SYSTEMS CONTROL AND OPTIMIZATION LABORATORY (SYSCOP),
DEPARTMENT OF MICROSYSTEMS ENGINEERING (IMTEK),
UNIVERSITY OF FREIBURG

THERMAL SYSTEM SIMULATION (THE SYSI),
DEPARTMENT OF MECHANICAL ENGINEERING,
UNIVERSITY OF LEUVEN

Optimal Control of Thermal Systems in Buildings using Modelica

Workshop schedule and abstracts

23.03.-24.03.2015

Systems Control and Optimization Laboratory (SYSCOP)
Department of Microsystems Engineering (IMTEK)
University of Freiburg

Room 00-010/14
Georges-Köhler-Allee 101
79110 Freiburg
Germany

Table of contents

Welcome ... 1
Program schedule ... 2
Monday, March 23rd ... 2
Tuesday, March 24th ... 3
Abstracts (in chronological order) ... 5
Monday, March 23rd ... 5
Tuesday, March 24th ... 8
List of participants ... 19

Welcome

Dear Participants,

welcome to Freiburg, welcome to the two day Workshop on Optimal Control of Thermal Systems in Buildings using Modelica!

Aim of this interactive workshop is to bring together researchers that work on optimal control of thermal energy systems in buildings and who use or want to use the Modelica language for the building simulators. A major question of interest is how to connect Modelica based simulation tools with state-of-the-art optimization tools, and which problem formulations make sense.

After a joint lunch and an introduction of the participants, we first focus on the modelling of thermal systems in Modelica as well as different possibilities for optimization within the scope of Modelica. On day 2, we will first discuss the topic of control models, and then focus on possibilities to apply model predictive control methods to Modelica models, while we close the day with talks about grid interaction optimization.

The workshop has 31 participants and 27 talks, so the schedule will be tight. Time for individual conversation and discussion can be found in the long coffee breaks, at the interactive sessions of day 2, at lunch on Monday and Tuesday at the Solar Info Center, and at the dinner at Tacheles on Monday evening. For a detailed description of the program and the order of presentations, please have a look at the program schedule on the following pages.

We wish you exciting and inspiring two days!

Yours sincerely,
the organizers

Lieve Helsen (KU Leuven),
Adrian Bürger (HS Karlsruhe / Univ. Freiburg),
Christine Paasch (Univ. Freiburg) and
Moritz Diehl (Univ. Freiburg / KU Leuven)

Program schedule

Monday, March 23rd

12:30	Welcome and introductions
12:30	**Lunch** (self-payment) Solar Info Center, Emmy-Noether-Str. 2, 79110 Freiburg
14:00	**Welcome** Chair: Lieve Helsen, KU Leuven
14:15	**People introductions** 2 min introduction per participant, the order can be taken from the list of participants on page 19
15:15	**Break**

15:45	Session 1: Dymola/Modelica/JModelica (Chair: Filip Jorissen)
15:45	**Dymola Modelica in Industrie und Hochschule** Marco Braun, HS Karlsruhe
16:00	**Optimization Tool Chain in JModelica.org** Toivo Henningsson, Modelon
16:20	**Modelica interoperability with CasADi** Joel Andersson
16:40	**Solar Thermal Modeling: components, libraries and user interfaces** Stefan Fortuin, Fraunhofer ISE
17:00	**Break**

17:30	Session 2: Optimization (Chair: Mario Zanon)
17:30	**Optimization of a Combined Heat and Power Unit (Discrete Optimization Problem)** Mehmet Elci, Fraunhofer ISE
17:45	**Optimization of a complex energy supply system using PyFMI** Gesa Böhme, Fraunhofer ISE
17:55	**Challenges in Applying Optimization Tools to Solar Air Conditioning** Angelika Altmann-Dieses, HS Karlsruhe
18:00	**Thermo-hydraulic optimization of low-exergy heating and cooling systems** Dominik Wystrcil, Fraunhofer ISE
18:10	**Calibration and validation of a building emulator model for testing controllers** Mats Vande Cavey, KU Leuven
18:30	**End, free time**
19:30	**Dinner** (self-payment) Tacheles, Grünwälderstraße 17, 79098 Freiburg

Tuesday, March 24th

09:00	Session 3: Control and control models (Chair: Arnout Aertgeerts)
09:00	**Development of controlling models for residential solar thermal systems using Modelica** Sunah Park / Axel Oliva, Fraunhofer ISE
09:15	**Automated identification of grey-box controller models for monitored buildings with JModelica.org** Roel De Coninck**,** KU Leuven
09:35	**Review of model selection and identification for continuous commissioning implementations** Joachim Verhelst, KU Leuven
09:55	**Optimal linearization of complex buildings envelope** Damien Picard, KU Leuven
10:15	**Effect of control model mismatch on model predictive control performance of sensible energy storage in dwellings with a heat pump and local electricity production** Brecht Baeten, KU Leuven
10:30	**Break**

