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# SHADER

## Executive summary

Buildings are among the most polluting entities, as research conducted by the European Commission found that they are responsible for approximately 40% of the overall energy consumption and 36% greenhouse emissions in the EU. It is therefore clear that an improvement in Buildings Energy Management (BEM) practices could have a significant impact in terms of energy savings and pollution reduction. The physical renovation of existing buildings and the adoption of the most advanced techniques for the construction of new ones should be coupled with radical innovations in the adoption of Digital Technologies for BEM, therefore creating so called Smart Homes, on which SHADER multidisciplinary project is focused.

SHADER has a significant role in the Building Energy Management (BEM) transition, as it aims at developing a platform that, by integrating heterogeneous data sources and creating a digital twin of a physical system, allows to run multiple scenario analyses, thus allowing to define the optimal control strategy for the Energy Appliances over time minimizing energy consumption and costs for the final user.

A thorough Political, Economic, Socio-Cultural, and Technological (PEST) analysis was conducted in order to better understand the potential opportunities and threats that may affect the Smart Home market in the European and Italian economic context, suggesting that huge opportunities can be exploited thanks to European Programs such as Next Generation EU. On the other side, potential threats derive mostly from the retail public's resistance to adopt such high-level technologies into their homes. Moreover, an in-depth analysis of the Smart Home industry was conducted, with a special focus on the Smart Energy Appliances segment, with the aim of understanding which are the Key Success Factors (KSF) required to successfully compete in this industry, as well as the main players in the market.

The development of an effective solution started with the analysis of the simulation frameworks developed by the PoliTo research group and by the Ariston-PoliMi Joint Research Centre. The first simulation consists of different models, each developed in a domain specific software, while the second was implemented in Modelica language creating the so called "AristonBuildingHVAC" Modelica library. Particular attention was given to the AristonBuildingHVAC library, where a sensitivity analysis on several parameters, which influence the heating control strategy of an apartment, was performed in order to find the optimal setting that maximizes the user comfort and minimizes the energy consumption.

Once the simulation parameters were optimised, different subsystems coming from the two different models were integrated by exploiting co-simulation, which was identified as the optimal methodology to run scenario analyses using digital twins of buildings and power grids. Co-simulation offers the possibility of modelling the system as a group of independent units communicating with each other. Our objective is to perform large scale simulations of energy consumption and production entities while offering the possibility of easily changing the components that make up the studied energy system. HELICS is the co-simulation framework of choice because of its performance and scalability. Functional Mock-up Interface (FMI) is the industry standard for the definition of a common interface for communicating with simulators, allowing to perform simulation steps, set options, and performing input and output operations. The framework was extended with several components developed in Python in order to provide a uniform and easy to set up common interface between HELICS and FMI. These components allow the easy definition of the single simulations to be orchestrated, together with the data to be interchanged between them.

Several tests were conducted in order to validate the feasibility of co-simulation, evaluating its effectiveness compared to traditional simulation methodologies on performance and accuracy. A first test demonstrated the accuracy of results obtained through co-simulation compared to the ones obtained through a traditional simulation while using different discretization periods. A second test demonstrated the possibility of scaling the simulation of multiple buildings by using a single machine, showing the possibility of predicting the change in performance given the hardware. A third test demonstrated an advantage of co-simulation in the possibility of extending the computation to multiple machines.

Lastly, a mathematical overview of the Model Predictive Control (MPC) framework, which is the main tool used to put in action the optimal control strategy that resulted from the co-simulated data, was carried out with a focus on the stochastic version of the MPC (i.e., Stochastic MPC), showing how it could be integrated into SHADER's co-simulation framework in order to become an active agent in the process.

Concluding, it was demonstrated how the international political landscape actively supports the vision of SHADER by providing huge economic incentives targeted at promoting ecological transition and digitalization, categories that SHADER falls into. Possible limitations due to technology and resistance to adoption were also investigated. The co-simulation platform that was developed proved to have several advantages in terms of scalability compared to the traditional simulation, and a clear path for future developments was set in order to further improve it. SHADER managed to validate co-simulation as a viable technology for the analysis and control of complex energy systems and to set the path for major innovations in Building Energy Management practices, which will strongly contribute to reduce carbon emissions and energy sources exploitation in the future.

