CI-NERGY Project – Deliverable 11

Detailed simulation platform prototype

Lead Beneficiary : AIT

Table of Contents

1. Introduction

The CI-NERGY Marie Curie Initial Training Network (ITN) aims to train young scientists to develop urban decision making and operational optimisation software tools to minimise non-renewable energy use in cities. As such, one of the expected outcomes of the project is a simulation platform prototype to help solve problems in urban energy system planning, design and operation. This tool is on the concepts and methods developed by the CI-NERGY ITN, which brings together a multi-disciplinary and cross-sectorial team of researchers, combining the academic excellence of renowned research institutes with the practical experience of companies and public authorities.

This report describes the prototype platform developed so far, the main components and explains the main reasons that led to the current design and implementations decisions. Given that such a platform relies upon the development of individual tools and methods carried out by the different ESRs during their PhDs, any integration effort carried out simultaneously is understandingly complicated by the lack of finished individual tools. Furthermore, the heterogeneity of purposes and case studies to be analysed within the CI-NERGY project has led to adopt structural and design decisions based (also) on pragmatic considerations regarding the timing and the overall usage of the platform.

The deliverable is structured as follows, each of the following points corresponding to a section.

- The overall vision of the CI-NERGY project, which defines the main goals
- The main characteristics of the platform with regards to its main components and functionalities
- Some results obtained by usage of the platform for some case studies
- The concluding remarks and a brief description of the upcoming steps.

2. Vision

Thriving to bring together the cross-sectorial expertise of the different partners of the project, the initial vision of the overall structure of the platform to be developed within the CI-NERGY project is represented and summarised in the schema in Figure 1.

The schema shows and incorporates both the (co)-simulation platform (described in this report) and the high level decision making platform (described in Deliverable 10 “High level decision support prototype”). It stems from interviews which took place between M12 and M18 of the project in order to have a better understanding of the research work and envisioned models of each ESR, and their potential contribution to the CI-NERGY tool.

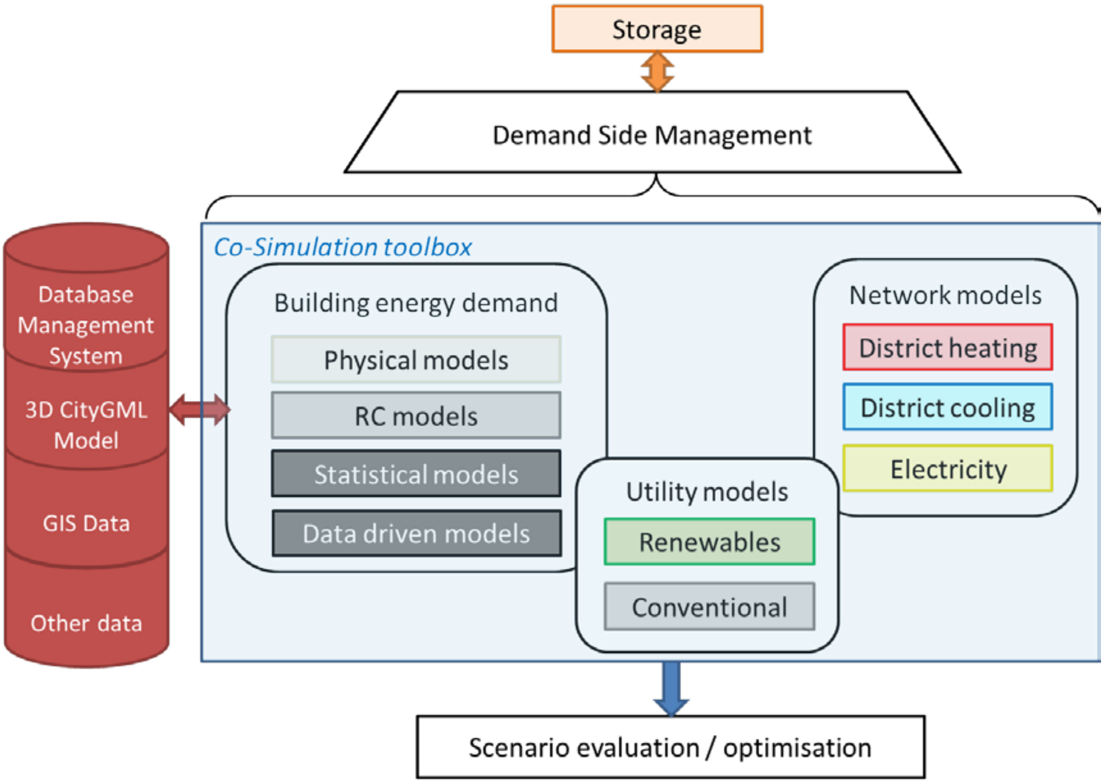

Figure 1 – Overall schema of the CI-NERGY framework

In the co-simulation toolbox, several simulation models are combined using either the FMI co-simulation standard or by means of a service oriented platform. This includes simulation of network models (district heating and electricity grid), energy demand models of buildings and utility models. The co-simulation platform is coupled to a spatial database (including also a CityGML-based semantic 3D model of the city) which stores all the data required for the simulation and decision support platforms in a systematic way, reproducible for any city if sufficient data is available.

The co-simulation framework can be used to test different scenarios, such as building refurbishment or integration of renewable energy sources on the thermal and electricity networks. Moreover, different demand side management strategies including short or long term storage can be tested.

The co-simulation toolbox is then combined with a high level optimisation framework. Please refer to the specific report for more details about it.

3. Main characteristics of the platform components

Maximizing energy conservation, improving energy efficiency and integration and control of renewable energy sources are critical in order to achieve a low carbon future. Integrated modelling systems are therefore needed in order to evaluate and improve energy performance of urban energy systems' design and operation, from both financial and environmental perspectives.