11:00	Session 4: MPC (Chair: Roel De Coninck)
11:00	**Comparing state estimation techniques for model predictive control (MPC) in Buildings** Mats Vande Cavey, KU Leuven
11:10	**Impact analysis of sensor/actuator bias on MPC-performance using Modelica** Joachim Verhelst, KU Leuven
11:20	**Robustness Analysis of Model Predictive Control applied to a Hybrid Ground Coupled Heat Pump System** Stefan Antonov, KU Leuven
11:30	**Optimal HVAC control for state-of-the-art office building: methodology and open questions** Filip Jorissen, KU Leuven
11:50	**Tips and tricks for cost function of complex building optimal controllers** Damien Picard, KU Leuven
12:10	**A Short Framework for Prototyping Nonlinear Model Predictive Control Loops** Michael Nöding, TU Braunschweig
12:30	**Lunch** (self-payment) Solar Info Center, Emmy-Noether-Str. 2, 79110 Freiburg

14:00	Session 5: MPC (Chair: Damien Picard)
14:00	**Numerical Optimal Control and MPC** Mario Zanon, University of Freiburg
14:15	**On the issue of model predictive control of solar thermal cooling systems** Adrian Bürger, HS Karlsruhe
14:30	**Quadratic MPC and adaptive MPC of variable speed air source heat pumps in buildings** Nilay Saraf, Fraunhofer ISE
14:50	**Practical implementation and evaluation of MPC for an occupied office building in Brussels** Roel De Coninck, KU Leuven
15:10	**Break**

15:40	Session 6: Building clusters/grid interaction (Chair: Stefan Antonov)
15:40	**Grid-interactive operation of heat pumps in office buildings using the building mass as a storage** Konstantin Klein, Fraunhofer ISE
15:50	**Netzfreundlicher Betrieb von thermoaktiven Bauteilsystemen (TABS) durch Lastverschiebung auf der Basis der MPC** Julien Höll, HS Offenburg
16:00	**Agent-based control of a neighborhood: A generic approach by coupling Modelica with Python** Arnout Aertgeerts, KU Leuven

16:15	Closing
16:15	**Take-home statements by all** Chair: Lieve Helsen, KU Leuven
17:00	**End of Workshop** Time for interactive sessions
18:30	**End of interactive sessions**

Abstracts (in chronological order)

Monday, March 23rd

15:45	Marco Braun	HS Karlsruhe

Dymola Modelica in Industrie und Hochschule

Already in 2002, we have used Dymola Modelica in modeling and simulation of vehicle air conditioning systems at Daimler. From this work, the joint development of the Air Conditioning Library for the German automotive manufacturers and suppliers has developed. Shortly after my application at the University of Applied Science of Karlsruhe, I started using this program in teaching the simulation of thermodynamic components. Now we are going to model a system for solar air conditioning in Dymola Modelica.

16:00	Toivo Henningson	Modelon

Optimization Tool Chain in JModelica.org

The talk aims to give a brief introduction to the Modelica based optimization tool chain in JModelica.org, what it does, and how. Supported problem formulations are described along with implemented solution procedures through collocation. The optimization capabilities are demonstrated with a small example, and some additional features are discussed.

16:20	Joel Andersson	

Modelica interoperability with CasADi

CasADi is an open-source framework for numerical optimization in particular and numerical optimal control in particular. From the very onset, interoperability with the Modelica modeling language has been a priority. In this talk, we give an overview of the latest developments in CasADi, in particular regarding the possibilities for performing numerical optimization using models formulated in Modelica, either directly or via the Functional Mockup Interface (FMI) format. An outlook on future developments is also given.

16:40	Stefan Fortuin	Fraunhofer ISE

Solar Thermal Modeling: components, libraries and user interfaces

Modelica is an object oriented modeling language whose hierarchical development allows for relatively easy modification (reuse) of developed components. It also has the ability to create user friendly component interfaces in a GUI. This also reduces errors. The potential for Modelica to be used in solar thermal is thus higher than other closed and non-hierarchical models (e. g. TRNSYS). For broad acceptance of the Modelica platform, component and system model libraries are to be developed, documented and made available. I have been working on this since the last two years.

17:30	Mehmet Elci	Fraunhofer ISE

Optimization of a Combined Heat and Power Unit (Discrete Optimization Problem)

In Germany, combined heat and power (CHP) district heating systems are a reasonable solution to meet a residential area's energy demand. While the produced heat is used to provide the buildings' space heating and domestic hot water requirements, often the generated electricity is fed into the grid at a fixed tariff. In future, the income from this supplied electricity is expected to depend on the national residual load – the load that remains after national photovoltaic and wind turbine power has been fed in – and hence be coupled with the electricity prices at the European Energy Exchange.
The control strategy for CHP units will therefore change from a heat led to an electricity oriented strategy. The aim will be to run the CHP units at times with high electricity prices and to turn them off at times with low prices, without compromising security of heat supply. With heat storages it is not necessary to use the heat immediately when it is produced. Hence, the CHP operation and the usage of the heat can be decoupled. By using predicted future heat load and electricity prices, the optimal control strategy for the CHP unit (ON or OFF / trajectory) can be calculated.
This is a non-linear discrete optimization problem. So far the problem was solved by coupling Modelica with the optimization program GenOpt and using a Particle Swarm Optimizer.

