potential for additional revenues from other energy sales (e.g. electricity), policy incentives, supply side values (e.g. waste heat disposal, waste management), and provide other energy system benefits, such as demand response services, balancing, etc.

Regulatory landscape

Regulation can be seen as a burden, but has been influential in many countries to de-risk schemes and create a level playing field with other utilities, whilst providing customer protection.

Local and national level supportive regulation and policy can provide certainty of demand and help promote extension of networks in suitable areas. The policy push will often be at a local level with authorities (e.g. London) providing strategic support through planning and funding.

The regulatory environment can limit the flexibility in network operation and management, such as determining tariff structures and levels. However, this creates long term certainty and a safer environment for customers leading to greater acceptance of networks, reducing investment risks.

Regulatory support of networks alongside other utilities can mitigate operational risks such as ensuring access to networks for operations and maintenance with appropriate wayleaves. With no regulation, heat networks are considered a private utility and will need large numbers of bespoke contracts to provide wayleaves and expansion potential.

The policy and regulatory environment is likely to have a significant impact on heat sources influencing fuel pricing and availability, CO_2 reduction requirements, and acceptability of different technologies. Policy incentives for competing individual heating system uptake as well should be checked. Financial incentives are often tightly focussed and can drive certain options. ■

dina.darshini@delta-ee.com
www.delta-ee.com

Overview and prospects

Co-Simulation: Leveraging the Potential of Urban Energy System Simulation

Simulation-driven assessments and developments are regarded as key methods in designing and operating urban energy systems. Co-simulation enables the flexible coupling of established tools for the respective subsystems such as buildings, district heating and cooling systems or power distribution systems. The authors present an overview of the general concept behind co-simulation, promising standards, tools and discuss new possibilities for simulation of urban energy systems.

A key element in the ongoing energy transition is a widespread substitution of renewables for fossil fuels. With the expansion of production from volatile renewable sources such as solar and wind, other parts of the energy systems must become more flexible to match the energy from these sources with the demand in terms of location, time and quantity. There are several options proposed to increase the overall system flexibility, including the integration of storage technologies, increasing demand and supply flexibility, coupling sectors and increasing the transmission capacities in electrical power systems. Cities consume 75% of natural resources and produce about 75% of the global carbon emissions; consequently, urban energy systems need to undergo significant changes.

Simulation-driven assessments and developments are regarded as key methods to address the growing complexity of these systems and to derive quantitative feedback to attain optimal design and optimal control of systems as well as input for a decision-support system for policy makers. Furthermore, in some applications, it is dangerous and/or costly to test new technologies.

New concepts for urban energy systems such as smart systems or the fourth generation of district heating systems lead to new challenges for modelling and simulation: due to the coupling of different sectors (e.g. heat, power), there is a need for multi-domain analyses (e.g. thermal, electrical). Furthermore, rapid prototyping methods are needed to enable an iterative and agile way of testing and comparing different concepts and system solutions.

In general, there are two possibilities for modelling and simulation of complex systems that consist of several subsystems such as produc-

Mag. ***Gerald Schweiger*** MA MA, researcher at AEE Intec, Gleisdorf/Austria, and lector at TU Graz/Austria; ***Cláudio Gomes***, PhD Student at University of Antwerp/Belgium; Dipl.-Ing. ***Irene Hafner***, researcher at dwh GmbH, Vienna/Austria; ***Georg Engel*** PhD, researcher at AEE Intec, Gleisdorf/Austria; ***Thierry Stephane Nouidui*** PhD, researcher at LBNL Berkeley/California; Dr. Dipl.-Ing. ***Niki Popper***, coordinator Center of Computational Complex Systems at TU Vienna/Austria and CEO and cofounder of the dwh GmbH, Vienna/Austria; ***Josef-Peter Schöggl*** PhD, researcher at KFU Graz/Austria