Over the last few decades, a number of high quality domain specific simulation tools have been developed to simulate dynamic system behaviour of urban energy systems (Keirstead et al., 2012). They are able to help to understand related problems in a certain domain. However, less effort appears to focus on creating integrated modelling systems to couple energy simulation models at various temporal and spatial scales from different domains within the urban energy systems modelling community.

At the same time, the energy domain is a highly heterogeneous and multi-disciplinary field. Within each field there are multiple participants requiring information with varying level of granularity. Moreover, these participants use diverse devices to access and visualize information. This makes it a challenging task to share, retrieve, update and visualize information in a seamless manner. With the recent advancement in Information & Communication Technology (ICT), Service Oriented Architecture (SOA) has been gaining a lot of momentum. SOA is an enabler that exposes software functionalities as Web Services.

To this end, two approaches have been explored and developed within the CI-NERGY project.

The first one focuses in particular on the definition and implementation of a standards-based urban energy co-simulation framework. Its modular design enables it to integrate different urban energy simulation tools encapsulated in Functional Mockup Unite (FMU). The corresponding urban energy modelling system developed by using this framework can provide an integrated representation of urban energy usage. Detailed simulation results from such system are able to provide a comprehensive solid basis of scientific analysis to facilitate urban planners and policymakers in planning and decision-making process.

The second one focuses in particular on problems related to the above-mentioned Service Oriented Architecture. The goal of such an approach is to provide the CI-NERGY users with an open web-service-based orchestration engine. This platform is conceived to enable users to combine services to address individual use cases. Furthermore, the platform is designed to support open interfaces and hence ensure seamless information exchange among connected components.

Both approaches rely on a semantic 3D city model of a city as integrated and harmonised source of data regarding all relevant entities at city level (buildings, networks, etc.) (Agugiaro, 2016a). The 3D city model is based on the OCG (Open Geospatial Consortium) open standard CityGML (Gröger et al, 2012).

CityGML is an international standard that defines physical layout of a city according to its semantics, geometry, topology and appearance. It is an information and data model for semantic city models at urban scale, which intends to support simulation, urban data mining, facility management and thematic inquiries. CityGML can be further extended by means of so-called Application Domain Extension (ADE), in that further classes and attributes can be added to cover particular need coming from specific domains.

For example, CityGML does not define currently all energy-related attributes and features of buildings in a systematic and standard way. To address requirement for building energy simulation based on CityGML, a so-called Energy ADE is being developed and implemented by an international consortium. A common data model plays a critical role in simulation integration and simulation compatibility, as well as in data exchange. Therefore, CityGML together with Energy ADE was chosen as data model used in both approaches mentioned above (Agugiaro, 2016b).

Finally, both approaches tackles specific problems related with energy simulation and, most importantly, with the need to integrate different tools in order to carry out specific, interdisciplinary tasks. They are therefore complementary elements of the overall planned framework represented in Figure 1.

3.1 FMI-based co-simulation platform

The standards-based urban energy co-simulation framework aims to contribute developing urban decision making and operational optimization software tools to minimize non-renewable energy use in cities.

Co-simulation technology is used by the framework to integrate urban energy subsystems across the borders of various traditional energy domains. Functional Mockup Interface (FMI) co-simulation standard is used in the framework to make it reusable and flexible to integrate multiple simulation models. As master algorithms are not part of the FMI standard, Mosaik, a smart grid co-simulation framework developed by OFFIS, is modified and extended to support the FMI standard and is used as a library to program master algorithms.

A short introduction to co-simulation key characteristics is presented, in order to provide the reader with some preliminary concepts and better understand the following sections.

3.1.1 Introductory notes to co-simulation

Integrating models of multiple aspects of urban energy system such as demand models, supply models, agent-activity models and urban energy supply network models is a complex task to analyse and implement. To tackle such challenge, co-simulation (i.e. co-operative simulation) approaches have been adopted by a number of researchers such as Palensky et al. (2014), Chapman et al., (2014), Kosek et al. (2014), Thomas et al. (2014), Stifter et al. (2013).

Co-simulation basically consists in jointly simulating phenomena modelled by different tools. In other words, existing domain-specific modelling tools, each with its own peculiarities and strengths, are coupled in a way that enables a dynamic multi-physics simulation of a hybrid system. Co-simulation can be implemented using different strategies. From the coupling point of view, the implementation can be done using either tight coupling (onion) or loose coupling (ping-pong) as indicated in Figure 2 (Hensen, 1995; Vaculín et al., 2004). Tight coupling requires an iterative solution among involved simulators to satisfy a predefined convergence criterion in each step. In loose coupling, simulators only use data from preceding step, which can have their own iterations, and there is no iteration required between the coupled simulators.

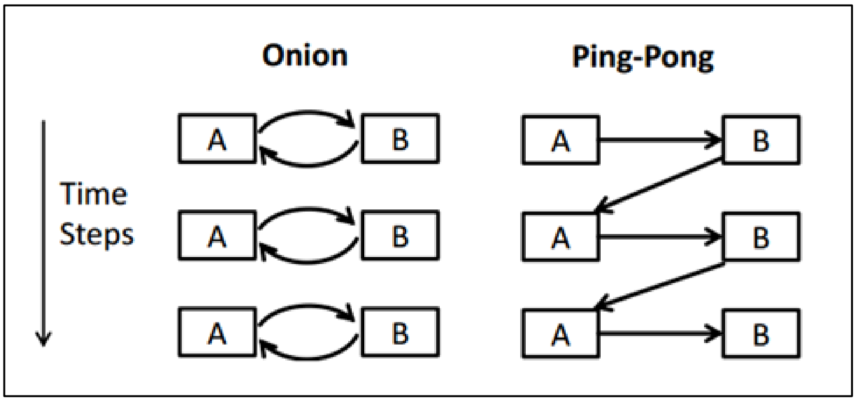

Figure 2 – Data exchange scheme of tight coupling (onion) vs. loose coupling (ping-pong)

In order to link different simulation tools and have them interact (e.g. exchange data) with each other in an harmonised way, the independent industry standard FMI (Functional Mock-up Interface) (Blochwitz et al., 2012) is adopted in order to support co-simulation of dynamic models. The co-simulation part of the FMI specification defines essential interfaces and enables diverse simulation tools to interoperate, covering all stages of the co-simulation process including instantiation, initialization, configuration, access, modification and manipulation.

