to local building parameter availability and application requirements.

This paper starts with a brief introduction of the specificities of the CityGML Energy ADE standard and presents the first simulation results based on the CitySim simulation. CitySim is an urban energy modelling able to quantify heating and cooling demand from a single building to the urban scale with simplified input physical and geometrical data (Robinson 2011). The aim of this study is to use as a first case-study the project of the EPFL campus in Lausanne to be completely described (geometrically and physically) using the CityGML Energy ADE with a level of detail allowing for hourly dynamic simulations. The first results are visualized with FZKViewer (Karlsruher 2015), a free program able to read and display geometrical 3D CityGML data. Further results showing the thermal behaviour of the campus today and in futures climatic scenarios, according to Institute panels of Climate Change (IPCC) - scenarios A1B, A2 and B1 (IPCC 2000), are stored using the CityGML Energy ADE. The paper concludes with an analysis of the future possibilities offered by the new data model.

METHODOLOGY

The methodology aims to show the gateway between CitySim and CityGML data models. It starts by explaining the paradigms behind the CitySim data model, and follows by detailing the one of the CityGML Energy ADE. The methodology ends by defining the case-study on which we will shift from the CitySim to the CityGML data model to demonstrate the exchange of information concerning geometrical properties of buildings and their annual energy demand.

CitySim data model

CitySim data model is based on XML (eXtensible Markup Language) format and composed of different modules defining each a building in the scene:

- Building thermal zone, which contains the information about volume, set-point

temperatures for heating/cooling, infiltration rate and thermal bridges, but also:

- Occupation (number of occupants, and their profile during the day)
- Description of the Walls (geometrical and physical, together with the characteristics of the windows and and photovoltaic systems).
- Description of the Roofs (same parameters).
- Description of the Floors (same parameters).
- Energy system for heating and cooling purposes.

The structure is tree-based with objects included in other objects such as Walls inside a Thermal Zone inside a Building.

CityGML with Energy ADE data model

CityGML with Energy ADE is structured by the following four interrelated modules, which are linked to the 3D information in the CityGML core through references:

- Building, Zones and Boundaries: contains information concerning buildings geometry, thermal zones, opening and schedules.
- Construction and Layers: defines physical characteristics of the envelope, such as material, and their physical and optical properties (emittance, absorptance, transmittance, and reflectance).
- Occupancy Module: describes the usage of the building, the presence of occupants, and the consequently usage of facilities and appliances.
- Energy System Module: describes the energy demand, supplied by different energy systems (conversion, distribution and storage).

The four modules are completely independent of each other, may also not be present and linked together through references.

The gateway between CitySim and CityGML Energy ADE data model

According to previous analysis, CitySim and CityGML data model have a common data organized in different structures. The structure of the CitySim data model is tree-based, where a district contains buildings, and each building contains thermal zones, which contain further information about the building such as physical and geometrical characteristics. On the contrary, the structure of the CityGML data format is organized in independent modules which may or may not be present for each building. Figure 1 summarizes the idealized structure of CitySim (a) and CityGML Energy ADE (b). In CitySim the building tag contains all information about the building; on the contrary with the CityGML Energy ADE each module is linked with the CityGML core and some modules are interconnected between them: Building, Zones and Boundaries are linked with

Occupancy and Energy System modules, and the latter is connected with Construction and Layer.

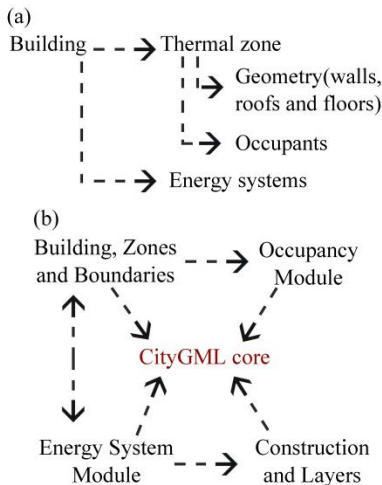


Figure 1 Idealized data structure of CitySim (a), and CityGML Energy ADE (b)

