OPENIDEAS – AN OPEN FRAMEWORK FOR INTEGRATED DISTRICT ENERGY SIMULATIONS

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ABSTRACT

Contemporary research focuses on net-zero energy buildings and their integration in larger energy systems. By consequence, a vast set of research questions become increasingly multi-domain and multi-scale. With this increasing complexity, the need for more elaborate building energy simulation tools rises. The presented paper reviews the development of the `OpenIDEAS` framework, an open framework developed for integrated district energy simulations consisting of `IDEAS`, `StROBe`, `FastBuildings` and `GreyBox` to answer the new research questions rising in the multi-disciplinary building energy domain.

The Modelica `IDEAS` Library allows simultaneous transient simulation of thermal, control and electric systems at (building and at) feeder level. The Python `StROBe` Module provides boundary conditions for `IDEAS` depicting the stochastic modelling of residential receptacle loads, internal heat gains, space heating set point temperatures and hot water redraws. The Modelica `FastBuildings` Library implements low-order building models that are compatible with `IDEAS`. The Python `GreyBox` Module implements a semi-automated parameter estimation tool to obtain grey-box models that may serve as controller model in a model predictive controller framework for `IDEAS`.

INTRODUCTION

Given the framework set by the European directives 2002/91/EC and 2010/31/EU on the energy performance of buildings, building energy measures are generally evaluated by comparison with *"minimum standards on the energy performance of new buildings and existing buildings that are subject to major renovation; based on a common methodology for calculating the integrated energy performance of buildings"*. However, as buildings and their energy systems are part of different technical and economic subsystems, a cost effectiveness quantification at the level of a single building unwittingly externalizes costs and neglects the possible physical impact on other systems. This certainly applies when considering district heating networks or an electrification of the building energy services, *e.g.* by the implementation of a heat pump as an energy efficient technology to provide space heating and/or domestic hot water, and the installation of rooftop photovoltaic installations, which have a possible impact on the distribution, transmission, billing

Figure 1: Graphical representation of an example low-voltage distribution island connecting 85 dwellings by seven radial three-phase feeders to a 10/0.4 kV transformer with a nominal capacity of 250 kVA.

and trading of electricity. With this increasing complexity, the need for more elaborate building energy simulation tools rises.

The presented paper reviews the development of the `OpenIDEAS` framework, an open framework developed for integrated district energy simulations which consists of `IDEAS`, `StROBe`, `FastBuildings` and `GreyBox`[1] and which can be obtained from KU Leuven and 3E (2014), allowing rapid prototyping for design and operation of district energy and control systems. We will discuss the main requirements for such framework, and outline the implemented software design principles, the library architecture and example research results based on the presented framework.

[1] The GreyBox Module is not part of the open-source development but is freely available for research purposes in structural collaboration by contacting the authors of this paper.

FUNCTIONAL REQUIREMENTS

The design of a (building and) district energy system requires the description of the overall system performance by an objective function $z(\boldsymbol{x})$ based on its description $\boldsymbol{x}$. The differentiation of actors with different objectives in a district energy design problem requires the introduction of a multi-objective and -commodity framework. Given the nature of building energy research questions, it is imperative that the effective objective functions $z_i(\boldsymbol{x})$ and respective constraint functions are defined by $z_i(\boldsymbol{x}) \triangleq Z_i(\boldsymbol{y}_t(\boldsymbol{x}, 1))$ where $Z : \mathbb{R}^m \to \mathbb{R}$ is the evaluation of $\boldsymbol{y}_t(\boldsymbol{x}, 1) \in \mathbb{R}^m$ being the state of a dynamic system with design parameters $\boldsymbol{x}$ defined after a predefined time period by simulation.

With respect to these equations, it is the main objective of the developed district energy system simulation platform `OpenIDEAS` to describe this system performance measurable for the definition of a cost function for any vector of design parameters at the spatial scale of the neighbourhood as graphically presented in Figure 1. Contrary, with respect to optimisation, a further integration with optimizers andor other tools is part of future work. To enable the simulation of all states $\boldsymbol{y}_t(\boldsymbol{x}, 1)$ for the cases related to the stated scope, the simulation platform has to fulfil a set of requirements.