In a FMI co-simulation environment, simulation models need to be distributed in one zip file called Functional Mockup Unite (FMU), which contains an XML file for describing the model and necessary FMI APIs library that is implemented as an executable (Windows dynamic link libraries (.dll) or Linux shared object libraries (.so)). The FMI APIs of an FMU can be used by master algorithms to create instances of the FMUs and to orchestrate them.

3.1.2 Co-simulation platform characteristics

The co-simulation platform is composed of a large variety of technologies and libraries. Figure 3 shows the overall architecture of the platform. Each layer of the co-simulation platform is explained in the following.

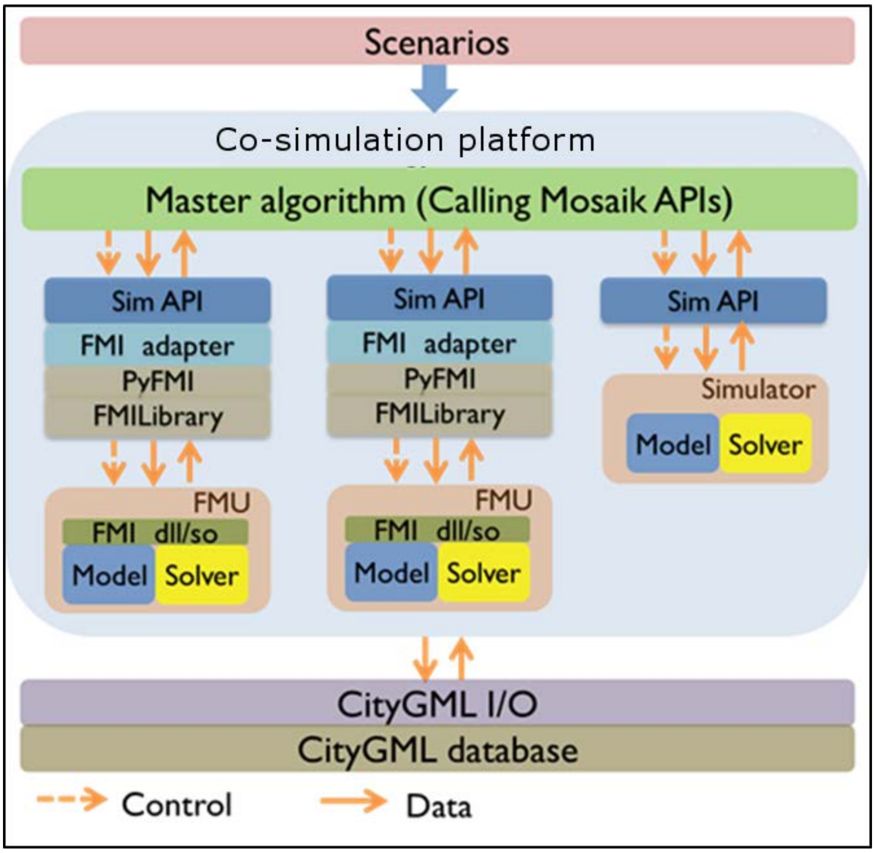

Figure 3 - Architecture of the urban energy co-simulation framework

Scenarios: Scenarios are designed by energy planning experts, who have technical knowledge about urban energy systems that are to be simulated as well as knowledge about the available simulation tools to be integrated. For the co-simulation platform, scenarios contain configuration information of simulators to be included, topology to connect model instances of these simulators, and data flow between model instances.

Master algorithm: The master algorithm provides ability to orchestrate the simulation and data flow of individual components. Mosaik scenario APIs and sim APIs are used to program the master algorithm. Mosaik scenario APIs are responsible for starting simulators and instantiate models from them, while Mosaik sim APIs allows orchestrating interactions between the integrated simulators.

Sim API: For simulators to be integrated to the co-simulation framework, Mosaik sim APIs need to be implemented.

FMI adapter: All simulators to be integrated need to be encapsulated in FMU format. In order to integrate FMUs to the co-simulation framework, Mosaik should have the ability to call FMI APIs. This is done by developing a FMI adapter for Mosaik, which maps Mosaik sim APIs and FMI APIs.

PyFMI, FMILibrary and FMUs: Currently, FMUs provide FMI APIs in binary form as DLL for Windows, and/or as shared object for Linux or Mac, which is implemented in C programing functions. Mosaik is developed in Python programing language. Therefore, the Mosaik FMI adapter and master algorithm of the co-simulation framework is implemented in Python because it calls Mosaik APIs and Mosaik FMI adapter. In order to enable master algorithm call C functions in the FMI dll/so provided by FMU, PyFMI and FMI Library are integrated to the framework. PyFMI is a Python package for loading and interacting with FMUs using Python native calls based on FMILibrary, which is a C package provides a complete interface to the FMI-standard making the interaction with FMU via FMI APIs.

3.2 Service-oriented platform

The Service Oriented Architecture implemented in the CI-NERGY project, three key standard technologies (i.e. SOAP, WSDL, UDDI) are used. Simple Object Access Protocol (SOAP) (Gudgin, 2007) defines a messaging standard based on XML and, with the help of HTTP, provides a communication protocol for accessing web services. Web Service Description Language (WSDL) (Christensen, 2001) is used to describe the web service access interface. Universal Discovery, Description and Integration (UDDI) (Clement, 20014) is a registry that allows advertisement and discovery of web services thereby providing the opportunity to dynamically bind a web service at runtime.