17:45	Gesa Böhme	Fraunhofer ISE

Optimization of a complex energy supply system using PyFMI

Simulation models play a crucial role in the planning phase of energy supply systems for buildings, as they allow for determining the best options for the sizing of heating ventilation and air conditioning (HVAC) components as well as they provide an estimate of the expected energy consumption of buildings. Furthermore, in case of complex energy supply systems, which involve several heat and power sources, storage capacities and varying demand schemes, simulation models are indispensable to support and optimize building performance during operation.
Here, I present a methodology and a tool chain, which allows reusing simulation models, which have been developed in the planning phase, for building performance optimization. As a demonstrator, I consider a complex energy supply system for a school campus in Germany involving heat pumps, solar absorbers and a large thermal ice storage. The simulation model, which was set up in SimulationX by our project partners, was exported as Functional Mockup Unit (FMU), and imported into a python framework using PyFMI. Then, in this python framework, different control schemes for the ice storage management and the heat storage management were developed and tested "offline", i.e. without interfering with the real system. The aim is to optimize in each time step the input values for the model, such as set values for volume flows and heat generators, taking varying climate conditions and user behaviour into account. Once an adequate strategy is found, an established connection to the building management system (BMS) allows for an "online" application of the developed strategy, where the results of the optimization procedure can be directly fed into the BMS.

17:55	Angelika Altmann-Dieses	HS Karlsruhe

Challenges in Applying Optimization Tools to Solar Air Conditioning

A short overview of modeling and optimization approaches applied to a projected test plant for solar air conditioning at University of Applied Sciences Karlsruhe is presented. In particular, challenges encountered when the developed models should not only be used for simulation but for optimization are discussed.

18:00	Dominik Wystrcil	Fraunhofer ISE

Thermo-hydraulic optimization of low-exergy heating and cooling systems

The contribution focuses on the optimization of control strategies for hydronic space heating and cooling systems. So-called low-exergy systems offer a high potential for the reduction of energy demand by utilizing environmental heat sources and sinks like e.g. geothermal energy. The heat distribution to the rooms can be realized by thermo-active building systems[1] (TABS) which support large surface areas for the heat exchange and therefore enable the use of low supply water temperatures in heating mode and high supply water temperatures in cooling mode. Hereby, high energy efficiency for the heat transformation in heat pumps and chillers can be achieved.
For the operation of low-exergy systems some conflicts of objectives arise:

- The low temperature gradient between the heat carrier fluid and the room makes (e.g. in comparison to conventional high temperature heating systems with radiators) high volume flow rates necessary to obtain a sufficient heat exchange with the rooms. This results in an increased energy demand for the circulating pumps.
- Thermo-active building systems have a high thermal capacity that leads to long time constants for the heat supply to the rooms compared e.g. to radiators. This makes the control of the thermal comfort difficult and can lead to an increased thermal energy demand for heating and cooling.

Therefore, the goal of this contribution is the thermo-hydraulic optimization of control strategies that minimize the energy demand for heating and cooling and maintain the thermal comfort requirements. Considered is a whole system consisting of a borehole heat exchanger, heat pump, hydraulic distribution network, TABS and two thermal zones of the building. Optimal control strategies for the setpoints for supply water temperatures, volume flow rates and operating times shall be identified with regard to the layout of the hydraulic distribution network.
The optimization shall be performed based on a thermo-hydraulic system simulation model that is implemented in Modelica. Until now, different approaches for a gradient-based optimization have been tested utilizing different software frameworks like OpenModelica, JModelica, CasADi and IPOPT.

[1] Pipes embedded in the concrete ceilings of the building.

18:10	Mats Vande Cavey	KU Leuven

Calibration and validation of a building emulator model for testing controllers.

Building energy systems are complex and non-linear systems. Many different control algorithms exist to control the HVAC system in buildings. A true comparison of different control algorithms is infeasible in practice (identical conditions cannot be guaranteed). Therefore, an emulator should serve as virtual test bench, on which different controllers can be tested in identical conditions. For the comparison to be meaningful, the virtual test bench should represent a real building, with all existing physical dynamic interactions.

The construction of a 'valid' detailed emulator model is a cumbersome and iterative process, which is facilitated by the object-oriented, graphical and physical modelling approach in Modelica. The resulting model has a very large amount of parameters of which some values are unknown or uncertain to the modeller. This leads to models, which might represent a building, but are not an appropriate model for the building under study. By tuning the unknown parameter values the model can be calibrated to better fit the measurement data. Considering large simulation times for large building models, the tuning should be handled in a smarter way than single handed adjusting and comparing.

The model calibration can be performed by the following two-step procedure. In a first step, a sensitivity analysis is performed rank the parameters based on their influence on the fit of model output with measurement data. In a second step, a number of these top ranked parameters are entered as optimization variables in Genopt, a general optimization tool. All parameters should be specified with initial guess, min and max values and a stepsize and are optimized to minimize the fit error between model output and measurement data. After these steps, one possible optimal parameter set for the given model highlights the model's shortcomings and drives model updates and refinements. This procedure is repeated until the model predicts all relevant system phenomena and the model, with a resulting set of parameter values is accepted. This final model will be a good representation of the building. However, it might not contain the optimal parameter values (local optimum in a highly non-linear problem) and should be validated (or recalibrated) for different times in the year. The modeller does improve his confidence in the model and assures himself this is an appropriate model for a building.