On building energy response. A first major requirement for integrated district energy simulations is the complete simulation of building energy systems including the stochastic influence of occupants on the systems. In detail, it is required to allow simulating the indoor thermal comfort based on a dynamic thermal building model together with a dynamic representation of the heating and ventilation system of the building, and its control based on the observed comfort. The latter means that not only the 'ideal' or nominal heating power has to be simulated, but also the start-up behaviour of the system, the forced shutdown periods based on the control strategies and the dynamic efficiency of the system components including thermal storage. Given the building and system model, stochastic boundary constraints representing the occupant have to be providable by means of additional thermal and electric loads and system control constraints. The implementation of the building energy system must allow describing the resulting relation between the thermal or electric load profiles and the comfort desires, and enable the use of additional information from the energy distribution system in the building energy control systems.

On district energy systems. The platform has to include the simulation of the energy distribution infrastructure. In a first stage of implementation, the focus lies on the low- to mid-voltage electricity distribution while an extension to thermal distribution networks should be taken in consideration. The implementation of the energy distribution system must allow describing the resulting relation between the thermal or electric load profiles and the system variables such as nodal voltages or transformer loads, and enable transfer of this information to the energy control systems. The following stages, the approach will be extended for district heating and cooling system.

On control. Given the building energy systems and the energy distribution system, control and energy management algorithms decentralized at the building system level and centralized at the district system level are a necessity for the efficient operation of district energy systems. It is as such required that the simulation platform enables the representation of such algorithms with a great flexibility in its architecture and allows external input signals reflecting price signals large-scale production plants, focusing on rule-based control between the different energy vectors and model-predictive control requiring a additional iteration. This requires data and information exchange between the different controllers and the models of the physical components.

The following section will give a description of the modelling work performed to meet the above stated set of requirements.

SCOPE OF CURRENT FRAMEWORK

The current focus of the `OpenIDEAS` framework depicts the integrated thermal and electric simulation and control of (building and) district energy systems.

The `IDEAS` library (short for Integrated District Energy Assessment by Simulation) allows simultaneous transient simulation of thermal, control and electric systems at building and neighborhood level; and is implemented using the equation-based object-oriented modelling language Modelica. The library uses the base classes of the IEA EBC Annex 60 Modelica library (Wetter et al., 2015) and it is therefore compatible with `Modelica.Fluid`, `Modelica.Media` and all the libraries using the same base classes. These base classes define basic models for physical phenomena such as conservation equations and flow resistances and partial models for creating component models.

In addition, the Python package `StROBe` (short for Stochastic Residential Occupancy Behaviour) provides boundary conditions for `IDEAS`. The package allows stochastic modelling of time series for occupancy, receptacle loads, internal heat gains, space heating set point temperatures and hot water redraws at a 1-minute time resolution for residential cases. For the use of `StROBe` at the neighbourhood level in `IDEAS`. The Modelica library `FastBuildings` implements low-order building models that are compatible with `IDEAS`. The Python toolbox `GreyBox` implements a semi-automated parameter estimation for the FastBuildings models to obtain grey-box models that serve as control model in a model predictive control framework for `IDEAS`. Altogether, `OpenIDEAS` forms an open framework to model, simulate and analyse integrated energy solutions at the building and district scale to answer the novel research questions rising in the multi-disciplinary building energy domain.

Given this scope, the modelling tools `SUNtool`, `CitySim` and `EnerGIS` (Robinson et al., 2011; Girardin, 2012), the research toolbox `URBS` (Richter, 2004) and the utility prediction system model `TUD-PS` (Tanimoto et al., 2008) and the similar approach of Yamaguchi and Shimoda (2010) are of most interest for comparison of the developed district energy system simulation tool.

DESIGN DECISIONS

As stated earlier, the `OpenIDEAS` framework consist of four subframeworks with a distinct function and we will elaborated on the main properties of all of them; whereas their integration into `OpenIDEAS` is elaborated in Figure 2.