As shown in Figure 4 the Ci-NERGY project uses the Service Oriented Architecture concepts and provide an open web-service-based orchestration engine. This platform is conceived to enable users to combine services to address individual use cases. Furthermore, the platform is designed to support open interfaces and hence ensure seamless information exchange among connected components.

What is more, the use of a Service Oriented Architecture approach in the Ci-NERGY project fosters the following innovation:

- Exchange of information among distributed tools (simulation/co-simulation, optimization, decision support etc.).
- Flexible web interfaces tailored to address different users and use cases
- Modular approach enables non-specialists to combine different modules to develop new energy related tools
- Visualization of results on heterogeneous devices (e.g. tablets, laptops, etc.)

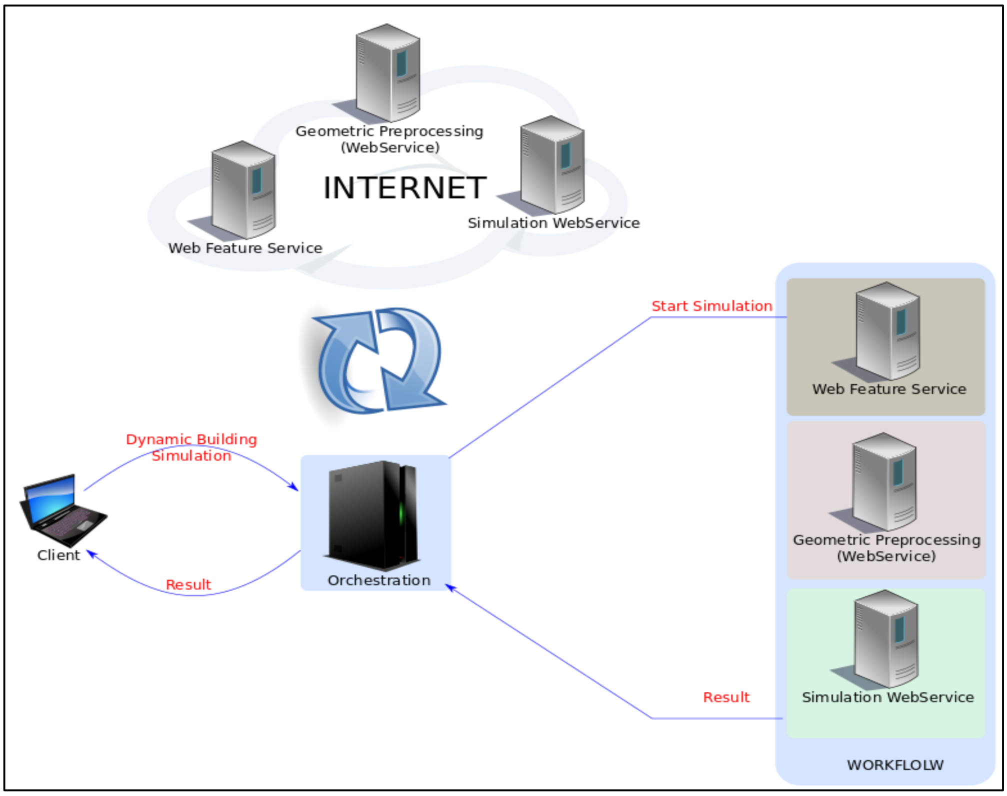

Figure 4 – Ci-NERGY urban energy simulation platform

3.2.1 Service-oriented platform characteristics

Ci-NERGY urban energy simulation platform aims to empower urban planners and city managers alike to define lowcarbon energy strategies with a variety of multi-scale energy analyses. Based on open 3D city models and with its modular workflow driven design make it highly extensible simulation platform. Figure 4 depicts the overall workflow-driven concept utilized by Ci-NERGY simulation Platform. Functionality of each workflow step is explained below.

Web Feature Service (WFS): The WFS is an input workflow step. It reads a CityGML model and extracts building information from CityObject. This information is then mapped into an internal data structure. The internal data structure assigns unique IDs to each wall and maintains the accuracy of buildings' geometric information with the help of vertices, edges and polygons. This step is essential to remove redundant information and provide spatio-semantic coherent data structure for energy simulation. Furthermore, the coherency and quality assurance of geometry data aids in reducing the uncertainty of simulation results. On successful completion of the input workflow step, preprocessing workflow step is triggered.

Pre-processing step: The pre-processing workflow step has a flexible design. This flexibility allows user defined modules to be integrated as plugins. Ci-NERGY platform by default provides two plugins, namely; geometric and physics. The geometry plugin computes geometric parameters such as surface area, orientations, gross volume, building heights and window-to-wall ratios [4]. While, building physics related parameters like construction type are derived from the physics plugin. Depending on a particular simulation requirement either or both plugins can be enabled.

Simulation step: On successful completion of pre-processing workflow step, simulation workflow step is triggered. Unlike pre-processing, which can integrate user defined plugins, simulation workflow step can integrate existing simulation tools. To showcase the flexibility of Ci-NERGY and its advantage as a distributed energy simulation platform, we have integrated INSEL.

4. Implementation examples

4.1 FMI-based co-simulation platform

In order to demonstrate the application of the platform, two simulation tools were coupled and tested.

4.1.1 Coupling EnergyPlus and No-MASS

EnergyPlus is a well-known free and open-source dynamic energy simulation software that engineers, architects, and researchers use to model both energy consumption for heating, cooling, ventilation, lighting, and plug and process loads in buildings (Crawley et al., 2001). The Nottingham Multi Agent Stochastic Simulation (No-MASS) is a multi-agent simulation framework which generates synthetic populations of buildings' occupants and their energy-related behaviours (e.g. interactions with the building envelope, lights and electrical appliances).