## Key Words

Co-simulation

Building Energy Management

Energy Appliances

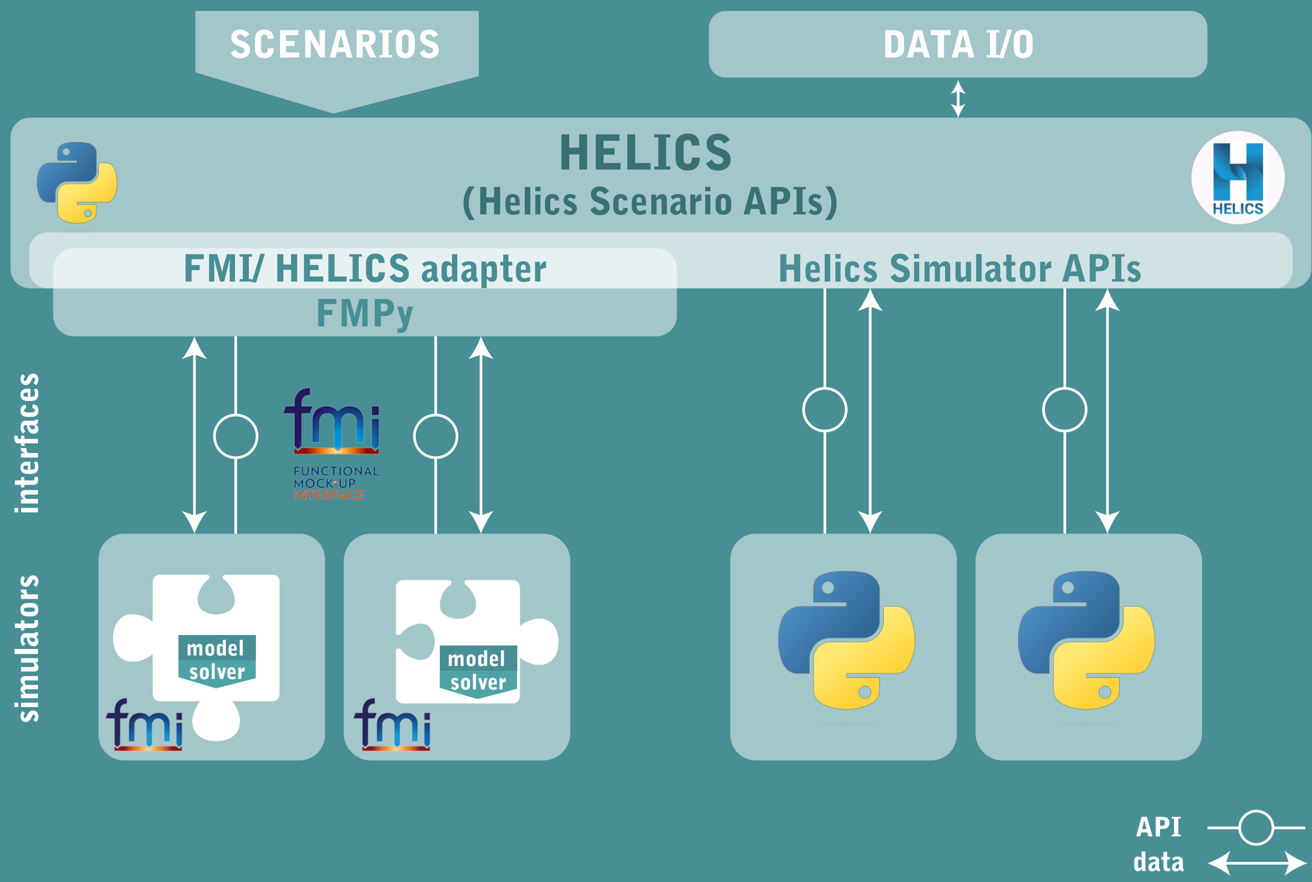
Smart Home

Automated control

Energy efficiency

Smart Home

Scheme of our multi-modellingco-simulation platform



## Project description written by the Principal Academic Tutor

The SHADER project aims to develop a platform for building energy management that optimises the use of energy. The platform considers multiple, possibly conflicting requirements, such as reducing energy consumption and preserving the end users' comfort. It defines an optimal control strategy that fulfils these requirement.