Tuesday, March 24th

09:00	Sunah Park / Axel Oliva	KU Leuven

Development of controlling models for residential solar thermal systems using Modelica

The building sectors take account approximately 40% of the final energy demand in Europe. In this perspective, a huge potential for low-temperature solar thermal (ST) system to deliver heat to buildings has been highlighted as means of "decarbonization". It is projected that ST will be able to cover half of the heating demand in Europe in the long term (2050) [ESTTP]. Proper operation of ST system is, therefore, one of the key issues to be guaranteed to achieve this goal.

The common ST system for residential buildings consists of four parts; collector circuit (in which the medium gains energy through collector), solar circuit (which directly charges the store), auxiliary (which provides supplementary heat to store) and load (thermal loads of users) side.

Not to mention, control strategy is highly necessary in solar system operation as it is a very decisive factor for the performance of the system. Different regulating methods in ST systems are developed in Dymola simulation interface.

The first control concept is the conventional on-off controller in which hysteresis control plays a main role. This scheme is introduced in the control unit of pump of the collector circuit to avoid unwanted oscillation.

Another control strategy is a matched-flow control [Wittwer, 1999]. Matched-flow is driven to achieve fast solar heat on useful temperature level as well as to prevent too high collector temperature by regulating the mass flow rate not only by the hysteresis but also by a PI(D) controller. When the set point collector outlet temperature is reached, then the PID controller keeps this level of temperature until the maximum mass flow rate is detected. However, PID controller is one of the major reasons of delaying computation time.

Flip-flop control is used to control the temperature of stand-by tank which is equipped in one of the technologies of DHW preparation. In this type of technology, the outlet temperature of the stand-by tank should always be over 60°C. Moreover the whole storage temperature should be more than 60°C at least once per day. The control can be made to change state of loading depending on signals of two inputs (storage temperature at top and bottom) as well as the previous state of charging.

The mass flow of DHW and SH is regulated to keep the desirable temperature level using energy balance equation.

Better performance of the system can be achieved through parameter optimization. Critical performance outputs that are taken into account evaluating solar thermal systems are 1) Solar thermal fraction, 2) Auxiliary operation hours, 3) CHP operation hours and 4) Collector stagnation hours.
The objective system parameters for optimization include:

- Collector aperture area
- Collector tilt angle
- Hysteresis upper and lower limit in the control of collector circuit
- Store thermal capacity
- Relative auxiliary volume in the store

09:15	Roel De Coninck	KU Leuven

Automated identification of grey-box controller models for monitored buildings with JModelica.org

One of the current bottlenecks in the implementation of MPC in buildings is the required controller model. Each building needs its own model of which the development currently involves a lot of manual work. A solution can be found in data-driven modelling techniques.
This presentation describes the development and validation of a grey-box modelling toolbox for buildings.
The Python toolbox is developed based on a Modelica library with thermal building and Heating, Ventilation and Air-Conditioning (HVAC) models and the optimisation framework in JModelica.org.
The toolchain facilitates and automates the different steps in the system identification procedure, like data handling, model selection, parameter estimation and validation.

To validate the methodology, different grey-box models are identified for a single-family dwelling with detailed monitoring data from two experiments.
This presentation will cover the methodological aspects of the toolbox and discuss the resulting models and their validation for a single-family dwelling in Munich (Germany) and an office building in Brussels (Belgium).
Acknowledgment: this contribution is based on the article "Development and validation of grey-box building models for forecasting and control", in review for publication in the Journal of Building Performance Simulation (submitted on 24th of December 2014).

09:35	Joachim Verhelst	KU Leuven

Review of model selection and identification for continuous commissioning implementations

To guarantee indoor thermal comfort in a typical European office building, about 40% of the total average yearly primary energy use can be attributed to its HVAC systems.
Unfortunately, many existing HVAC systems (both new and old) are operated in a suboptimal way. The process of continuous commissioning (CCx) can keep track of energy wasters, through the investigation, follow-up and (if needed) modifications of building and HVAC installations or settings. Some CCx-functions that can be implemented in offices by using building and HVAC models are:

- Identification, implementation and follow-up of energy conserving opportunities (ECO)
- Fault detection, diagnosis and evaluation (and overhaul) to maintain or increase HVAC efficacy (FDDe)
- Improved (model based) HVAC control (MBC)

During the last decade, Internet of Things and Big Data paradigms have boosted the market penetration of (manual) CCx dashboards, especially for ECO and FDDe, however only limited standardisation has occurred, since a plethora of technologies and algorithms are available. Also, fully automated CCx implementations are still quite rare.
This contribution gives an overview of real-life, model-based (MB)-CCx implementations, both by academics and building energy management systems (BEMS) manufacturers, with a focus on model requirements, identification methods and implementation examples for three distinct CCx-subtopics (as described above). The relations between model structure, identification procedure, sensor data quality and calculation power is highlighted.
This sheds a light on the reusability potential of MB-CC-models and suitable identification procedures for MB-CC models. These insights are crucial for office building managers, BEMS manufacturers and researchers involved or interested in the selection and implementation of MB-CCx strategies.