In the co-simulation framework, EnergyPlus FMU and No-MASS FMU are orchestrated by a master algorithm. At each time step, the master algorithm controls data exchange and synchronization between EnergyPlus and No-MASS, which is shown in Figure 5.

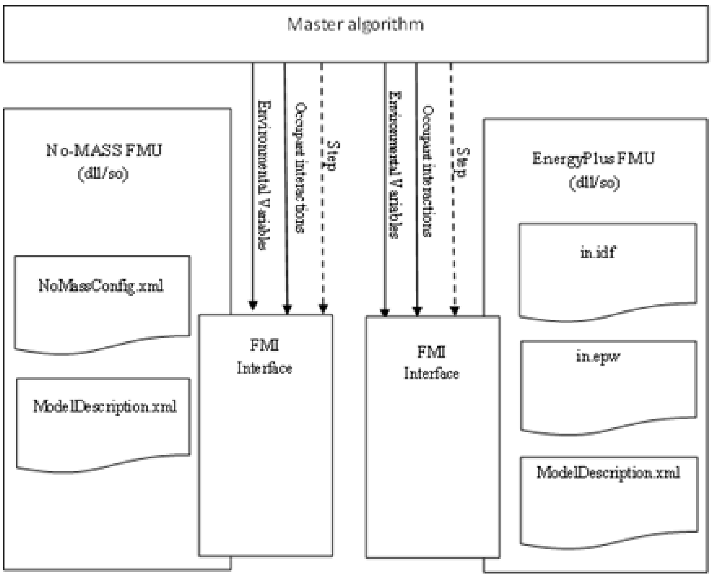

Figure 5 – EnergyPlus and No-MASS orchestration diagram in the co-simulation platform

EnergyPlus simulates the building's energy flows and passes environmental variables to No-MASS at each time step during co-simulation process, as illustrated in Figure 6. Correspondingly, No-MASS parses the environmental conditions to predict agents' behaviours and interacts with shading devices, windows and lighting and returns the number of occupants in a zone, their metabolic gains, appliance gains, the window status, the blind shading fraction, the lighting status and heating set-points to EnergyPlus. After receiving outputs from No-MASS, EnergyPlus computes the consequences of these interactions when simulating the building's energy flows in the next step. This process continues until the end of the simulation. Although this example only shows two tools coupled, actually many more tools can be coupled as slaves that are orchestrated by a master algorithm.

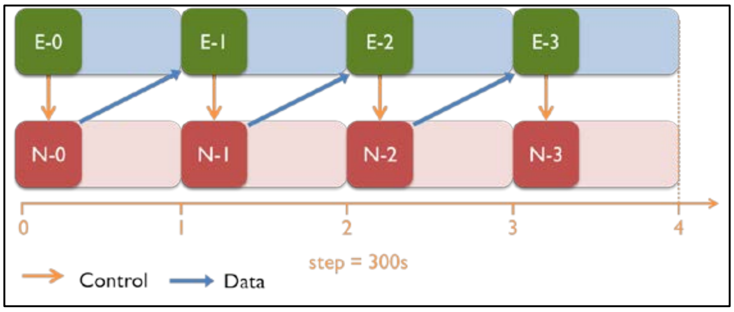

Figure 6 – EnergyPlus (E) and No-MASS (N) co-simulation

In order to test the functionality of co-simulation platform, tests were carried out using different configurations of input models (a single building or several buildings at the same tile) in order to simulate the energy demand of buidings with consideration of variations in building performance arising from occupants interactions by coupling EnergyPlus and No-MASS.

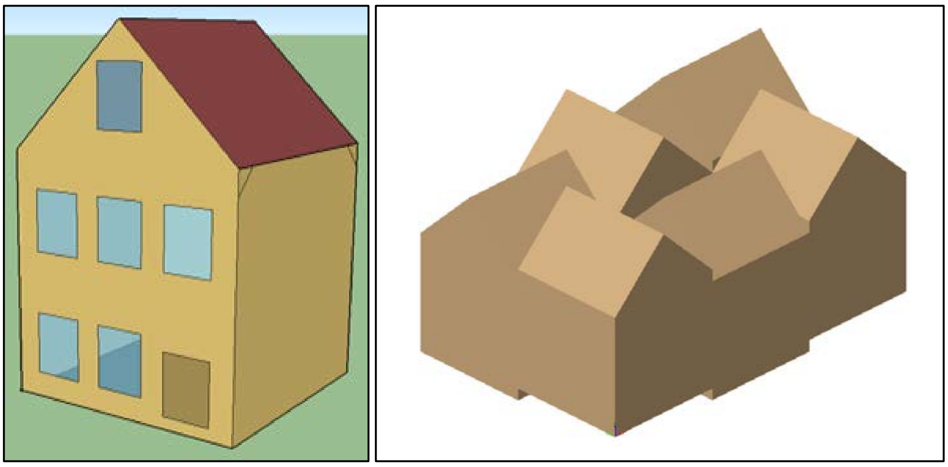

Figure 7 – Example of building models used for testing the co-simulation platform. A detailed single building, on the left, and a group of less detailed buildings, on the right

4.2 Service-oriented platform

The example prototype of the service-oriented platform has been demonstrated with the aim to simulate the urban scale estimation of the solar heat gains through the building envelope. The example specifications have been explained in Wate et al. (2016). The illustration in Figure 8 depicts the coupling between the shortwaves irradiation simulation algorithm and the input building geometry data model. However, at urban scale, the task becomes highly challenging. In order to estimate solar heat gains at urban scale three key complexities need to be addressed: (1) data processing and exchange, (2) modelling and (3) computational.