The IDEAS Library, a district energy system simulation library

The Modelica IDEAS Library is a new district energy commodity flow modelling environment and forms the core of the `OpenIDEAS` framework. `IDEAS` integrates multi-zone thermal building energy simulations, including both building envelope and heating, ventilation and air-Conditioning (HVAC) systems, and electric system simulations; as shown in Figure 2. It differs herein from existing district energy modelling environments in the white-box approach of the modelled physics. The model environment is built on discretised partial differential equations, ordinary differential equations and algebraic equations, which are solved simultaneously by using a general-purpose differential algebraic equation solver.

Approach. In order to give an impression of the model complexity in the Modelica IDEAS Library, a brief overview will be presented of the main component models used to construct the district energy simulation models adopted in this work. The physical implementation of `IDEAS` is structured in separate Modelica packages and their models describing the climatic conditions, the thermal building response, the hydraulic system response and the electricity system.

`IDEAS.Climate` contains the models required to define all climatic conditions during the simulations based on a $*$`.tmy3` file format; including the calculation of the thermal radiant temperature of a cloudy sky and anisotropic diffuse solar irradiation.

`IDEAS.Buildings` contains models required to define the thermal response of a building as elaborated by Baetens (2015). Here, the ambient temperature, radiant temperature and the solar radiation on a surface as defined in `IDEAS.Climate` define the radiative and convective heat exchange with the outer environment together with the building surface properties. For the heat transfer within these components, finite element equations are used for the isotropic layers. Shortwave radiation through multi-pane windows is computed using the specular output of the Window & Daylighting Software `WINDOW 7.0` developed at Lawrence Berkeley National Laboratory. At the inner surface, coupling to other building components is achieved via longwave radiative heat exchange based on a radiant star node temperature computed by approximating a wye-delta transformation of the surface-to-surface heat transfer based on the Lambertian geometric factors, and via convective heat transfer to a zone air node. An exception is made for surfaces in contact with the ground for which a transient model is implemented based on the heat transfer equations in the European Std. ISO 13370.

`IDEAS.Fluid` contains components for hydronic and hydraulic circuits for heating and ventilation systems in buildings. These components are compatible through object-inheritance and instantiation with the *partial* `Annex60.Media` and `Annex60.Fluid` base classes as developed in the IEA EBC Annex 60 and described by Wetter et al. (2015). As such, the models are defined by:

- `Annex60.Fluid.Interfaces.ConservationEquation`, which defines the conservation equations for mass fractions, trace substances and energy when applicable, *i.e.* both steady-state or dynamic as desired in each component.
- `Annex60.Fluid.BaseClasses.PartialResistance`, which defines the pressure drop $\mathrm{d}P$ due to friction as $K_v \triangleq \dot{m}/\sqrt{\mathrm{d}P}$ for $\dot{m}$ inside the turbulent regime.

Given these base classes, a dynamic radiator model is implemented using the heat transfer equations from the European Std. EN 442-2 and a dynamic embedded pipe model for floor heating and thermally activated building structures is implemented based on Koschenz and Lehman (2000). Air- or ground-coupled heat pumps and gas boilers are modelled with a multivariate performance map based on state variables, and optionally a set point for the outflowing temperature or heating power. The ground-coupled heat pump can be connected to a borefield model which has accuracy in the short- and long-term time constants as described by Picard and Helsen (2014). An energy storage model for stratified water tanks is also implemented. Heat distribution is modelled with pumps and fans applying a hydraulic head, mass flow rate or speed-dependent pressure curve. Control valves are based on an actuator signal controlling the K_v-value of the valve.