The ongoing energy transition towards renewable sources is making control strategies more difficult to develop, as individual buildings cannot be considered as independent and isolated units, but are part of a complex and highly interconnected energy system that produces and consumes energy coming from multiple energy vectors.

This complexity calls for technological solutions that carefully capture the relations between individual buildings and the overall energy system. Moving from this state of things, SHADER investigates the use of a simulated environment (digital twin) to model the energy system. In particular, SHADER proposed co-simulation techniques, where heterogeneous models can be seamlessly integrated to capture the various aspects that define the energy system.

The project shows that co-simulation is effective in (1) integrating different models, by combining models independently developed by PoliTo and by the Ariston-PoliMi Joint Research Centre; (2) modelling large-scale systems, by deploying multiple simulators on different physical computers and thus exploiting the computational resources of a distributed computing environment.

SHADER studied Model Predictive Control (MPC) as the theoretical framework to exploit the results of complex simulation and define optimal control strategies for individual building and for the network.

In summary, SHADER developed a co-simulation platform to study complex energy systems and studied how to use it to define optimal control strategies for building energy management. These results may contribute to optimise energy use and reduce carbon emissions.

## Team description by skill

The SHADER team has a multidisciplinary background that proved crucial to the development of the project at all stages. It consists of 7 students with very different backgrounds and courses of study:

**Virginia Capone**, Architecture student at Politecnico di Milano
**Yi Yu Ivan Chen**, Mathematical Engineering student at Politecnico di Torino
**Simone Corti**, Automation and Control Engineering student at Politecnico di Milano
**Luigi Fusco**, Computer Science and Engineering student at Politecnico di Milano
**Pablo Pozo**, Structural Engineering student at Politecnico di Milano
**Silvia Trimarchi**, Energy Engineering student at Politecnico di Milano
**Francesco Zanon**, Management Engineering student at Politecnico di Milano.

The team was split mainly in two big sub-teams according to the Work Packages required by the project, based on the course of study and on the previous knowledge of each team member. The two sub-teams were composed as follows:

Virginia Capone, Pablo Pozo and Francesco Zanon
Yi Yu Ivan Chen, Simone Corti, Luigi Fusco and Silvia Trimarchi

The first segment mainly focused on the managerial aspects of the project. They have analysed the market and the state of the art of smart homes. Moreover, they focused on the different requirements of the customers that this project should satisfy, also through an analysis of the different stakeholders.

On the other hand, the second sub-team focused on implementing the proposed solution. Silvia and Simone were mainly focused on the simulation framework, while Luigi oversaw the co-simulation segment. Finally, Ivan focused on the different possible applications and scenarios of the model predictive control.

## Goal

SHADER's main goal is to create a system that can improve energy management in buildings to address two macro problems: the first, of an environmental nature, which consists of the increasingly looming pollution caused by buildings nowadays, due essentially to the obsolescence and inefficiency of both energy appliances and the smart grids on which they rely; the second, of a social nature, which consists in the inability and very often impossibility for users due this obsolescence, to have any control over their environmental and economic impact when using energy appliances.

In order to ensure, therefore, optimal control over energy appliances, SHADER focuses on creating a platform that, by integrating heterogeneous data sources and creating the digital twin of the physical system, allows to run multiple scenario analyses, and consequently define the optimal control strategy of Energy Appliances.

This is being carried out in collaboration with Ariston, and in particular with its Smart Home division, which in recent years has already worked on several systems to improve both user comfort and the synchronized performance of the various devices connected to the system.