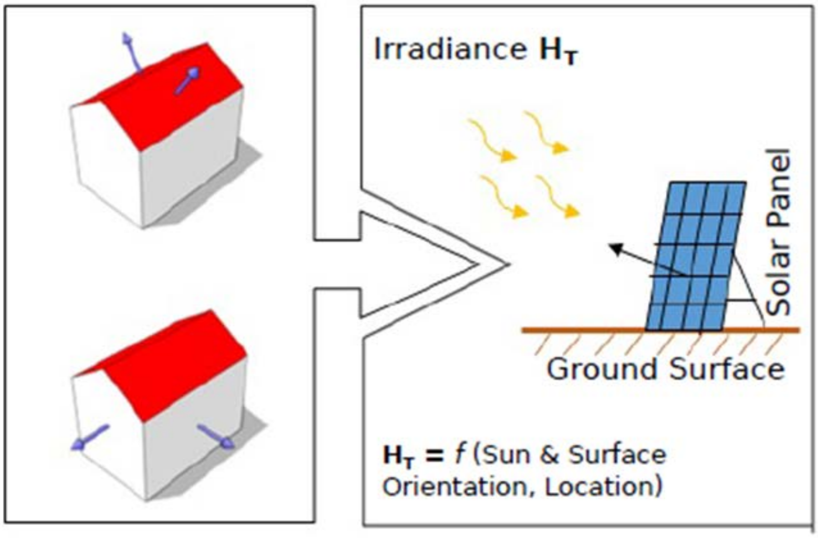

Figure 8 – Coupling between processing and modelling

Data processing at an urban scale requires automated extraction and processing of building geometry parameters. Furthermore, the extracted data needs to be modelled into a compatible format required by different simulation programs. This is necessary, as it will ensure that the generated data model can be easily fed to any simulation algorithm. Modelling complexity involves practical considerations of adjacency and proximity between buildings to account for detailed modelling of shadowing effects, while computational complexity relates to graphics hardware available for processing of large urban scenes. In order to realize our use case we will use two simulation tools: the simulation platform CI-NERGY and INSEL. Using web services, it is possible to couple these two tools to perform processing and modelling functionalities on-the-fly and run a simulation targeting urban scale. The following steps provides a brief overview of the concept.

Input Data step: The building geometry and the semantic data are the inputs of the entire workflow. The building to be simulated can be retrieved by specifying the building ID (Figure 9).

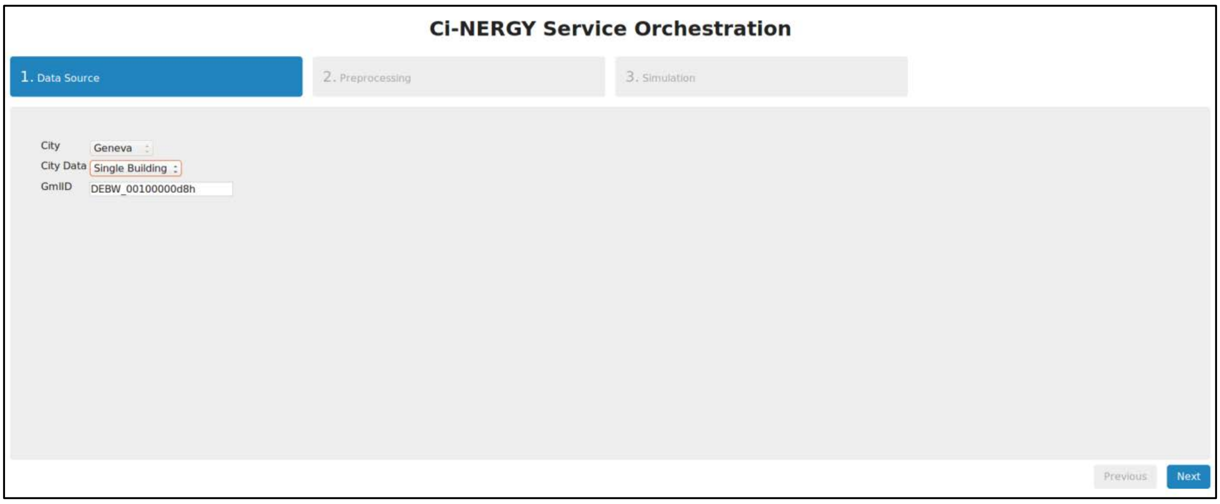

Figure 9 – Service-oriented platform: example of the data input step

Data pre-processing step: The required geometry parameters are extracted from the building geometry using functions implemented in the pre-processing step. The values of the derived parameters can be presented in CSV format or in the more universal program-readable XML format (Figure 10).

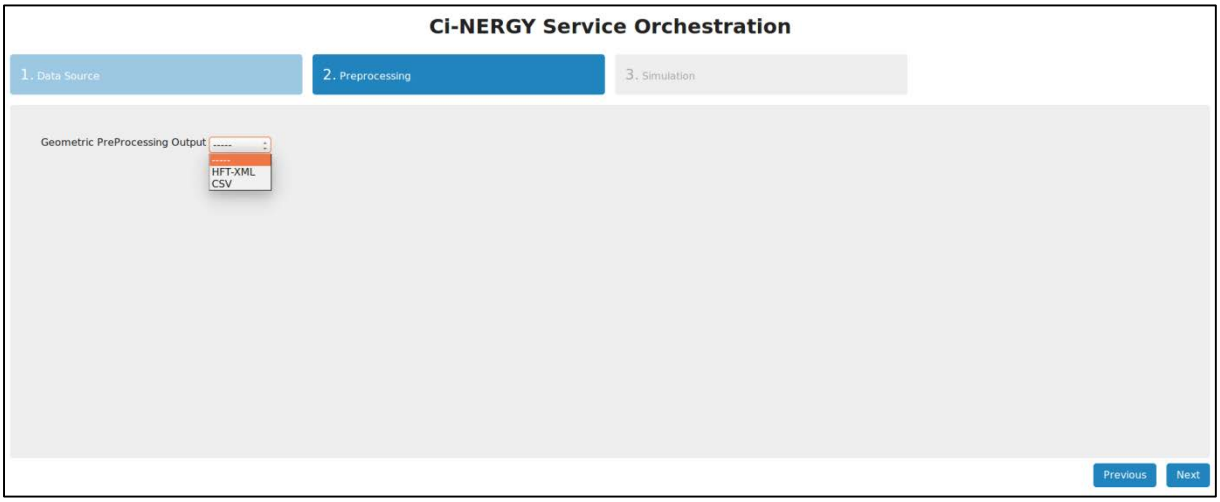

Figure 10 – Service-oriented platform: example of the pre-processing step

Simulation step: The actual simulations are then conducted using the data values from the previous step. The geographic location of the subject building can be specified from the interface (Figure 11).