Within the presented work all simulations are based on `Annex60.Media.Water.Simple`, modelling water as an incompressible liquid with constant density, specific heat capacity, ther-

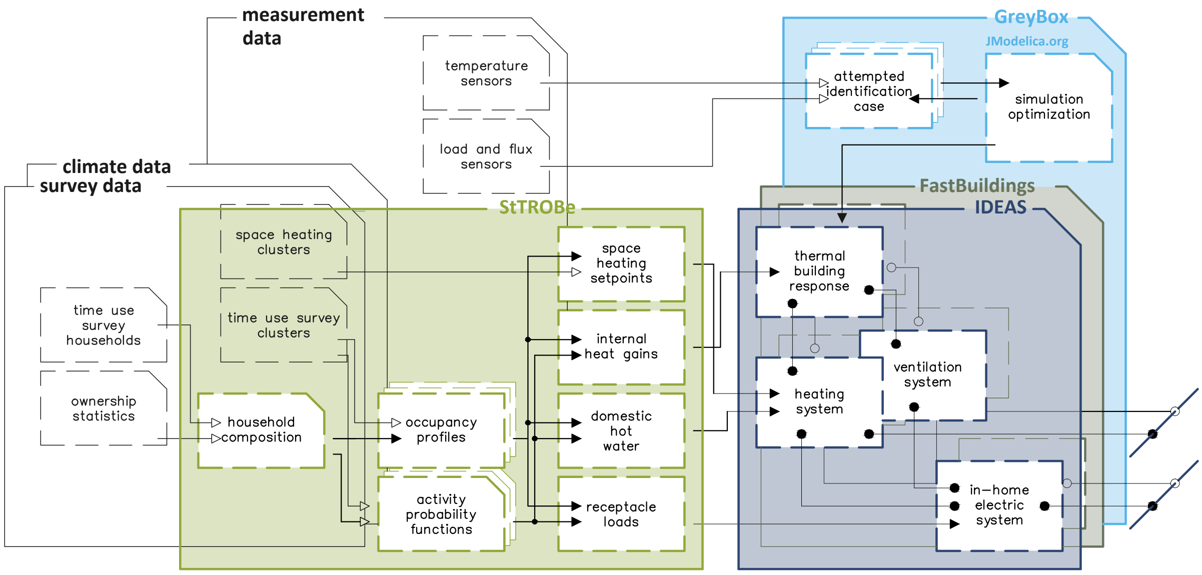

Figure 2: Overview of the `OpenIDEAS` *Framework for integrated district energy assessments by simulation; based on* `IDEAS` *for the transient simulation of the (building and) district energy system, on* `StROBe` *for its boundary conditions regarding stochastic occupant behaviour, and on* `GreyBox` *for generating low-order component models through system identification of measurements signal based on their implementation in* `FastBuildings`*.*

mal conductivity and viscosity, and based on `Annex60.Experimental.Media.AirPTDecoupled` modelling (unsaturated) moist air using a gas law in which pressure and temperature are independent, and with constant specific heat capacity at constant pressure.

`IDEAS.Electric` contains the models required to define all variables in the electricity system. Here, alternating currents in radial electricity distribution networks are described quasi-stationary based on a complex phasor representation and the assumption of a fixed frequency. Voltages and currents are obtained in all nodes and lines based on Kirchoff's circuit laws and Joule's Law for linear conductors given the active and reactive loads as described by (Van Roy, 2015). For local generation, the energy balance of photovoltaic systems is based on the stated irradiance models, the radiative and convective heat exchange with the outer environment and the parametrisation of the equivalent electric circuit by De Soto et al. (2006). Two-winding transformers are described by the standard positive sequence equivalent circuit.

Compilation and simulation. Special care is taken while developing the models such that they run fast and reliable. For instance models inherited from the Annex 60 library are designed such that a unique solution to the problem exists (Wetter et al., 2015). Models often also have a variable degree of detail such that simplifications can be made depending on the user's requirements. Furthermore code was designed to be as efficient as possible. One of the implications is that solar irradiance on building envelope surfaces is calculated centrally, since many surfaces have the same orientation and repeating the same calculation for each surface would therefore generate a lot of overhead. Improving the code efficiency is however an ongoing process.

The thermal building component models are verified based on the 600- and 900-series of BESTEST method which was developed in conjunction with Task 8, Task 12 and Task 22 of the IEA SHC Programme and Annex 21 of the IEA EBC Programme, and based on the Twin House experiment developed in Annex 58 of the IEA EBC Programme (Baetens, 2015; Reynders, 2015).