09:55	Damien Picard	KU Leuven

Optimal linearization of complex buildings envelope

Optimal climate control for building systems is facilitated by linear, low-order models of the building and of its heat, ventilation and air conditioning systems (HVAC). The difficulty of obtaining such linear models greatly hampers the commercial implementation of these optimal controllers. This work focuses on obtaining a linear controller model of the building envelope, consisting of the walls, windows, floors, etc. but also the air present in the building. We present a work-intensive method on how to obtain the best possible linear model and we quantify its Np-steps ahead prediction performance. The obtained models can be used as benchmark for linear models obtained by for example system identification or for investigating the influence of the prediction performance on a model based controller. Furthermore, the method greatly automates the setting up of a model-based control method in a Modelica© simulation environment. The following paragraphs briefly pinpoint the non-linearities presents in the building envelope and outline the proposed method.

The non-linearities in a building envelope are mainly due to the Stefan-Boltzmann law for long- and short-wave radiation where the radiative heat transfer of a body is proportional to its absolute temperature to the fourth power. Other non-linearities are the absorption and transmission of radiation through glazing and the convective heat transfer which is a non-linear function of the temperature. Finally, the partial differential equation of heat transport in a solid is three-dimensional and time dependent and its boundary conditions are non-linear.

In this work, we built a detailed building envelope model in Modelica© using the IDEAS-library taking these non-linearities into account except for the heat transfer equation (a partial differential equation) which is simplified to ordinary differential equations with a finite number of parameters representing only one-dimensional heat transport. The model is based on the dimensions and the physical properties of a real building. The obtained model is then linearized around a chosen operating point using its equations implemented in Modelica© directly, resulting into a state-space model of hundreds of states, their initial value and their initial derivative. Its inputs are the convective, conductive and radiant heat supply by the HVAC system and its outputs can be any states of the original model. Finally, we apply a model reduction technique to reduce the number of states to 30 and we compute the Np-steps ahead prediction performance of the reduced-order model. Since prediction performance requires an observer for state estimation, state-estimators (Kalman Filter or Luenberger observer) are designed based on the reduced-order model obtained from the large-scale linear model. The obtained model is the best linear approximation of the non-linear model around the chosen working point as it is uniquely derived from the original equations. The model can be used to benchmark controller models obtained by system identification on the original model or it can be used directly into a model-based controller implementation.

10:15 Brecht Baeten KU Leuven

Effect of control model mismatch on model predictive control performance of sensible energy storage in dwellings with a heat pump and local electricity production

By introducing a hot water storage tank in a space heating system including a heat pump, the system gains flexibility towards the electricity grid. Electricity can be converted to heat at favourable times and used when required. Model predictive control of such a system requires a controller model which is able to represent the non-linear behaviour of the storage tank. In this contribution model predictive control of a building with heat pump and hot water storage tank with local electricity production, using a novel iterative linear optimal control approach is compared to the traditional ideal stratification formulation. Although the difference in model mismatch in a single open loop simulation is significant, the difference in total simulated energy cost or thermal discomfort when using model predictive control is limited due to the updating of the model states. As the ideal stratified linear program is solved significantly faster it can be used in simulated model predictive control. However for real-world model predictive control, where the solution time of both methods are acceptable, the iterative linear program results in a 2% decrease of energy costs while maintaining thermal comfort.

11:00	Mats Vande Cavey	KU Leuven

Comparing state estimation techniques for model predictive control (MPC) in Buildings

MPC involves the knowledge of the complete state vector and the most significant system perturbations in order to determine the best control performance. However, this information may not be directly or completely available through measurement. In building applications often some information is lacking and the number of sensors deployed and their quality is greatly varying. As a consequence the building system models used by MPC contain several unmeasured state variables, e. g. the temperatures of the walls representing thermal inertia of the building. An optimal control sequence should be able to correctly account for the dynamic effects caused by the thermal inertia, which means that these states' values should be estimated.
Three different state estimation techniques, namely deterministic state optimization (1), moving horizon estimation (2) and unscented Kalman filter (3), are compared. They are implemented in a python framework for data handling and estimate the state vector of a simulation model in Modelica. Python addresses the Modelica models through JModelica.org for optimization (1,2) and through pyfmi for simulation (3).

(1) Deterministic state optimization assumes a perfect, deterministic model used to simulate over a past horizon. The past state vector at the start of the horizon is optimized to fit the model output to the measurement data, which finds the current state vector (at the end of the past horizon).
(2) Moving horizon estimation assumes process noise and measurement noise to simulate over a past horizon. The past state vector at the start of the horizon is assumed to be known and minimized series of process noise is added to find the current state vector.
(3) Unscented Kalman filter can assume a perfect, deterministic model, to simulate over one past timestep. The past state vector at one timestep back is assumed to be known and the current state vector is calculated by the filter.