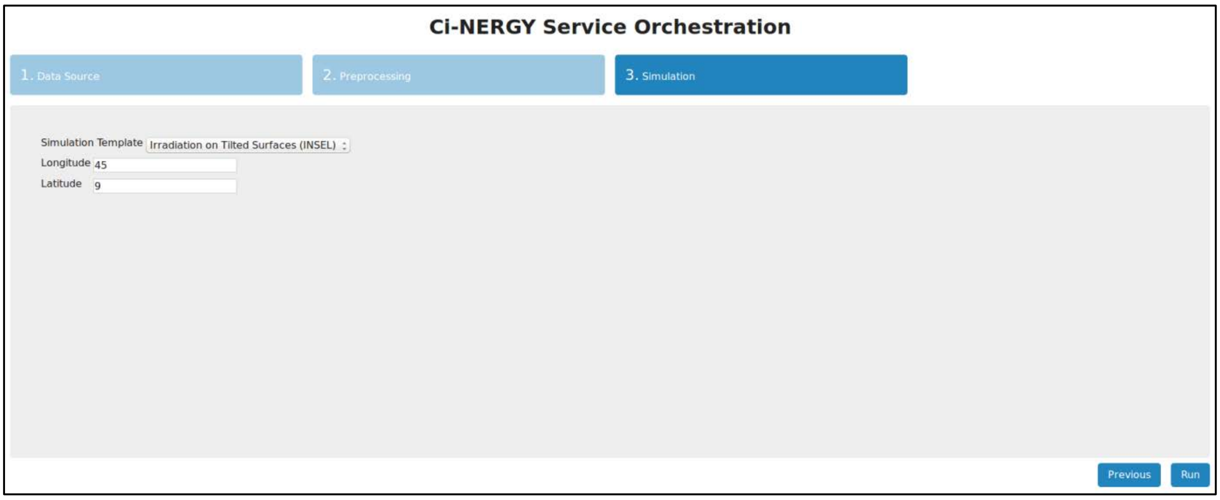

Figure 11 – Service-oriented platform: example of the simulation step

Reporting step: Finally, the simulation results are reported by the orchestration service and visualised in the interface to the user (Figure 12).

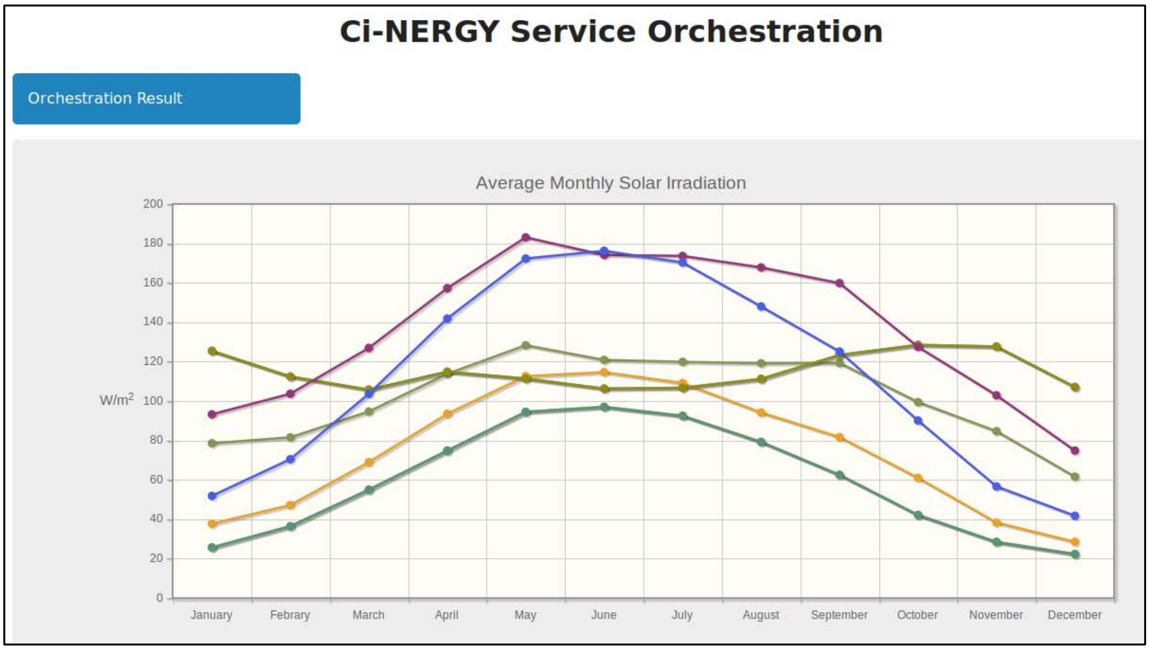

Figure 12 – Service-oriented platform: example of the reporting step

5. Conclusions

The platform described in this report has been implemented and tested in a number of use cases which represent some of the requirements within the CI-NERGY project. Further testing is still on-going, as well as the extension of the application to more use cases.

In any case, regarding the co-simulation platform, tests carried out so far show the feasibility of integrating heterogeneous simulation tools for co-simulation purposes. Results from tests confirm that synchronization and interaction between the master algorithm and the coupled co-simulation components work as intended. FMI support enables the platform to be easily extended by integrating more FMUs with minimum effort and cost.

