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Model Predictive Control for Buildings

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Prague, June 2013 *Jiří Cigler*

Declaration

I declare that I worked out the presented thesis independently and I quoted all used sources of information in accord with Methodical instructions about ethical principles for writing academic thesis.

Abstract

Energy savings in buildings have gained a lot of attention in recent years. Most of the research is focused on the building construction or alternative energy sources in order to minimize primary energy consumption of buildings. By contrast, this thesis deals with an advanced process control technique called model predictive control (MPC) that can take advantage of the knowledge of a building model and estimations of future disturbances to operate the building in a more energy efficient way.

MPC for buildings has recently been studied intensively. It has been shown that energy savings potential of this technique reaches almost 40 % compared to conventional control strategies depending on the particular building type. Most of the research results are, however, based on simulation studies subject to number of assumptions. On the contrary, the objectives of this thesis are *i)* evaluate MPC energy savings potential on a real building, *ii)* develop and evaluate an alternative MPC formulation for buildings that is less sensitive to model mismatch and weather forecast errors, *iii)* develop and evaluate an alternative MPC formulation that takes into account mathematical formulas for thermal sensation of occupants.

First of all, this thesis deals with the implementation of the MPC controller on a pilot building of Czech Technical University (CTU) in Prague. The development of a grey-box thermodynamical model for control, the formulation of the underlying optimization problem and the development of the software platform for optimization problem solving and communication of the optimal control moves to the building automation system are topics treated in detail. Moreover, the evaluation of the energy savings potential is provided, showing that for the investigated building, the savings are between 15 % and 28 %, power peak demand was lowered by 50 %, while the thermal comfort in the building was kept on a higher level.

Then this thesis presents a tool that was used for the development of the MPC controller applied for the CTU building. The tool enables tuning and debugging of MPC controllers for buildings and allows users to explore controller behavior for different scenarios (e.g. weather conditions, occupancy profiles or comfort regimes).

Afterwards, based on the assessment of the long term operation of the MPC controller applied to the control of the building of the CTU, the main issues for practical applicability of MPC are pointed out and an alternative optimal control problem formulation tackling the issues is proposed showing a better closed-loop performance even in situations when there is a model mismatch or disturbance prediction errors when comparing the performance to the formulations presented in the literature.

Finally, this thesis deals with the development of a computationally tractable method for solving an alternative MPC problem formulation, which incorporates thermal comfort index predicted mean vote and which leads to a general constrained optimization problem. The advantage of this formulation is that it implicitly contains user perception of the thermal comfort in the cost function and thus it is possible to achieve better thermal comfort even with less input energy.

Keywords

Predictive control; Energy savings; Building control optimization; Thermal comfort

Abstrakt

Energetické úspory v budovách se v posledních letech staly častým předmětem výzkumu, který se v této oblasti zaměřuje zejména na možnosti využití lepších konstrukčních materiálů anebo alternativních a energeticky efektivnějších zdrojů energie s ohledem na to, aby byla minimalizována primární energie spotřebovaná v budově. Tato disertační práce se ale zabývá alternativní metodou, jak dosáhnout energetických úspor ve vytápění a chlazení budov. Metoda je založena na pokročilé technice procesního řízení zvané prediktivní řízení, jejíž předností je schopnost na základě modelu řízené soustavy a predikcí poruchových veličin ovlivňujících systém (v tomto případě se jedná například o počasí nebo obsazenost budovy) řídit budovu energeticky efektivnějším způsobem než tomu je u běžných řídicích strategií budov.

V posledních letech výzkum v oblasti prediktivního řízení budov ukázal, že prediktivní regulátor má potenciál až na 40 % úspory energie v porovnání s běžnými strategiemi řízení a to v závislosti na řadě faktorů. Většina výzkumných výsledků je ovšem založena na simulačních studiích opírajících se o celou řadu předpokladů. I proto je cílem práce ověřit potenciál energetických úspor díky MPC na reálné budově, dále vyvinout MPC formulaci, jenž sníží citlivost řízení na chyby v matematickém modelu budovy a nepřesnosti v předpovědi počasí a konečně vyvinout MPC formulaci, která bude přímo pracovat s vnímáním tepelné pohody v budově.