The following example illustrates the geometrical properties in CitySim and CityGML data model. In CitySim the geometrical data are contained in the building tag and directly correlated with the envelope properties, thermal zone and energy system:

```
<Building>
  <HeatTank ... />
  <CoolTank ... />
  <HeatSource ... />
  <CoolSource ... />
  <Zone>
    <Occupants ... />
    <Roof ...>
    <V0 x="0.00" y="0.00" z="0.00"/>
    <V1 x="2.0" y="0.00" z="0.00"/>
    <V2 x="2.0" y="0.0" z="3.0"/>
    <V3 x="1.0" y="0.0" z="3.5"/>
    <V4 x="0.0" y="0.0" z="3.0"/>
  </Roof>
</Zone>
</Building>
```

On the contrary, in CityGML the geometrical properties are stored into the Building, Zones and Boundaries module, and the ID of each surface is recalled in further modules, adding specificities (Construction and Layers, Occupancy Module and Energy System Module).

```
<cityObjectMember>
  <bldg:Building>
    <bldg:lod2Solid>
      <gml:Solid>
        <gml:exterior>
          <gml:CompositeSurface>
            <gml:surfaceMember>
              <gml:Polygon gml:id="b3411_p_w_111290">
                <gml:exterior>
                  <gml:LinearRing>
                    <gml:posList>
                      0.00 0.00 0.00
```

```
                2.00 0.00 0.00
                2.00 0.00 3.00
                100 0.00 3.50
                0.00 0.00 3.00
                0.00 0.00 0.00
            </gml:posList>
          </gml:LinearRing>
        </gml:exterior>
      </gml:Polygon gml:id="b3411_p_w_111290">
    </gml:surfaceMember>
  </gml:CompositeSurface>
</gml:exterior>
</gml:Solid>
</bldg:lod2Solid>
</bldg:Building>
</cityObjectMember>
```

An adequacy between both data model can be defined: each 3D geometrical and physical data from CitySim data model can be transformed to CityGML data model. The same process can be established for the simulations results: urban models simulated with the software CitySim can be saved using the CityGML Energy ADE including the annual heating and cooling demand of each building.

Case study: the EPFL campus in Lausanne

The simulation model of the EPFL campus is an existing case study, where the energy model realized with the software CitySim is exported in CityGML format. The EPFL campus, located near the Leman lake, is composed of four districts (North, East, West, South and Central district), subdivided into twenty-seven main buildings, as shows in Figure 2.

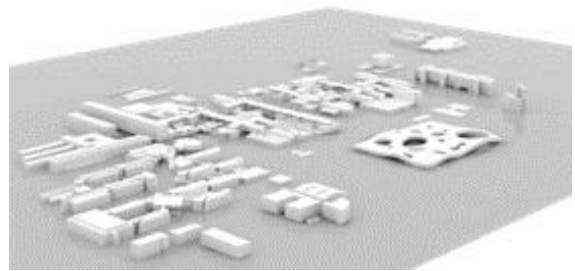


Figure 2 Geometrical 3D view of the EPFL Campus in Lausanne

The campus was built in two main phases, which characterize the geometry and materials of buildings: first phase in 1972-1984 and second one in 1980-2002 (DII 2004); later buildings were added to the site such as the Rolex Learning Centre and Swiss Tech Convention Centre. The characteristics of buildings' envelopes are defined according to the period of construction: buildings built in the same period are part of a homogenous architectural plan and present the same physical characteristics. The geometrical model of the campus is based on an existing 3D model (Carneiro 2011), and the occupancy profile is defined according to SIA 2024/2006 (SIA 2006): the number of occupants and their presence is based on the liveable surface of the

building and its function (office, restaurant, classroom and dormitory).

The roofs of buildings are covered by photovoltaic panels, with a total power of 2 MW peak and a total area of 12,285 m². Photovoltaic panels were installed in three different phases -in 2010, 2011 and 2014- by the electricity carrier Romande Energie. Each phase of construction is characterized by a different type of panel (monocrystalline, polycrystalline, thin film and silicium) and manufacturer (EPFL 2014). Detailed data concerning the set-up of the model are available (Coccolo, Kämpf, and Scartezzini 2015).