When it comes to the service-oriented architecture, an open web-service-based orchestration engine was conceived, implemented and so far successfully tested. This platform is meant to enable users to combine services in order to address individual use cases. Furthermore, the platform is designed to support open interfaces and hence to ensure seamless information exchange among connected components. What is more, the use of a service-oriented architecture approach in the Ci-NERGY project fosters the following innovation:

- Exchange of information among distributed tools (simulation/co-simulation, optimisation, decision support, etc.);
- Flexible web interfaces tailored to address different users and use cases;
- Modular approach, which enables non-specialists to combine different modules and to develop new energy related tools;
- Visualization of results on heterogeneous devices (e.g. tablets, laptop, etc.).

The CI-NERGY simulation framework, in the form of both its two main components (the FMI co-simulation platform, and the service-oriented platform) are conceived to foster interoperability and reuse of existing implementations, in order to facilitate further extension on one side, and to facilitate the adoption and reuse of the framework in future research projects to integrate simulation tools for their own purposes.

5.1 Future improvements

A number of enhancements and improvements to the framework are already planned. Regarding the co-simulation platform, for example, a strategy will be developed to generate the master algorithm automatically through parsing scenario files that contain configuration information of the simulators to be integrated, connections and the data flow between simulators. In addition, the CitySim and district heating network simulation tools will be integrated in order to evaluate more complex use cases. The role of data model will also be investigated further through examining the new use cases.

When it comes to the service-oriented platform, it currently only supports CityGML LoD2 models. In future it is planned to support LoD3 and LoD4 CityGML models. Furthermore, two more aspects are planned to be addressed in a more comprehensive way: namely; automation and orchestration. In particular:

1. Automation and extension: The platform could be extended to provide the computation of monthly heating energy demand prediction as a web service. Then, these two service components - (a) already presented radiation estimation service and (b) next step of heating energy demand estimation service could be interconnected in a process chain of service-oriented mechanism offering an overall service for the integrated concept of urban energy demand (given by (b)) fulfilled by the available renewable energy potential (given by (a)).
2. Orchestration of the simulation model functionalities: A more comprehensive platform prototype has been envisioned by making use of available modelling functionalities in a synchronised and logically orchestrated manner. This could lead to the improvements in the plausibility of the simulation outcomes, ultimately aiding to the robust and risk based energy planning and decision making.

6. References

Agugiaro, G., 2016a, Enabling "energy-awareness" in the semantic 3D city model of Vienna. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., IV-4/W1, pp. 81-88., doi:10.5194/isprs-annals-IV-4-W1-81-201.

Agugiaro, G., 2016b, First steps towards an integrated CityGML-based 3D model of Vienna. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. III-4, pp. 139-146. XXIII ISPRS Congress, Commission IV, 12-19 July 2016, Prague, Czech Republic, doi:10.5194/isprs-annals-III-4-139-2016.

Alam, N., Wagner, D., von Falkenhausen, J., Coors, V., Pries, M., 2014, Towards automatic validation and healing of CityGML models for geometric and semantic consistency. Innovations in 3D Geo-Information Sciences, pp. 77-91.

Chapman, J., Siebers, P.-O., Robinson, D., 2014, Coupling multi-agent stochastic simulation of occupants with building simulation.

Christensen, E., 2001, Web Services Description Language (WSDL) 1.1. http://www.w3.org/TR/2001/NOTE-wsdl-20010315

Clement, L., 2004, Universal Description Discovery & Integration (UDDI) version 3.0.2. http://uddi.org/pubs/uddiv3.0.2-20041019.htm

Crawley, D.B., et al., 2001, EnergyPlus: creating a new-generation building energy simulation program. Energy and buildings, 33(4): p. 319-331.

Gröger, G., Plümer, L., 2012, CityGML – Interoperable semantic 3D city models. ISPRS Journal of Photogrammetry and Remote Sensing, 71:12–33, ISSN 0924-2716.

Gudgin, M., 2007, Simple Object Access Protocol (SOAP) version 1.2 part 0: Primer (second edition). http://www.w3.org/tr/2007/rec-soap12-part020070427

Keirstead, J., Jennings, M., Sivakumar, A., 2012, A review of urban energy system models: Approaches, challenges and opportunities. Renewable and Sustainable Energy Reviews, 16(6): p. 3847-3866.

Kosek, A.M., et al., 2014, Evaluation of smart grid control strategies in co-simulation-integration of IPSYS and Mosaik. In: 18th Power Systems Computation Conference (PSCC2014).

Palensky, P., Widl, E., Elsheikh, A., 2014, Simulating Cyber-Physical Energy Systems: Challenges, Tools and Methods. Systems, Man, and Cybernetics: Systems, IEEE Transactions, 44(3): p. 318-326.

Thomas, D., et al., 2014, Multiscale co-simulation of EnergyPlus and CitySim models derived from a building information model. In: Bausim 2014: Fifth German-Austrian IBPSA Conference.

Stifter, M., et al., 2013, Steady-state co-simulation with PowerFactory. In: Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES).

Hensen, J., 1995, Modelling coupled heat and airflow: ping pong vs. onions. In: Document-air infiltration centre AIC proc. Citeseer.

Vaculín, O., Krüger, W.R., Valášek, M., 2004, Overview of coupling of multibody and control engineering tools. Vehicle System Dynamics, 41(5): p. 415-429.

Wate, P., Rodrigues, P., Duminil, E., Coors, V., 2016, Urban energy simulation based on 3D city models: a service-oriented approach. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., III-4/W1, 75-80, doi:10.5194/isprs-annals-III-4-W1-75-2016.

Acknowledgements

This report was written by Preston Rodrigues (HFT), Parag Wate (HFT), Kunpeng Wan (AIT/Unott), Jean-Loup Robineau (EPFL) and Giorgio Agugiaro (AIT) in September 2016.