Nejdříve budou v práci uvedeny detaily o implementaci prediktivního regulátoru na budově ČVUT v Praze. Zejména se jedná o způsob získání parametrů matematického modelu s předdefinovanou strukturou, formulaci optimalizačního problému, který je jádrem každého prediktivního regulátoru, popis softwarové platformy pro řešení optimalizačního problému a komunikaci optimálních vstupů do řídicího systému budovy. Na základě analýzy kvality řízení je ukázáno, že prediktivní regulátor dosahuje 15 % až 28 % úspor v porovnání s dobře naladěným stávajícím regulátorem. Navíc prediktivní regulátor snižuje špičkový odběr energie na polovinu a udržuje v budově lepší tepelný komfort.

V další části se práce věnuje nástroji, který umožňuje ladit parametry prediktivního regulátoru pro budovy. Tento nástroj zejména umožňuje uživateli zkoumat chování regulátoru při různých podmínkách (například při různém počasí, obsazenosti budovy nebo různých požadavcích na teploty v místnostech).

Na základě analýzy dlouhodobého chování prediktivního regulátoru na budově ČVUT a poznatků z literatury k tématu byly stanoveny hlavní problémy, se kterými se při praktickém nasazení prediktivního regulátoru setkáváme. V práci jsou rozebrány tyto problémy a je navržena alternativní formulace optimalizačního problému, která do jisté míry problémy řeší a v uzavřené smyčce vykazuje lepší chování i v situacích, kdy nejsou přesné předpovědi poruchových veličin nebo existují nepřesnosti v matematickém modelu soustavy.

V neposlední řadě se práce zabývá návrhem výpočetně jednoduché metody pro řešení alternativní formulace problému prediktivního řízení, která v sobě zahrnuje index tepelného komfortu PMV a jenž svým zařazením spadá do skupiny obecného nelineárního programování. Výhodou této formulace je to, že přímo obsahuje matematický předpis pro vnímání tepelného komfortu a tak lze dosáhnout lepšího komfortu i za cenu menší spotřebované energie.

Klíčová slova

Prediktivní řízení; Energetické úspory; Optimalizace řízení budov; Tepelný komfort

Contents

Abbreviations

Here is a list of abbreviations that will further be used in the thesis.

CTU	Czech Technical University in Prague
FEE	Faculty of Electrical Engineering
EU	European Union
US	United States
MPC	Model Predictive Control: an advanced method for constrained optimal control, which originated in the late seventies and early eighties in process industries
SMPC	Stochastic Model Predictive Control: a subcategory of MPC techniques dealing with stochastic models of the controlled system
HVAC	Heating Ventilation and Air Conditioning: a technology of indoor and automotive environmental comfort
TABS	Thermally Activated Building Systems
BAS	Building Automation System: a control system of a building
BEPS	Building Energy Performance Simulation tools: simulation programs primarily used for long term energy calculations for buildings
SCADA	Supervisory Control and Data Acquisition: a type of industrial control system
PMV	Predicted Mean Vote index: a thermal comfort index that is used in various international standards for assessment of thermal comfort not only in buildings
LTI	Linear Time Invariant
4SID	Subspace State Space System Identification
DSPM	Deterministic Semi-Physical Modeling
RC	Resistance Capacitance
QP	Quadratic Programming

1. Introduction

1.1. Motivation

In recent years, there has been a growing concern to revert or at least diminish the effect of the climate changes or the climate changes themselves. Moreover, there is a permanent effort for energy savings in most of the developed countries. In addition, the European Union (EU) presented targets concerning energy cuts defining goals by 2020 [1]: *i)* Reduction in EU greenhouse gas emissions at least 20 % below the 1990 levels, *ii)* 20 % of EU energy consumption to come from renewable resources, *iii)* 20 % reduction in primary energy use compared to projected levels, to be achieved by improving energy efficiency. Similar goals, in some cases even more restrictive, have been stated by the US government with minor differences on the level of each state [2].