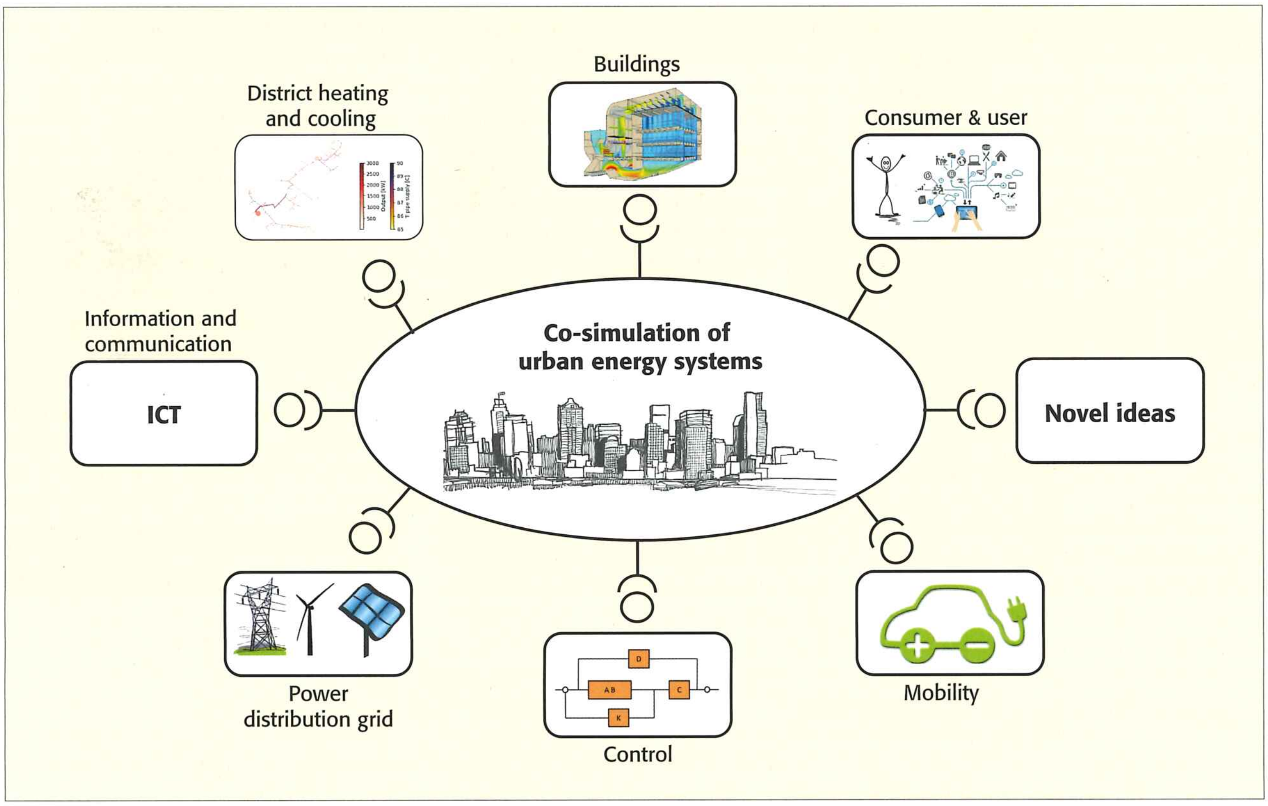

Figure 1. Co-simulation of urban energy systems

tion units, buildings, on-grid energy systems or storage:

- the entire system is modelled and simulated in a single tool which is referred to as monolithic simulation; or
- established tools for the respective subsystems are coupled in a co-simulation (*figure 1*).

As our knowledge of each domain matures, so do the modelling and simulation tools become more specialized in that domain. Currently, there are already specialized simulation tools for several domains and sectors (for example EnergyPlus for building simulation). As such, leveraging the existing simulation tools, and coupling them in dynamic simulations, provides a quick way to approximate inter domain interactions.

Complex systems and the history of co-simulation

Co-simulation is a broad topic (see [1;2] and references thereof). It encompasses: synchronization of several simulators, often having to simulate at a rate close to real-time; decomposition of systems into subsystems for coupled simulation thereof; coordination among multi-abstraction models; standardization of simulator interfaces and protocols to ease the development of co-simulation frameworks; and guarantees of intellectual property protection.

The need for simulator synchronization and real-time constraints can be traced to the early seventies, when the first discrete event synchronization protocols to coordinate distributed simulations where published. In the early eighties, the first continuous system decomposition techniques were published, with the purpose of accelerating the simulation of large scale electrical circuits. Multi-domain simulator synchronization can be traced to the hardware-software co-simulation frameworks, published in the early nineties. Furthermore, this idea was quickly generalized to multi-abstraction co-simulation, accommodating circuits containing many different subcomponents that could be simulated with dedicated solvers depending on the level of detail needed.