Figure 3 shows an extract of the XML file written by the software CitySim for the model of the EPFL campus in Lausanne. As described before, the hierarchical structure of the XML has its vertex in the building, which contains the energy systems and the thermal zone, which is characterized by its geometry and occupants.

```

<Building Name="AAB" id="3411" key="126" Vi="12461.347778683068" Ninf="0.3"
  <HeatTank id="1" name="default Heat Tank 1" brand="Rack" model="RTB-25"
  <CoolTank id="2" name="default Cool Tank 1" brand="Unknown" model="Unknou
  <HeatSource beginDay="243" endDay="121">
    <Boiler id="1" name="PARKER T300L" brand="PARKER" model="T300L" fuel
  </HeatSource>
  <Zone id="0" volume="12461.347778683068" psi="0.0" groundFloor="true">
    <Occupants n="372" d="NaN" type="1"/>
    <Roof id="1278" Area="157.66" GlazingRatio="0.0" GlazingGValue="0.5"
      <V0 x="3743.76171875" y="2495.94775390625" z="9.88703441619873"/
      <V1 x="3743.76171875" y="2492.450439453125" z="10.55961513519287
      <V2 x="3832.3017578125" y="2492.450439453125" z="10.559615135192
    </Roof>
    <Roof id="1282" Area="153.56" GlazingRatio="0.0" GlazingGValue="0.5"
      <V0 x="3832.3017578125" y="2489.040771484375" z="9.9215621948242
      <V1 x="3832.3017578125" y="2492.450439453125" z="10.559615135192
      <V2 x="3743.76171875" y="2492.450439453125" z="10.55961513519287
    </Roof>
    <Wall id="111290" Area="74.53" GlazingRatio="0.5" GlazingGValue="0.5
      <V0 x="3832.3017578125" y="2486.5302734375" z="-2.09038496017456
      <V1 x="3832.3017578125" y="2486.5302734375" z="2.126281738281248
      <V2 x="3796.9472278676303" y="2486.5302734375" z="2.126281738281
    </Wall>
    <Wall id="111291" Area="169.33" GlazingRatio="0.5" GlazingGValue="0.
      <V0 x="3761.5926979227606" y="2486.5302734375" z="6.342948436737
      <V1 x="3832.3017578125" y="2486.5302734375" z="6.342948436737059
      <V2 x="3832.3017578125" y="2486.5302734375" z="8.46961498260498
      <V3 x="3743.76171875" y="2486.5302734375" z="8.46961498260498"/>
    </Wall>
    <Wall id="111292" Area="223.61" GlazingRatio="0.5" GlazingGValue="0.
      <V0 x="3832.3017578125" y="2486.5302734375" z="6.342948436737059
      <V1 x="3761.5926979227606" y="2486.5302734375" z="6.342948436737
      <V2 x="3796.9472278676303" y="2486.5302734375" z="2.126281738281
      <V3 x="3832.3017578125" y="2486.5302734375" z="2.126281738281248
    </Wall>
  </Zone>
</Building>

```

Figure 3 Extract of the EPFL campus model in CitySim XML format

On the contrary, the model of the EPFL campus written in CityGML format (Figure 4) presents a modular structure, not hierarchically organized around the building, but based on the four interconnected models (Building, Zones and Boundaries, Construction and Layers, Occupancy Module and Energy System Module).

```

<cityObjectMember>
  <blgd:Building Name="Bldg-3411">
    <blgd:lod2Solid>
      <gml:Solid>
        <gml:exterior>
          <gml:CompositeSurface>
            <gml:surfaceMember>
              <gml:Polygon gml:id="b3411_p_w_111290">
                <gml:exterior>
                  <gml:LinearRing>
                    <gml:posList>
                      3832.30 2486.53 -2.09
                      3832.30 2486.53 2.13
                      3796.95 2486.53 2.13
                      3832.30 2486.53 -2.09
                    </gml:posList>
                  </gml:LinearRing>
                </gml:exterior>
              </gml:Polygon>
            </gml:surfaceMember>
            <gml:surfaceMember>
              <gml:Polygon gml:id="b3411_p_w_111291">
                <gml:exterior>
                  <gml:LinearRing>
                    <gml:posList>
                      3761.59 2486.53 6.34
                      3832.30 2486.53 6.34
                      3832.30 2486.53 8.47
                      3743.76 2486.53 8.47
                      3761.59 2486.53 6.34
                    </gml:posList>
                  </gml:LinearRing>
                </gml:exterior>
              </gml:Polygon>
            </gml:surfaceMember>
          </gml:CompositeSurface>
        </gml:exterior>
      </gml:Solid>
    </blgd:lod2Solid>
  </blgd:Building>
</cityObjectMember>

```

Figure 4 Extract of the EPFL campus in CityGML XML format

DISCUSSION AND RESULT

Using the previously described methodology, we present in what follows the abilities of the CitySim software to export the geometrical information to the CityGML data format, and to further export the annual simulation results for heating and cooling demands using the CityGML Energy ADE.