As buildings account for about 40 % of total final energy consumption and more than half of the end energy is consumed in heating, ventilation and air conditioning (HVAC) systems [3], an efficient building climate control can significantly contribute to the reduction of the power consumption as well as the greenhouse gas emissions.

It is also important to mention the current state of the building sector to find a way to achieve energy cuts. For instance in the US, there are about one to two million buildings newly constructed every year. However, there are approximately 110 million existing buildings consuming much more energy *per se* than new buildings constructed according to current standards. Even if each of the new buildings use net-zero-energy technology, it would take long time to achieve significant difference on the overall energy bill [4]. A much more productive approach for achieving the strict energy cuts would be to focus also on the retrofit of the existing buildings e.g by implementing energy efficient control algorithms into building automation systems (BAS), which can nowadays control HVAC systems, as well as the blind positioning and lighting systems [5, 6].

Besides sophisticated rule based control algorithms, there have emerged two main research trends in the field of advanced HVAC control recently [7]:

- Learning based approaches like neural networks [8, 9]; fuzzy and adaptive fuzzy neural networks [10, 11], genetic and evolutionary algorithms [12, 13], etc.
- Model based predictive control (MPC) techniques that are based on the principles of the classical control [14].

In this thesis, we will only focus on the latter techniques.

1.2. Model Predictive Control

MPC is a method for constrained optimal control, which originated in the late seventies and early eighties in the process industries (oil refineries, chemical plants, etc.) (see e.g. [15, 14, 16, 17]). MPC is not a single strategy, but a class of control methods with the model of the process explicitly expressed in order to obtain a control signal by minimizing an objective function subject to some constraints. In building control, one would aim at optimizing the energy delivered (or cost of the energy) subject to comfort constraints.

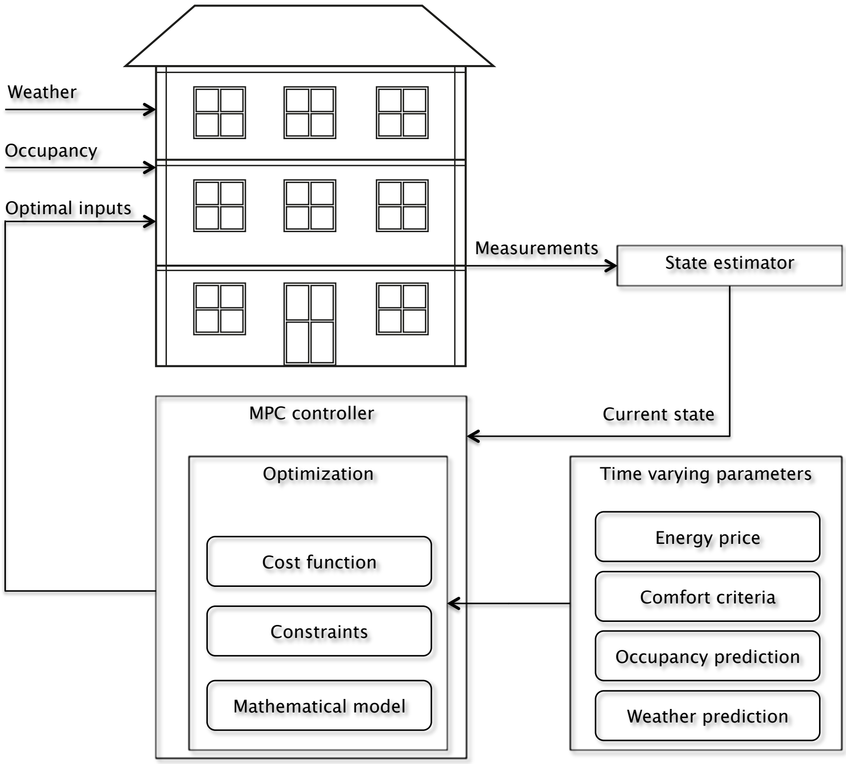

Fig. 1. Basic principle of MPC for buildings

During each sampling interval, a finite horizon optimal control problem is formulated and solved over a finite future window. The result is a trajectory of inputs and states into the future, respecting the dynamics and constraints of the building while optimizing some given criteria. In terms of building control, this means that at the current control step, a heating/cooling etc. plan is obtained for the next several hours or days, based on a weather forecast. Predictions of any other disturbances (e.g. internal gains), time-dependencies of the control costs (e.g. dynamic electricity prices), or of the constraints (e.g. thermal comfort range) can be readily included in the optimization.