The StROBe Module; a residential human behaviour model

The Python StROBe Module is a new stochastic residential occupant model serving as input for integrated (building and) district energy simulations with `IDEAS`. The current implementation assumes the stochastic user behaviour as part of a pre-processing and input for an `IDEAS` simulation, without any possible rebound or feedback of the system states to the behaviour of individuals.

A detailed description of the Python StROBe Module is available from Baetens and Saelens (2015).

Approach. In order to give an impression of the model complexity in `StROBe`, a brief overview is presented of the main algorithms that are used to construct the stochastic residential occupant behaviour adopted in this work; as shown in Figure 2. The physical implementation of `StROBe` is structured in separate Python classes and their methods describing the household data, behavorial probabilities, and the resulting space heating setpoints, receptacle loads, hot water redraws and internal heat gains. The majority of the used statistics is based on two surveys, *i.e.* the decennial Belgian Time-Use Survey and Household Budget Survey collected in 2005 by the Directorate-general Statistics and Economic Information. These datasets relate to a population of 6400 individuals from 3474 households who completed questionnaires describing the chronological course of activities in 10-minute increments throughout 24 hours; and are clustered by Aerts et al. (2013) based on the behavorial observations.

The `StROBe.Household` class forms the core of the module. At instantiation, owned household appliances and household composition is defined, wherafter all household individuals are appointed to one of the predefined clusters based on their employment types. Its main method `simulate(..,yr)` starts by generating occupancy chains $o_i(n)$ for each individual i independently at a 10-minute resolution; based on a combination of survival analysis and heterogeneous Markov chain methods, and the probabilities from the designated clusters defined by Aerts et al. (2013). Three states are considered, *i.e.* being *awake at home*, *asleep at home*, and *absent*. Additionally, all activity proclivities $a_i(n)$ are defined for each household member as a function of the possible occupancy states and designated clusters. Resultingly,

- Given $o_i(n)$ and $a_i(n)$, 1-minute profiles are generated for receptacle loads $P_r(n)$ and domestic hot water by modelling their switching behaviour in the `StROBe.Equipment` class based on a heterogeneous discrete-time Markov chain method and defining durations based on survival analysis.
- Given $o_i(n)$, 10-minute profiles are generated for the space heating setpoints based on the clustering of setpoint observations by Leidelmeijer and Van Grieken (2005) and the clear link between the average occupancy patterns obtained from clustering the time use surveys.
- Given $o_i(n)$ and $P_r(n)$, internal heat gains can be estimated straightforwardly.

The `StROBe.Feeder` class combines the properties of `Household(..)` instantiation and Python class methods to obtain results for an entire neighborhood based on the general concepts of Monte Carlo methods.

The necessary 'overhead' code for data handling, and all class-independent functions for Monte-Carlo survival analyses and discrete-time Markov chains are gatherd in `data.py` and `stats.py` respectively.

The FastBuildings Library; a low-order building model library

The Modelica `FastBuildings` Library provides low-order alternatives to the white-box models in `IDEAS`, focusing on single and multi-zone building energy models. It differs herein mainly from `IDEAS` in two ways. First, the components target different goals, *i.e.* they are used as embedded models in (model predictive) control algorithms, forecasting algorithms or used in fault detection and diagnosis. Second, the components are parametrized differently. Whereas `IDEAS` is developed for forward modelling, meaning that parameters are defined based on prior knowledge, `FastBuildings` is designed for inverse modelling, meaning that parameters are obtained from a parameter estimation procedure based on simulated or measured signals. For this purpose, the `GreyBox` module has been developed.

Approach. For maximum compatibility and resulting interchangeability, `FastBuildings` starts by adopting the `IDEAS` Modelica Interfaces for thermal building zones, space heating and ventilation systems, and user behaviour; as shown in Figure 2. An alternative building energy model can, as such, be easily generated by instantiating one of the predefined templates in `FastBuildings.Building` and redeclaring the desired submodels.