Geometrical information

The model of the EPFL campus in Lausanne is presented in Figure 5 read and displayed by the FZKViewer. The geometrical data exported maintain a distinction between walls, roofs and floors.

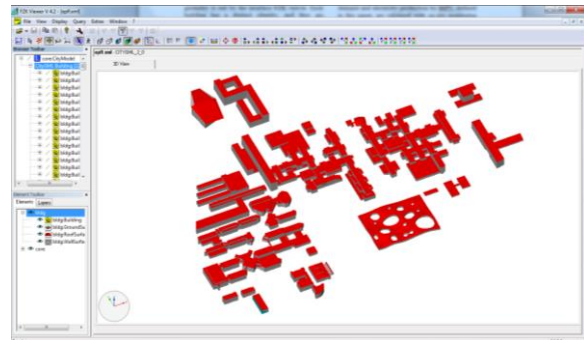


Figure 5 EPFL campus in Lausanne exported in GML format

Annual PV production and energy demand for heating and cooling

The EPFL Campus, located in Lausanne (Switzerland) is analysed with the software CitySim, showing the dynamic heating and cooling demand of the site. Figure 6 shows the 3D model of the campus with photovoltaic panels (coloured in grey) and the annual solar irradiation (shortwave, expressed in kWh·m⁻²).

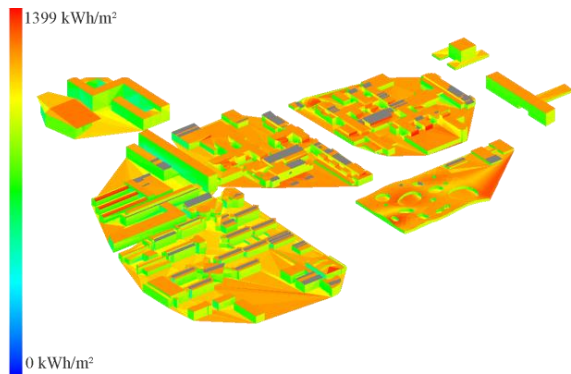


Figure 6 Annual solar irradiation on the campus, with PV geometry on the roofs (grey surfaces)

Figure 7 shows the energy demand for heating: buildings AI and SV have the highest energy demand (around $150 \text{ kWh}\cdot\text{m}^{-2}$) because they host the Life Sciences faculty, with its experimental laboratories that need an important ventilation rate (heated during the winter period) to maintain the correct indoor temperature. New constructions (BC building, Rolex Learning Centre and Swiss Tech Convention Centre) are built according to the Minergie standards, and they present a performing envelope and an efficient air exchange system. The EPFL annual heating demand and electricity production by BiPV, defined in this paper, are validated with on-site monitoring (correlation factor $R^2=0.89$ and $R^2=0.93$ respectively). Experimental laboratories present wide difference between model and monitoring, because of their powerful machines and high ventilation rate; for example in buildings ELG and ELH the difference between simulation and monitoring data rise up to 26%.

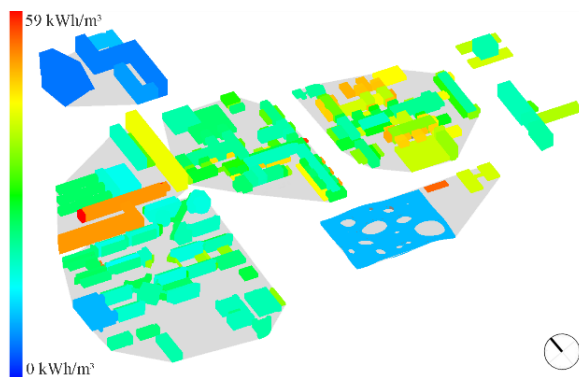


Figure 7 Annual heating demand of the campus, expressed in ($\text{kWh}\cdot\text{m}^{-2}$)