The first step of the control plan is applied to the building, setting all the heating, cooling and ventilation elements, then the process moves one step forward and the procedure is repeated at the next time instant. This receding horizon approach is what introduces feedback into the system, since the new optimal control problem solved at the beginning of the next time interval will be a function of the new state at that point in time and hence of any disturbances that have acted on the building.

Figure 1 summarizes the basic principle of MPC for buildings. Time-varying parameters (i.e. the energy price, the comfort criteria, as well as predictions of weather and occupancy) are inputs to the MPC controller. One can see that the modeling and design effort consist of specifying a dynamic model of the building, as well as constraints of the control problem and a cost function that encapsulates the desired behavior. At each sampling interval, these components are combined and converted into an optimization problem depending on the MPC framework chosen. A generic framework is given by the following finite-horizon optimization problem:

$$
\begin{aligned}
&\min_{u_0,\dots,u_{N-1}} && \sum_{k=0}^{N-1} l_k(x_k,u_k) && \text{Cost function} && (1)\\
&\text{subject to} && && && \\
&x_0 &=\;& x && \text{Current state} && (2)\\
&x_{k+1} &=\;& f(x_k,u_k,w_k) && \text{Dynamics – state update} && (3)\\
&y_k &=\;& g(x_k,u_k,w_k) && \text{Dynamics – system output} && (4)\\
&(x_k,u_k) &\in\;& \mathcal{X}_k \times \mathcal{U}_k && \text{Constraints} && (5)
\end{aligned}
$$

where k is the discrete time step, N is the prediction horizon, $x_k \in \mathbb{R}^n$ is the system state, $u_k \in \mathbb{R}^m$ is the control input, $y_k \in \mathbb{R}^p$ is the system output, $w_k \in \mathbb{R}^l$ is the vector of known/estimated disturbances acting on the system, $\mathcal{X}_k$ and $\mathcal{U}_k$ denote the constraints sets of the state and inputs respectively and are explained below.

All of the components in the above MPC formulation are detailed below with the discussion how they affect the system and the resulting optimization problem. Please note that this is not a comprehensive overview of MPC formulations, but rather a collection of formulations, which are frequently used or reasonable in the field of building control. For a more comprehensive overview on MPC formulations, the reader is referred e.g. to [14].

Cost function

The cost function generally serves two purposes:

- **Stability.** It is common to choose the structure of the cost function such that the optimal cost forms a Lyapunov function for the closed loop system, and hence will guarantee stability. In practice, this requirement is generally relaxed for stable systems with slow dynamics, such as buildings, which leaves the designer free to select the cost strictly on a performance basis.

- **Performance target.** The cost is generally, but not always, used to specify a preference for one behavior over another, e.g., minimum energy or maximum comfort.

Generally, the main goal is to minimize energy cost while respecting comfort constraints, which can be formalized by the following cost function:

$$l_k(x_k,u_k) = (y_k - y_{r,k})^T Q_k (y_k - y_{r,k}) + R_k u_k, \tag{6}$$

where Q_k and R_k are time varying matrices of appropriate size and $y_{r,k}$ the reference signal at time k. The trade-off between precision of reference tracking and energy consumption is expressed by proportion of the matrices Q_k and R_k. The reference tracking is expressed as a quadratic form because it significantly penalizes larger deviations from the reference. The energy bill is usually an affine function of a total amount of consumed energy. Therefore, the control cost is weighted linearly.

Current state

The system model is initialized to the measured/estimated current state of the building and all future (control) predictions begin from this initial state x. Depending on what the state of the building is describing, it might not be possible to measure all of its components directly and e.g. Kalman filtering needs to be employed in order to obtain an estimate of the current state.