The current implementation of the thermal zone models available in `FastBuildings` is based on a resistor-capacitance network analogy which is often used for the modelling of thermal processes, *e.g.* by Bacher and Madsen (2011) and Bacher and Madsen (2011). An example of one of the third-order models in the library is given in Figure 3. The use of RC-models is however not required: any model that specifies a relationship between the heat flows and temperatures at the interface of a thermal zone can be implemented. For HVAC models, there are two approaches. Currently, only lumped HVAC models are implemented without hydraulic mass and energy balance equations. In these models, heat and cold producing units are modeled with performance curves and an RC analogy can be used to represent a state for the supply water De Coninck et al. (2015). In the near future, simplified counterparts of the hydraulic components present in `IDEAS` will be added, allowing the modelling of mass flow rates in hydraulic circuits.

Compilation and simulation. The `FastBuildings` library is designed to be compatible with all Modelica tools. It has been tested to compile and simulate with JModelica.org and the OpenModelica tool chains. Moreover, all models in `FastBuildings` are twice continuously differentiable with regard to all variables (except time). Therefore, the models can be used in gradient-based optimization frameworks such as provided by JModelica.org and OpenModelica. As will be illustrated in the next section, this property is exploited by the `GreyBox` toolbox.

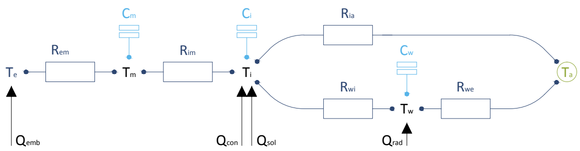

Figure 3: Example of a third-order thermal zone model in the `FastBuildings` *library*

The GreyBox Module; a data-driven grey-box toolbox

Obtaining a good control model remains one of the main challenges for the implementation of model-predictive control in buildings. The Python GreyBox Module targets model identification of low-order models such as presented in `FastBuildings` based on measurement signals.
The toolbox is described in more detail by De Coninck et al. (2015); including a validation exercise.

Approach. The prerequisites for model identification with `GreyBox` are a dataset and a set of model candidates. The dataset can come from a monitored building or from (high-order) building simulation. The model candidates are provided by the `FastBuildings` library. The aim of the toolbox is to find the model candidate *and* the corresponding set of parameters that is most suited to represent the building that generated the dataset. The resulting low-order grey-box model can be used for control, forecasting or fast simulations.
The `GreyBox.Case` class forms the core of the module. Every instantiated `Case(..)` object represents an (un-)successful attempt to obtain a model for the given building, and keeps track of the model structure, the identification data, the initial guess, solver settings and the results of a single parameter estimation attempt.
The `GreyBox.GreyBox` class object contains many different instances of the main `GreyBox.Case` class and its methods gather the main functionality of the module dealing with the required data handling, model selection, defining of initial guesses, the effective parameter estimation, validation and model selection.
Two features of the toolbox deserve explicit mentioning. First, a latin hypercube sampling procedure is implemented to obtain a good set of initial guesses in order to increase the chance of finding a global optimum of the non-convex parameter estimation problem. Second, a forward selection approach avoids overfitting and returns the most simple model that results in the lowest model error on cross-validation.

Dependence. The Python GreyBox Module heavily relies on the `JModelica.org` platform, which is *"an extensible Modelica-based platform for optimization, simulation and analysis of complex dynamic systems"*. For simulation purposes, `JModelica` uses the Functional Mockup Interface (Blochwitz et al., 2011) while it offers various algorithms for optimisation purposes and supports the Modelica language extension `Optimica` (Å kesson et al., 2009). The latter allows for high-level formulation of dynamic optimisation problems in a Modelica-like syntax.

ILLUSTRATIVE EXAMPLES

To illustrate the novelties of the framework, the possible use of `OpenIDEAS` is elaborated on with some illustrative examples dealing with three distinct topics whoe full modelling process is explained by Baetens and Saelens (2015) and De Coninck (2015), *i.e.* the sensitivity of low-voltage distribution grid operation towards the design of heat pump based dwellings, the uncertainty in district energy simulations regarding occupant behaviour, and the potential of rule-based and model predictive control of thermal dwelling systems towards neighborhood objective functions dealing with the low-voltage grid.