Figure 8 shows an extract of the corresponding CityGML ADE Energy XML file. The energy demand for heating (`<energy:id> SpaceHeating_1 </energy:id>`) is defined for each building, in this case building BC, and expressed in kWh (`<energy:uom uom="kWh"/>`) for the whole year (`<energy:timeIntervalunit="year">1</energy:timeInterval>`) under the tag `<energy:values> 354000 </energy:values>`.

```
<energy:EnergyDemand>
  <energy:endUse>SpaceHeating</energy:endUse>
  <energy:energyAmount>
    <energy:RegularTimeSeries>
      <energy:id>SpaceHeating_1</energy:id>
      <energy:temporalExtent>
        <gml:TimePeriod>
          <gml:beginPosition>01.01.2014</gml:beginPosition>
          <gml:endPosition>31.12.2014</gml:endPosition>
        </gml:TimePeriod>
      </energy:temporalExtent>
      <energy:variableProperties>
        <energy:TimeValuesProperties>
          <energy:acquisitionMethod>Sim</energy:acquisitionMethod>
          <energy:interpolationType>Con</energy:interpolationType>
          <energy:qualityDescription>No</energy:qualityDescription>
          <energy:source>On-site sensor</energy:source>
          <energy:uom uom="kWh"/>
          <energy:variableLabel>Heating</energy:variableLabel>
        </energy:TimeValuesProperties>
      </energy:variableProperties>
      <energy:timeInterval unit="year">1</energy:timeInterval>
      <energy:values>
        354000
      </energy:values>
    </energy:RegularTimeSeries>
  </energy:energyAmount>
</energy:EnergyDemand>
```

Figure 8 Heating demand of the EPFL campus in Lausanne, today scenario. Extract of the CityGML ADE XML file

Figure 9 shows an extract of the corresponding CityGML ADE Energy XML file for the cooling demand of the same building. The energy demand for cooling (`<energy:id> SpaceCooling_1 </energy:id>`) is expressed in kWh (`<energy:uom uom="kWh"/>`) in hourly values (`<energy:timeIntervalunit="hours">1</energy:timeInterval>`) for a summer day. The energy demand is expressed under the tag `<energy:values> 259.51 </energy:values>`.

```
<energy:EnergyDemand>
  <energy:endUse>SpaceHeating</energy:endUse>
  <energy:energyAmount>
    <energy:RegularTimeSeries>
      <energy:id>SpaceCooling_1</energy:id>
      <energy:temporalExtent>
        <gml:TimePeriod>
          <gml:beginPosition>01.01.2014</gml:beginPosition>
          <gml:endPosition>31.12.2014</gml:endPosition>
        </gml:TimePeriod>
      </energy:temporalExtent>
      <energy:variableProperties>
        <energy:TimeValuesProperties>
          <energy:acquisitionMethod>Sim</energy:acquisitionMethod>
          <energy:interpolationType>Con</energy:interpolationType>
          <energy:qualityDescription>No</energy:qualityDescription>
          <energy:source>On-site sensor</energy:source>
          <energy:uom uom="kWh"/>
          <energy:variableLabel>Cooling</energy:variableLabel>
        </energy:TimeValuesProperties>
      </energy:variableProperties>
      <energy:timeInterval unit="hour">1</energy:timeInterval>
      <energy:values>
        259.51
      </energy:values>
    </energy:RegularTimeSeries>
  </energy:energyAmount>
</energy:EnergyDemand>
```

Figure 9 Cooling demand of the EPFL campus in Lausanne, today scenario. Extract of the CityGML ADE XML file

CONCLUSION

Several computer tools quantify the energy demand and thermal behaviour of buildings, from the urban to the edifice scale, but none of them is actually able to convert and exchange information between them at the urban scale. For this reason, a new paradigm called the CityGML Energy ADE is under development. This paper presents a methodology to establish a gateway between one of the urban simulation tools CitySim and the CityGML Energy ADE data format. The future EPFL campus in Lausanne is presented as case study, demonstrating the storage possibility of the CityGML Energy ADE of geometrical properties and annual heating and cooling demands for each building. The connection between CitySim and CityGML Energy ADE represents an innovative approach for the urban energy analysis: city model can be simulated, stored and exchanged between both format creating a common database of knowledge, in which researchers and municipalities could share their results. Future development of this research topic will focus on displaying results obtained through different software in graphical user interfaces.

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