Dynamics

The controller model (i.e. the mathematical description of the building thermal dynamics) is a critical piece of the MPC controller. Typically, the linear dynamics is considered

$$x_{k+1} = Ax_k + Bu_k + Vw_k \tag{7}$$
$$y_k = Cx_k + Du_k + Ww_k. \tag{8}$$

Here the real matrices A, B, C, D, V, W are so called system matrices and are of appropriate dimensions. This is the most common model type and the only one that will result in a convex and easily solvable optimization problem.

Constraints

The ability to specify constraints in the MPC formulation and to have the optimization routine handle them directly is the key strength of the MPC approach. There can be constraints on the states or the output, as well as on the input. Linear constraints are the most common type of constraint, which are used to place upper/lower bounds on system variables

$$u_{min,k} \leq u_k \leq u_{max,k}, \tag{9}$$

or generally formulated as

$$G_k u_k \leq g_k. \tag{10}$$

The constraints can be similarly defined for system states and outputs.

1.3. Organization of the Thesis

This thesis is further structured as follows: Chapter 2 defines the goals to be achieved, Chapter 3 presents state-of-the-art in the area of MPC for buildings. The following Chapter 4 deals with the author's results. As this thesis is meant as a unifying text of author's published papers related to the topic of this doctoral thesis, the chapter contains four main papers with a brief description how the particular paper fits into the mosaic of this work. The main body of the text is concluded by Chapter 5 and a list of cited works.

2. Goals of the Thesis

Evaluation of MPC Energy Savings Potential on a Real Building

The objective here is to find a suitable pilot building for performing experiments with MPC controller, implement MPC controller and interconnect it with the building automation system of the building. Once the MPC controller is implemented, the objective is to evaluate the controller performance in terms of energy usage and satisfaction of thermal comfort. The performance is to be compared to a well-tuned state-of-the art control algorithm.

Development of a MPC Formulation Less Sensitive to Model Mismatch and Prediction Errors

Typically, the most common MPC formulation does not perform well in closed loop. Hence the second objective of this thesis is to develop and evaluate an alternative MPC formulation for buildings that is less sensitive to model mismatch and errors of weather prediction.

Development of a Computationally Tractable PMV Based MPC

Thermal comfort is a complicated quantity. According to the international standards defining requirements for thermal comfort in buildings, the thermal comfort can be expressed in two ways:

a) by a temperature range for operative temperature,

b) by a range for PMV index.

On the contrary to the first goal of the thesis, when a temperature range is used for the definition of the thermal comfort, the objective here is to use PMV index for representation of the thermal comfort directly in the MPC formulation. As the PMV is a nonlinear function of several quantities, the goal is to develop a computationally tractable MPC method solving this case.

3. State-of-the-Art

In this chapter, we present a literature overview of methods that are based on the formulation of the building control as an optimization problem. The building physics is formulated in a mathematical model that is used for the prediction of the future building behavior according to the selected operation strategy and weather and occupancy forecasts. The aim is mainly to design a control strategy that minimizes the energy consumption (or operational costs), while guaranteeing that all comfort requirements are met.

In the following, we will briefly mention related works in a structured way and we will start with early works dealing with MPC for buildings.

3.1. Early Works

A study presented by Grünenfelder and Tödtli [18] was among the first papers which formulated the control of the thermal storage as an optimization problem. The control of a simple solar domestic hot water system considering the weather forecast and two energy rates is discussed there. Some early papers [19, 20] deal with a least-cost cooling strategy using the building mass as a thermal storage.

An overview of the active use of thermal building mass is given by Braun [21], where a variable energy price and the cost of the power peak are considered in the formulation of the optimization problem.

Predictive control of radiant floor heating was studied by Chen [22], where the author first identified a model for MPC and then demonstrated on simulation results that the behavior of MPC is superior to the conventional controllers in terms of response speed, minimum offset and on-off cycling frequency.