The three algorithms are compared based both on quantitative goodness of fit (GOF) and qualitative indicators. Also, the computational performances, the ease of use and tool/model requirements are reported. The state estimation algorithms are first evaluated using simulation data and will be tested in a real multi-zone office building in Brussels for which an MPC is implemented. This allows assessing the impact of model mismatch, perturbation, and uncertainties on the ability to correctly estimate the unmeasured state variables.

11:00	Joachim Verhelst	KU Leuven

Impact analysis of sensor/actuator bias on MPC-performance using Modelica

To guarantee indoor thermal comfort in a typical European office building, about 40% of the total average yearly primary energy use can be attributed to its HVAC systems. The energy use intensity of a building depends on many factors, amongst them: weather, building envelope, building use, etc.
When applying model predictive control (MPC), the control model is often a low order model, which is a simplified presentation of the real system capturing most of the relevant building dynamics. This model mismatch is usually taken into account when evaluating the controller performance. Another important -and often neglected- aspect related to real implementation is the bias on sensors and actuators. Both sensor and actuator bias can have a major impact on the achieved model based control (MBC, among them MPC) performance, especially when hard constraints are used. The impact of this bias can be evaluated through measurements (à posteriori) or through emulation.

This contribution gives a simple example of the impact of sensor and actuator bias on a deterministic MPC controller (using the Modelica Library IDEAS), and discusses several methods of bias modelling in Modelica (manual coding, module, Dymola script). Also, the possibilities to include white noise or multiplicative errors on sensor and actuator signals during the controller model development are discussed.
This sheds a light on the robustness of the controller models towards sensor and actuator bias. These insights are critical when the (low order) models are used for evaluating in-use performance, or when they are to be included in a controller implemented in real installations.

11:20	Stefan Antonov	KU Leuven

Robustness Analysis of Model Predictive Control applied to a Hybrid Ground Coupled Heat Pump System

In practice Model Predictive Control (MPC) is prone to model mismatch, state estimation error and disturbance prediction uncertainties which might cause instability of the controlled system. Therefore, the robustness of the controlled system should be guaranteed according to a certain level of uncertainties in the MPC.
In the context of MPC, two main types of approaches for robustness analysis exist. One type is to analyze the robustness properties of an existing control system and to conclude up to what extent of uncertainty the system with conventional MPC is robust. The other type is to design robust MPC so that the optimization problem explicitly takes into account specific measures to guarantee robustness.
The presented work is focused on robustness analysis of an existing MPC formulation. The approach is based on the method of Primbs [Primbs, 2000] which checks for satisfaction of a sufficient condition for the particular system with MPC to be robust to a given level of uncertainties. The method executes an offline routine, which is based on the optimization problem formulation and on the controller model only.
The main principle of the method is to check whether the objective function value decreases over time, which is an indication for stability. Therefore, the optimization problem is represented by means of matrix quadratic functions. This allows applying the so called S-procedure [Yakubovich, 1971], which provides a sufficient condition for the non-negativity of one or more matrix quadratic functions to imply the non-negativity of another quadratic function. An extension of the S-procedure is suggested for the needs of the particular case investigated here.
The MPC robustness analysis method is adapted and implemented for the case of a hybrid ground coupled heat pump system. The resulting linear matrix inequality problem is solved in Matlab using the YALMIP interface to call the SeDuMi solver.

11:30	Filip Jorissen	KU Leuven

Optimal HVAC control for state-of-the-art office building: methodology and open questions

Model Predictive Control (MPC) is a well-known control strategy. However practical implementation in building applications happens only rarely. Reasons for this are that the required tools are far more complex than rule based control and that only few good demonstration cases of its potential exist. Our goal is to overcome these difficulties through the development of a methodology for implementing MPC in office buildings, applied to a state-of-the-art cases study: the Solarwind office building in Luxemburg.

My presentation will first focus on the case study and the systems it contains. A qualitative description of the three major parts: building envelope, HVAC and control systems, will be given. Then the underlying mathematical description of individual component models will be discussed to provide insight in the control problem type, based on the model equations. Secondly an MPC control strategy will be proposed. The application of direct optimization methods would be too slow due to the size of the problem. Therefore the model will need to be simplified. This includes the use of 1) Model Order Reduction for the building envelope, 2) fitting performance curves to non-linear (individual or groups of) HVAC components and 3) handling pressure drops. The goal is to automate this process as much as possible using the Modelica language, coupled to python.

11:50	Damien Picard	KU Leuven

Tips and tricks for cost function of complex building optimal controllers

Optimal climate control for building systems is facilitated by linear, low-order models of the building and of its heat, ventilation and air conditioning systems (HVAC), and by a quadratic or at least convex cost function for fast optimizations towards a global optimal solution. While the building envelope behavior is relatively linear (see other abstract: *Optimal linearization of complex building envelope*), HVAC systems are typically highly non-linear. This work presents the main difficulties in setting up a convex cost function and linear controller models for model-based controllers of complex building systems. We also propose ways to tackle non-linearities caused by radiation, latent heat, temperature dependent coefficient of performance, hydraulic losses, multiplication of control inputs, etc. by means of hierarchical MPC with sub-controllers, linearization, feedback linearization and convex envelope. The techniques are illustrated on a detailed office building modelled in Modelica©.