In the same decade, the Distributed Interactive Simulation standard was created, and, in the field of continuous system modelling and simulation, there was a call to standardize the interactions with differential equation-based models. In the early 2000s, with the concurrent engineering practices, it became useful to organize all the information regarding a component of a larger system into a unified repository. This artifact, aptly name Digital Mockup Unit, could be used to assemble a virtual prototype of the whole system, for visualization and simulation. In 2007, the Functional Mockup Interface (FMI) Standard was proposed to harmonize the interactions between simulation tools. The standard excludes the protocol, recognizing that more research is needed in the interactions of simulators. While FMI was not the first standard to be proposed for this effect, it was the first to recognize the need to support Intellectual Property protection. Overall, if the trend is to use more and more modelling and simulation at all stages of the lifecycle of a complex system, then co-simulation will play an increasingly important role.

Promising concepts, standards and tools

Considering the computed dynamic behavior of the regarded systems, continuous, discrete event and hybrid systems can be distinguished. States of time-continuous systems can theoretically change at every given point in time and can – in theory – also be observed continuously (*figure 2*). An example of a continuous system could be the heat transfer between different parts of a city. Within discrete event systems, changes (events) occur at discrete points in time only, like in package tracking systems, where the events would be the changes of status of a package (its location, which is only known at certain points in time) or in communication networks simulations (*figure 2*).

Systems consisting of parts which change continuously as well as parts showing discrete behavior are called hybrid systems. In this case, abrupt changes can happen either at predefined points in time (timed events) or when a certain value is reached by a continuous part (state events). This can easily be understood when a heating system in an office building is considered which is switched on at 8 o'clock in the morning (timed event) and switched off as soon as a certain temperature is reached (state event).

Although continuous systems are typically discretized to approximate their solution in a digital computer, the modelling and simulation approaches for continuous and discrete event systems are highly heterogeneous. Consequently, algorithms to couple these systems need to fulfill different requirements and offer different interfaces, which – apart from other ways of distinction – has led to the development of three different areas of research within co-simulation in this respect: co-simulation of purely continuous systems (continuous co-simulation), co-simulation of discrete event systems (discrete co-simulation) and co-simulation of continuous as well as discrete event partial systems (hybrid co-simulation). In complex applications like urban energy systems, hybrid simulation is of great importance as it allows the consideration of strongly diverse parts of the system, tackling them with the most appropriate approaches and coupling them thereafter in a holistic simulation. Due to the heterogeneity in the subsystems, hybrid co-simulation faces even more challenges than purely continuous or discrete event co-simulation. One of the most interesting and challenging aspects in hybrid simulation are interdependencies like state events triggered by inputs from the continuous part while events of the discrete parts likewise influence the behavior of the continuous part.

Traditionally, co-simulation is practiced with two tools, each specialized in a different domain. However, as models are created for more domains, there is a need to couple more simulation tools together. To this end, different standards have been developed which allow arbitrary tools to be combined in a co-simulation if every tool supports the standard. Two widely accepted standards are the FMI and High-Level Architecture. Examples of tools with which co-simulation is already implemented and commonly used in the field of urban energy system simulation are Dymola, EnergyPlus, Matlab Simulink, TRNSYS and SystemC. Examples of tools that can coordinate the co-simulation with other tools for both continuous and discrete event co-simulation (as long as they are purely continuous or discrete event based) are Fumola and Mosaik; hybrid co-simulation as well as continuous and discrete event co-simulation can be realized among others with Ptolemy II and most Modelica-based simulators which implement the FMI for co-simulation (see [1] for additional tools that can coordinate co-simulations).

Enhancing urban energy systems simulation with co-simulation

Within the Austrian Research Studio – EnergySimCity, a toolbox was developed to model complex urban energy systems that are: intersectoral, dynamic, interactive (considering the complete energy supply chain) and intermodular (models with varying degrees of detail) [3]. The replaceability of the individual modules allows the models to be adapted to the corresponding planning status. The working principle of the toolbox is based on the coupling of different simulation environments (Dymola, Ida-Ice, Matlab and TRNSYS) via co-simulation.