Performance of MPC applied to the control of a radiant floor heating was later assessed by Cho [23] showing that the savings potential of MPC reaches 10 % during cold winter months and somewhat higher during mild weather conditions.

The Group around Tödli had been continuously developing MPC solution for Siemens company, which resulted in three patents [24, 25, 26] and a short conference paper [27]. In all these patents, a particular model structure is presented for the particular case, which of course restricts usage of this technique in these cases.

3.2. Energy Peak Reduction

Besides the energy minimization, predictive control can also contribute to energy peak reductions [28, 29]. Energy peak reduction can significantly lower the costs of the building operation and the initial cost of mechanical parts if considered in the building design. Grid thrifty control can also help to keep supplier–consumer balance in a grid.

Current grid load and energy peak reduction was considered in a simulation study of Oldewurtel et al. [30] dealing with power supply to several commercial buildings trying to find a trade-off between minimizing cost on side of building and flattening grid load profile.

Ma et al. [31] treated demand response control where MPC applied on cooling system of a multi-zone commercial building resulted in pre-cooling effects during the off-peak period and autonomous cooling discharging from the building thermal mass during the on-peak period.

3.3. Control Hierarchy

The hierarchy of the HVAC system controllers plays also an important role. MPC is generally suitable as a top-level controller only and the question always is, how to achieve a symbiosis between low-level control loops and the top-level MPC.

There have been couple of contributions on how to integrate MPC into the control hierarchy of the BAS [32]. Zhang and Hanby [33] addressed a building system with renewable energy sources which are generally of low intensity and temporally inconsistent. Supervisory control system is then responsible for deploying the energy directly into the building, storing for later use or rejecting to the environment.

The centralized MPC topology for multi-zone buildings is often undesirable and difficult to implement, as computational demands required to solve the centralized problem grows exponentially with the number of zones/subsystems. Another drawback of the centralized strategies is their poor flexibility and reliability, comparing to a decentralized or distributed control structure. In the case of the decentralized MPC, the large optimization problem is split into smaller ones (each with its own objective function and constraints) neglecting some interactions between building zones, while in the case of the distributed control structure, several MPC controllers minimize a global cost function. By using this technique, the overall computation time can be significantly reduced and, at the same time, the robustness of the whole control system can be increased. However, this solution comes at the cost of increased communication effort and sub-optimal performance.

Moroşan et al. [34] and later in [35] addressed heating of a multi-zone building with a decentralized and distributed MPC. While the performance of the decentralized one strongly depends on the level of interactions between subsystems, the distributed one, as each controller knows about control actions of its neighbors, keeps the same performance as the centralized one.

An alternative approach was presented by Ma, Anderson, and Borrelli [36] where the problem of distributed MPC is implemented using sequential quadratic program and dual decomposition.

3.4. Stochastic MPC

A stochastic model predictive control (SMPC) approach applied on a room temperature regulation problem is proposed in a pioneering work by Oldewurtel, Jones, and Morari [37]. The idea is to consider weather forecast (ambient temperature and solar radiation) to be a stochastic disturbance, therefore a weather prediction error model has to be constructed. Moreover, chance constraints are introduced into the optimization problem in order to meet hard constraints in at least 1-α % cases (because if the random distribution is unbounded, then the optimization problem with any hard constraint is infeasible).

A convex approximation technique outperforming the previous one and solving the same optimization problem was proposed by Korda and Cigler [38].

Later, Ma, Vichik, and Borrelli [39] presented an approach where the chance constraints are decoupled using Boole's inequality and for the resulting optimization problem, the authors proposed a tailored interior point method to explore the special structure of the resulting SMPC problem.

3.5. Building Modeling

MPC inherently requires an appropriate model of the controlled plant, which is then used for the computation of the optimal control inputs. This model must be sufficiently precise, in order to yield valid predictions of the relevant variables (e.g. room temperatures), but at the same time, the model must be as simple as possible for the optimization task to be computationally tractable and numerically stable.