## Understanding the problem

Houses are not autonomous entities: for this reason, to control them in terms of energy use, cost, and impact, we have to take into account exogenous and heterogeneous aspects. Moreover, being in a non-isolated context, we could control global aspects, such as the balancing of a smart grid.

For this reason, SHADER aims at developing a complex platform that can run multiple scenario analyses and find the most suitable strategy to manage the Energy appliances over time. For this reason, it is necessary to integrate heterogeneous data sources and creating a digital twin of the physical system, that through a process of optimization can lead to the optimal setting between three indicators: energy consumption, costs and user comfort. The system must be therefore composed of a series of external data coming from the Smart Grid and inputs data coming from the Energy Appliances: by setting different parameters for every Appliance and by running simulations each time, it is possible to achieve the optimal setting.

Next generation BEM (Building Energy Management) systems heavily rely on the possibilities introduced by co-simulation, through which the complexity of a System like the one described can be exploited at its best. Co-simulation, in fact, allows to split the system into heterogeneous specific systems (Systems of Systems) in order to achieve two fundamental advantages: scalability of the system, as single simulations can be run through a series of different solvers, which synchronization and data exchange is controlled by the orchestrator, and replaceability of the single sub-system with a physical smart appliance or replaceability of a physical smart appliance with another one.

Following the co-simulation setup, and consequently the development of the platform, it is then possible to run different simulations changing parameters to achieve the desired performance in terms of trade-off between execution time and level of detail.

Finally, the last step for the platform to be effectively applied to a physical building, must be model predictive control implementation, as a real use case involves a level of stochasticity due to people's behaviour and external events that cannot be tracked by the co-simulation platform itself.

## Exploring the opportunities

SHADER research on the co-simulation platform starts from the analysis of two different simulation frameworks already existent: one developed by the PoliTo research group, and one developed by the Ariston-Polimi Joint research centre. The last one is composed by a Modelica Library called "AristonBuildingHVAC" composed in order to simulate the thermal behaviour of an apartment. Particular attention was put into the identification of inputs and outputs in order to consider only sections of the model for the simulation platform to be merged with the Polito models. The PoliTo platform, in fact, is composed by different subsystems simulating an entire building which can be integrated in the co-simulation platform as well.

Subsequently, an optimisation process in terms of energy consumption and user comfort has been carried out on the Polimi model, by changing the value of two parameters: slopes zone and room influence zone. This optimization demonstrated that, while the room influence zone does not affect the thermal behaviour of the apartment, and can be consequently left at its default value, the preferred slope parameter value is determined (to be equal to 0.2).

Once established the feasibility of integrating different subsystem of the two studied frameworks into the co-simulation platform, the research shifted to finding the framework on which to base the co-simulation platform. For this purpose, an in-depth analysis and comparison of two co-simulation frameworks considered as the most appropriate ones, MOSAIK and HELICS, is carried out, based on 3 essential parameters for SHADER purpose: scalability, simulator integration, ease of implementation. This comparison led to the choice of HELICS as the most suited co-simulation framework, as HELICS was developed with the aim of simulating modern power systems, achieving very high levels in terms of execution speed and flexibility.

## Generating a solution

Once built the co-simulation platform, the research finally focused at tuning the main co-simulation parameters in order to understand how different set-ups could influence two main metrics, performance and accuracy, which result to be heavily influential one on the other. This process aimed at proving co-simulation as a viable solution for co-simulation of buildings, even complex ones, according to different components and scenarios. In fact, co-simulation was demonstrated to be highly competitive in terms of accuracy and performance, with the added value of scalability and possibility of interchanging components. It was shown that a proper tune setting can lead to improved performance without sacrificing on accuracy, and that the performance can be positively affected by the distribution of the co-simulation across multiple machines.

The next step for the co-simulation platform devised by SHADER will be to take advantage of the Model Predictive Control integration in order to provide users with a customisation of the ideal parameters according to their needs and improve the end-product experience using the SHADER system.

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