The second example will show what added value co-simulation could create for existing simulation platforms. To support urban scale simulation, the Lawrence Berkeley National Laboratory has developed a web-based data and computing platform called CityBES [4]. CityBES reads city models represented using the open standard CityGML. It then creates multiple EnergyPlus building models; parallel computing is used to simulate all buildings. Because CityBES uses EnergyPlus it cannot be applied to use cases that require features not supported by EnergyPlus. A possible extension of CityBES could be to provide it with a co-simulation interface. This interface could allow linking EnergyPlus building models with on-grid energy system models and simulators for the design and operation of smart energy systems.

Chances for industry and research

In recent decades, modelling and simulation has become a state-of-the-art method and indispensable for innumerable purposes in industry and academia. Due to the following opportunities, co-simulation is expected to play a major role.

High efficiency research and development always requires rapid prototyping to be able to evaluate concepts at an early stage. This is often hindered by the limitations of the specific simulation tool and/or its libraries at hand. Co-simulation may allow for a breakthrough in this respect by giving the user access to all sorts of simulation tools and associated libraries in one joint simulation. This is not only of practical usefulness for rapid prototyping, but also opens the gate for easy implementation of complex so-called multi-domain or cross-sector holistic system simulations. Another opportunity lies in the significant simplification of cross-company collaborations, allowing each company/group to work with its preferred simulation tool, finally to be combined in one holistic collaborative simulation. Co-simulation also intrinsically supports intellectual property protection, e.g. by sharing black box models. Last but not least, its framework can be exploited straightforwardly for parallelization and distributed computing, i.e. to make time-consuming simulations fit for supercomputers, and also for coupling the simulation to experiment, such as in the context of hardware-in-the-loop. These opportunities are applicable to not only urban systems, but also other fields of industry and research.

References

[1] Gomes, C. et al.: Co-simulation: a Survey. ACM Computing Surveys, to appear.

[2] Hafner, I.; Popper N.: On the terminology and structuring of co-simulation methods. Proceedings of the 8th International Workshop on Equation-Based Object-Oriented Modeling Languages and Tools, Wessling/Germany 2017.

[3] Schweiger, G. et al.: EnergySimCity: Modellierung urbaner Energiesysteme. EnInnov, Graz/Austria 2018.

[4] Hong, T. et al.: CityBES: A Web-based Platform to Support City-Scale Building Energy Efficiency. 5th International Urban Computing Workshop, San Francisco/USA 2016. ■

gerald.schweiger@tugraz.at
www.tugraz.at/institute/ist/institute/

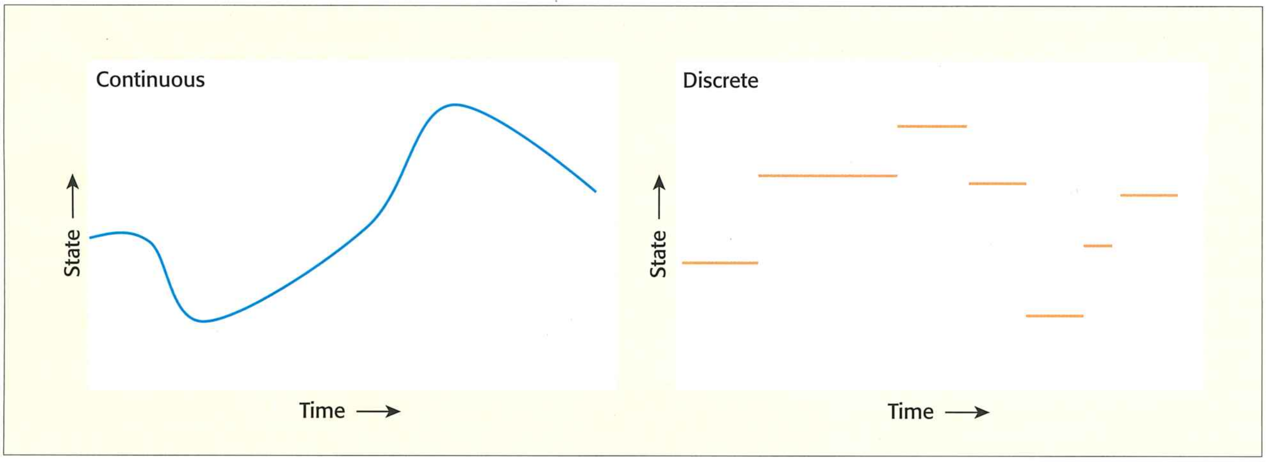

Figure 2. States of time-continuous systems and discrete event systems