12:10	Michael Nöding	TU Braunschweig

A Short Framework for Prototyping Nonlinear Model Predictive Control Loops

A software framework for prototyping of Nonlinear Model Predictive Control (NMPC) loops is presented that is based on the standardized model exchange format FMI (Functional Mock-up Interface). This approach has become even more attractive since the second version of FMI provides additional information concerning directional derivatives with respect to states and inputs. Arising optimal control problems are solved by an efficient implementation of the direct multiple shooting method, which is especially suitable for nonlinear and stiff system models. Using co-simulation, an optimizer, plant and estimator can be coupled to a closed MPC loop. Several stages of a typical control design process are supported, ranging from virtual simulation experiments to real plants with prototype NMPC controllers. Two examples illustrate this approach. First, a traditional vapor compression cycle is controlled in a very energy efficient manner. Second, the inlet temperature of a thermoactive ceiling is computed in order to reduce energy consumption and to guarantee a room temperature within certain limits.

14:00	Mario Zanon	University of Freiburg

Numerical Optimal Control and MPC

Optimal Control has been applied in many different disciplines due to its ability to compute possibly constrained system trajectories which minimize a prescribed cost function. Model Predictive Control (MPC) is an advanced control technique for constrained nonlinear systems which relies on the repeated (online) solution of an Optimal Control Problem (OCP). Solving the OCP can be extremely difficult and several numerical methods have been developed over the years. Among these, direct methods have shown to be particularly suitable for practical applications, as they do not require any a priori knowledge of the structure of the optimal solution and can handle large scale systems. In the MPC context, several OCPs need to be solved online in real time and general purpose implementations fail to be real time feasible for fast dynamic systems. By exploiting similarities between subsequent OCPs, tailored algorithms, e.g. the Real Time Iteration (RTI) scheme, have been developed in order to exploit the specific features of the problem and achieve real-time feasibility also for fast mechanical systems. In the group of Moritz Diehl several software solutions for optimal control and MPC have been developed, including CasADi and ACADO.

14:15	Adrian Bürger	HS Karlsruhe

On the issue of model predictive control of solar thermal cooling systems

The presentation will give an overview of my PhD project “model predictive control for solar thermal cooling systems” that started in November 2014. First, a short introduction to the topic is given and relevant techniques, software and technical components are introduced. Then, a more detailed presentation is given on the different fields of work, from modeling the system in Modelica to parameter estimation and optimal control within CasADi using automatically exported representations of the Modelica model. The talk will also cover actual and upcoming challenges, especially in the fields of software and software interfaces, to energize further discussion.

14:30	Nilay Saraf	Fraunhofer ISE

Quadratic MPC and adaptive MPC of variable speed air source heat pumps in buildings.

The use of air source heat pumps is an efficient way to provide heat for space heating and domestic hot water in residential buildings. Capacity controlled heat pumps are gaining increased market share and provide high flexibility in operation. The possibility to use thermal storage to decouple heat generation from the heat pump from electric load, offers opportunities for innovative operation strategies, hereby increasing the possibility to integrate electricity from renewable energy sources or to apply load management under variable electricity prices.

In the work presented the control problem is described in detail, highlighting its non-linear and mixed integer characteristics. The transformation into a Quadratic Programming Problem is described. This is done via a division into sub-problems, an approximation of the objective function, a linear time invariant system model and a correction step after the optimization to take care of mixed integer results. Currently the problem is formulated in python and solved with cvx-opt. First results comparing the approach to a conventional operation as well as experiences and limitations will be discussed.

In the second part reformulation and adjustment of the introduced control problem is presented. The aim of the on-going work is to explore the use of online parameter estimation methods to minimize the cost of installation and configuration and improve the quality of the controls. In this presentation the approach is described and first results are presented.
The authors want to use the experience gained at the workshop to decide, whether a change to Modelica and/or the open-opt framework is an attractive option. Further the discussion with experts working on similar topics is of high interest.

14:50	Roel De Coninck	KU Leuven

Practical implementation and evaluation of Model Predictive Control (MPC) for an occupied office building in Brussels

This contribution presents the results of different MPC's applied in a real office building in Brussels, Belgium.
The building is a medium-sized office building with two floors and a total size of 960 m². The controllable system is the hybrid heat production consisting of two air/water heat pumps and a condensing gas boiler. The practical situation does not allow controlling end-units in the different thermal zones.
To test and compare different MPC implementations in a fair way (thus having identical conditions), a real building is not sufficient. Therefore, an emulator model is developed with sufficient detail to consider it as a virtual copy of the real office. Most experiments are performed on the emulator, and the promising controls are implemented in the real building.
The MPC makes use of grey-box models (see abstract entitled Automated identification of grey-box controller models for monitored buildings with JModelica.org) and solving of the optimal control problem (OCP) with JModelica. The OCP may be linear, non-linear and time-discrete. The experiments cover differences with regard to model complexity, objective functions, constraints, discretizations and time horizons.
The presentation will briefly cover the aspects of monitoring, model identification, forecasting of disturbances, state estimation, solving the OCP and sending of the control signals. More time will be devoted to the results. The different MPC strategies are analysed quantitatively with regard to energy use, thermal comfort and numerical properties. Real-life issues with regard to practical implementation are also presented.