On building externalities

A *first novel* opportunity of the `OpenIDEAS` framework lies in combing the thermal and electric modelling aspects in transient simulations at (building and) district scale based on the Modelica `IDEAS` Library.
The latter is of main interest for examining the rapid integration of heat pump based space heating systems and rooftop-mounted photovoltaic systems in the residential built environment (Baetens et al., 2012; Baetens and Saelens, 2013); especially in the proposal of thermal building solution for electric problems as projected by Baetens and Saelens (2015) and De Coninck (2015). As an example, by simulations including the building envelope, thermal heating systems and electric low-voltage distribution, correlations are obtained by Protopapadaki et al. (2015) between thermal building parameters and grid constraint indicators based on a Monte Carlo approach and a maximin latin hypercube sampling of the former parameters as shown in example Figure 4. For a *weak*, *moderate* and *strong* low-voltage distribution network, relevant correlations are found *e.g.* between the average overal heat transfer rates and the characteristic voltage deviation U_{ϕ}^{rms} describing the quadratic mean of the daily peak voltage deviation in comparison to the reference voltage $u_0^{(k)}$, *i.e.* 230 V.
The proposed work renders the suggestion that building externalities in the low-voltage grid may be metamodeled based on the building parameters, and be part of future building energy assessments.

On aleatory uncertainty

A *second novel* opportunity of the `OpenIDEAS` framework lies in combing the stochastic aspects regarding occupancy behaviour in the Python `StROBe` Module with the physical aspects at (building and) district scale to quantify the (aleatory) uncertainty in transient

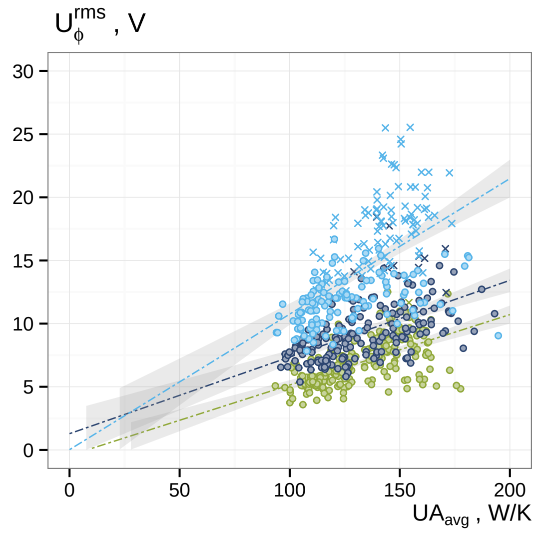

Figure 4: Correlation between the average UA-value of heat pump based dwellings on the charactersitic daily voltage deviation U_ϕ^{rms} in the low-voltage feeder regarding three feeder strengths (redrawn from Protopapadaki et al. (2015)). Denoted with '×' are the infeasible building solutions regarding distribution grid regulations.

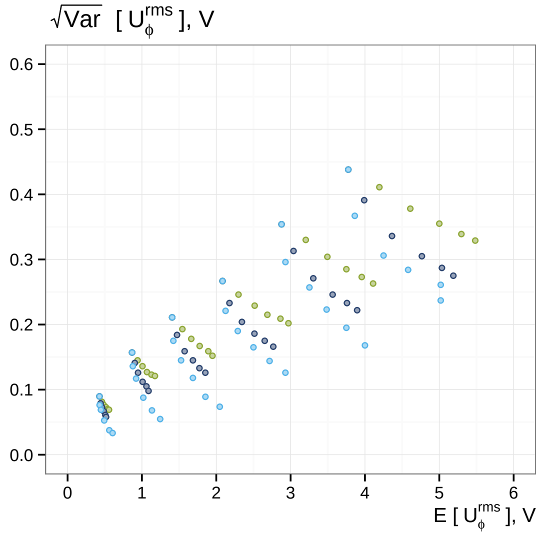

Figure 5: Standard deviation of the aleatory uncertainty of the characteristic voltage deviation U_ϕ^{rms} in the low-voltage feeder by occupant behaviour regarding six different feeder sizes and five degrees of implementation of heat pump and photovoltaic based building energy systems (redrawn from Baetens and Saelens (2015)).