In the HVAC engineering community, building energy performance simulation (BEPS) tools (e.g., EnergyPlus, TRNSYS, ESP-r, etc.) are typically used for modeling of the building physics [40]. These tools contain numerous complex calculations, non-linearities, switches and iterative procedures that make their usage in online optimization prohibitive as the resulting models are in an implicit form[1]. An attempt to use a BEPS model within an optimization routine was reported by Coffey et al. [41], but generally, researchers seek models with lower complexity and computational demands. BEPS models can then be used for MPC algorithm evaluation when co-simulation scheme is used [42].

So-called linear time invariant (LTI) models are much more suitable for the use within an MPC framework. The usage of LTI models typically leads to a convex optimization problem that, in general, can be solved well by standard optimization software tools. Obtaining an appropriate LTI model of the controlled building is, however, a delicate and laborious task even for experienced and knowledgeable engineers. A brief review of methods that can be used for building modeling is mentioned by Prívara et al. [43]. Generally, following techniques can be used to obtain an LTI model:

a) *Black-box identification.* The model structure and parameters are identified in a statistical-empirical manner from on-site measurements or from signals generated from BEPS. Following identification methods are available options for buildings: *i)* Subspace state space system identification methods (4SID) [44]. *ii)* MPC relevant identification (MRI) (multi-step ahead prediction error is minimized) [45]. The black-box approach is conceptually simple, but technically tricky, and it crucially depends on the availability of appropriate input data sets that encompass sufficient long sequences of all relevant excitation-response signal pairs. These are very hard to obtain from a real building during normal operation.

a) *Grey-box modeling.* This approach describes a building's thermal dynamics based on a thermal resistance capacitance (RC) network [46, 47, 48, 49]. It presents an analogue to an electric circuitry, with temperature gradients and heat fluxes replacing electric potentials and currents. A plausible model structure (RC network topology) is first specified a priori, and then the model parameters are identified from measurements or BEPS simulations. The advantage of this approach is that basic knowledge of possible thermal interactions (e.g., neighbourship of building zones) can easily be introduced. However, the parameter identification is far from trivial.

a) *White-box modeling.* This approach also relies upon a thermal RC network. Here both the RC network's topology and its R and C elements (the model parameters) are derived directly from detailed geometry and construction data (see e.g. work by Sturzenegger et al. [50]). Compared to grey-box modeling, this approach has an even stronger physical basis. However, similarly to BEPS studies, it requires availability and processing of a large amount of building-specific information.

[1] In this context, we call a model explicit if there are mathematical formulas describing a state evolution, i.e. a set of differential or difference equations is available. Otherwise the model is called implicit.

3.6. Thermal Comfort Representation

Thermal comfort in buildings is usually evaluated using the operative temperature [51], which is, in the simplest way, defined as the average of the air temperature and the mean radiant temperature (i.e. usually computed as area weighted mean temperature of the surrounding surfaces [52]). However, the thermal comfort is a more complicated quantity and, in accordance with ISO 7730 [51] and ASHRAE 55 [53] international standards, it can be defined in a more general way as "*The condition of mind which expresses satisfaction with the thermal environment*", pointing out that it is a cognitive process influenced by various quantities, physical activity, physiological and psychological factors and typically, this process is described by the thermal comfort index called predicted mean vote (PMV).

The PMV index as a part of MPC cost function was presented by Freire, Oliveira, and Mendes [54], where the authors show that making use of PMV index, MPC can achieve even higher energy savings. On the other hand, the non linear character of the PMV index complicates the usage of this thermal comfort index. Several MPC problem formulations having PMV index in the cost function are compared by [55]. The comparison is carried out on a real building of a solar energy research centre.

In addition, there has been developed a direct relationship between PMV index and productivity rate of the occupants of the office buildings. As the cost of office laborers in the developed countries is much higher than the operational costs of a building, the fulfilment of thermal comfort (in terms of PMV) can result in a substantial economic benefit [56, 57].

3.7. Occupancy Predictions

Occupancy predictions can also be readily included into the MPC problem formulation. Investigation of the energy savings potential when using occupancy information to realize a more energy efficient building climate control is presented by Oldewurtel, Sturzenegger, and Morari [58]. The authors showed that this additional information can lead to significant energy savings (up to 50 % of energy required by HVAC system is saved depending on occupants' vacancy intervals).