15:40	Konstantin Klein	Fraunhofer ISE

Grid-interactive operation of heat pumps in office buildings using the building mass as a storage

The share of renewable energies in the German energy system is rising, which causes temporal fluctuations in energy availability (represented by fluctuations in electricity price, residual load etc.). Buildings with heat pumps and/or CHP can contribute to reducing these fluctuations by changing their electricity consumption or production profiles accordingly, storing the energy decentrally as heat. Buildings with low-temperature heat distribution systems (e.g. Thermo-active building systems TABS) are particularly suitable for this due to their large storage potential, but at the same time, the high thermal inertia of these systems makes effective control of the room temperatures challenging.
The goal of this work is to develop new HVAC control concepts and tools (or toolchains) for office buildings with heat pumps or CHP units as heat generators and TABS as a main heat distribution system. The goal of the control strategies is to consume electricity at times of higher electricity

availability in the energy system (for CHP units: export energy at times of lower electricity availability), while ensuring that other defined criteria (thermal comfort, energy consumption, energy expenditures) are not violated.
The components, state variables and their significances for the control problem are illustrated in Figure 1. It becomes clear that the entire control problem is highly involved due to the large number and high interdependency of the various components and state variables as well as the large inertias between actuating variables and control variables. Therefore, it is attempted to split the control problem into (at least) two sub-problems.
The first problem deals with the heat delivery profile and incorporates the components “zone throttle valve“ to „zone“. Its goal is to find the most “grid-friendly” heat delivery profile to the zone without a violation of the comfort criterion. The second problem deals with the optimal heat generation profile and incorporates the components “heat pump“ to “hot water storage“. Its goal is to find the most grid-friendly heat pump operation profile which keeps the temperature of the hot water storage within the defined operating limits under consideration of the load profile determined in problem 1.
The thermal simulations are conducted in Modelica using mainly components from the Buildings library. The optimization is carried out in a tool yet to be determined. The communication between the individual tools is realized using GNU R (or Python).

15:50	Julien Höll	HS Offenburg

Netzfreundlicher Betrieb von thermoaktiven Bauteilsystemen (TABS) durch Lastverschiebung auf der Basis der Model Predictive Control (MPC)

16:00	Arnout Aertgeerts	KU Leuven

Agent-based control of a neighborhood: A generic approach by coupling Modelica with Python

The research of optimal control in residential building clusters is approached from different disciplines: building simulations and control engineering. Control engineers focus on the research and development of sophisticated optimal control strategies combined with highlevel simulation tools but less accurate building models for fast prototyping of new control strategies. On the other hand, building simulation experts develop detailed building models which provide realistic and accurate building representations, however often in a simulation environment which is less suited for control. This paper proposes a methodology to extend a detailed neighborhood model in Modelica, which is an objectoriented modelling and simulation language, with a Python control layer in order to bridge the gap between both disciplines. The methodology tries to leverage the advantages of both approaches by enabling the combination of both in an integrated simulation while keeping the development of the building models and control strategies separate. Control algorithms developed in Python can then easily be tested on a detailed neighborhood model in Modelica. As such, the Modelica simulation model is used as an emulator or virtual test bed. These integrated simulations can provide new insights in the behavior of building clusters by using sophisticated control algorithms. The methodology is tested by implementing a central model predictive control distributed by a multiagent control system in Python on a residential neighborhood in Modelica. The results are promising: the test implementation shows improved control performance compared to rulebased control1 using a simple aggregated model for the MPC. Using this methodology, more complex and sophisticated MPC models could easily be implemented.

Besides illustrating the methodology for interfacing both disciplines, this case study allows identifying the shortcomings and potential future work related to current simulation tools.

List of participants

Participant	Affiliation
Lieve Helsen (Chair)	KU Leuven
Filip Jorissen	KU Leuven
Damien Picard	KU Leuven
Stefan Antonov	KU Leuven
Roel De Coninck	KU Leuven
Mats Vande Cavey	KU Leuven
Joachim Verhelst	KU Leuven
Bram van der Heijde	KU Leuven
Arnout Aertgeerts	KU Leuven
Brecht Baeten	KU Leuven
Mario Zanon	Univ. Freiburg
Gesa Böhme	Fraunhofer ISE
Göksel Delikaya	Fraunhofer ISE
Mehmet Elci	Fraunhofer ISE
David Fischer	Fraunhofer ISE
Stefan Fortuin	Fraunhofer ISE
Konstantin Klein	Fraunhofer ISE
Axel Oliva	Fraunhofer ISE
Sunah Park	Fraunhofer ISE
Nilay Saraf	Fraunhofer ISE
Dominik Wystrcil	Fraunhofer ISE
Angelika Altmann-Dieses	HS Karlsruhe
Marco Braun	HS Karlsruhe
Adrian Bürger	HS Karlsruhe
Michael Nöding	TU Braunschweig
Satya Gopisetty	HS Offenburg
Julien Höll	HS Offenburg
Florian Opitz	HS Offenburg
Peter Treffinger	HS Offenburg
Toivo Henningsson	Modelon
Joel Andersson	