`IDEAS` simulations.

The latter is of main interest in the framework of policy recommendations and occuring difference between observed and simulated cases; especially if proposed solutions are sensitive to occupant behaviour as projected by Baetens and Saelens (2015). Here, the uncertainties inherent to the nondeterministic phenomena in occupant behaviour are determined for (building and) grid constraint indicators as shown in example Figure 5, based on a Monte Carlo approach varying the user behaviour in 100 design of experiments. For the integration of heat pump based space heating systems combined with 0, 2 or 4 kVA photovoltaic systems, standard deviatons are defined *e.g.* for characteristic voltage deviation U_ϕ^{rms} in relation to the expected value or as a function of the neighborhood size.

The proposed work renders the suggestion that the sensitivity of results on occupant behaviour can be reduced with an appropriate system design, and that the uncertainty could be neglected once a *critical* feeder size is reached.

On demand control

A *third novel* opportunity of the `OpenIDEAS` framework lies in combing the thermal and electric modelling aspects in `IDEAS` for intagrated central and decentralized control at district scale founded on the concept of demand side management.

The latter is of main interest for examining the rapid integration of heat pump based space heating systems and rooftop-mounted photovoltaic systems in the residential built environment; especially in the proposal of a demand side management approach for the heat pump control to solve electric distribution problems as projected by De Coninck et al. (2013). Here, five concepts of *responsive* rule-based control of the heat pump for space heating or domestic hot water are elaborated aiming to reduce the overall energy losses in the low-voltage distribution feeder as shown in example Figure 6, *i.e.* the ohmic loses and curtailment of the photovoltaic system. Here, the saved energy in the feeders is weighted against the increasing energy demand of the heat pump due to the control interventions. The proposed work renders the suggestion that curtailment of the photovoltaic inverter can be strongly reduced by simple rule-based controles and small hot water storage tanks.

CONCLUDING

With the increasing complexity of current building energy regulations, the need for more elaborate building energy simulation tools rises. This paper presents and discusses the development of the `OpenIDEAS` framework, an open framework developed for integrated district energy simulations consisting of `IDEAS`, `StROBe`, `FastBuildings` and `GreyBox` to answer the novel research questions rising in the multi-disciplinary building energy domain; focussing at the spatial scale of a low-voltage distribution system.

Its novel approach allows integrating electric and thermal (building and) district energy models in a single simulation model to research their mutual dependence.

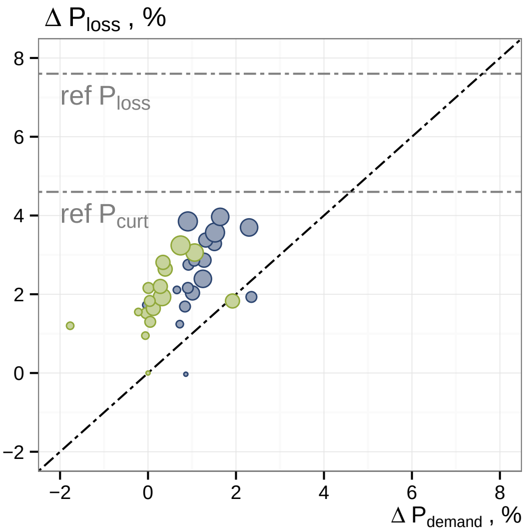

Figure 6: Loss-benefit space of the rule-based controls of the heat pump aiming to reduce the ohmic and curtailing losses with a 200 liter (green) and 500 liter hot water storange tank. (redrawn from De Coninck and Helsen (2015)).

The use of stochastic residential occupant behaviour for all considered commodities enables the quantification of the aleatory uncertainties in the proposed approach; whereas the use of a large single model empowers the simulation of centralized and decentralized control algorithms in district energy systems.

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