3.8. Deployment of MPC

There have been several attempts to validate MPC technique by a real operation to prove energy savings potential.

Supervisory MPC controller was successfully tested by Henze et al. [59] on the control of an active and passive building thermal storage inventory in a test facility. The controller uses a three-step procedure consisting of *i)* short-term weather prediction, *ii)* optimization of control strategy over the next planning horizon using a calibrated building model, *iii)* post-processing of the optimal strategy to yield a control command for the current time step. The energy consumption was in this case reduced by about 10 % and costs were reduced by about 17 %.

Different MPC setups applied to a thermal storage of the building cooling system have been continuously tested in the campus of the University of California, Merced. A controller that minimizes cooling costs with respect to the time-varying electrical energy price is presented by Ma et al. [60]. The aim is to take advantage of night-time electricity rates and to lower the ambient temperature while pre-cooling the chilled water tank. Experimental results of pre-cooling are later presented in [61], where a more detailed building load model was used and where where MPC achieved up to 25 % energy savings. Later, the results were summarized in [47].

Last but not least, there are the results reported in [46], where the MPC applied to a heating system of a university building saves 30 % of energy in cross comparison with conventional control strategies like heating curve, lowers power demand peaks by 50 % and keeps thermal comfort in the building on a higher level.

3.9. Software Tools Dedicated to MPC for Buildings

In the literature, there have been reported several software tools capable of running MPC for buildings.

The development of a SCADA (Supervisory Control and Data Acquisition) system allowing MPC control for buildings is reported by e.g. Figueiredo and Costa [62]. The optimal control law is computed in MATLAB and the variables are transmitted into BAS via Dynamic Data Exchange protocol. The authors show the functionality on a real life example.

An alternative way to communicate optimal control moves is reported in [46]. Here, the optimization task is solved in Scilab environment and transmitted to BAS via a proprietary protocol.

These tools are dedicated mainly to interconnection of BAS and the computational core solving MPC optimization problem. On the other hand, there are two analyzation on-line tools *i)* `http://buildinglab.felk.cvut.cz`, *ii)* `http://bactool.ethz.ch/`. The former one is used for a design phase, allowing user to tune the controller performance, while the latter evaluates the mean behavior of the controlled system over a long time period in the order of months or a year and indicates whether the particular building is suitable for predictive control.

It is also important to mention the project GenOpt aiming at employing the predictive control framework directly without the need of a simple model. GenOpt rather uses detailed models developed in EnergyPlus or in other building performance simulation tools [41].

A similar project is MLE+, allowing users to easily interconnect simulation models developed in EnergyPlus with Matlab code and test algorithms for building automation systems [63].

4. Results

This chapter deals with authors' results related to the thesis. The chapter is not written in a common way but the core of it lies in the reviewed papers, which are included here with a short comment on how the particular paper contributes to the thesis. This format is approved by a directive issued by the Dean of Faculty of Electrical Engineering (FEE) of the Czech Technical University in Prague (CTU). This directive is called "Directive of the dean for dissertation theses defence at CTU FEE" and is available at `http://www.fel.cvut.cz/cz/vv/doktorandi/predpisy/SmobhDIS.pdf`, unfortunately only in Czech.

In the following, the three most important journal papers are presented accompanied by a conference paper that has recently been accepted for the conference Clima 2013 (`http://www.clima2013.org/`). This paper, however, presents important results related to the thesis and therefore it is included here aside the reviewed papers published in journals with impact factor.

4.1. Experimental Analysis of Model Predictive Control for an Energy Efficient Building Heating System

Full citation:
J. Široký, F. Oldewurtel, J. Cigler, and S. Prívara. "Experimental analysis of model predictive control for an energy efficient building heating system". In: *Applied Energy* 88.9 (2011), pp. 3079–3087. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2011.03.009
Co-authorship: 25 %
Citations:

- Web of Science: 23 (out of which 5 are self citations)
- Google Scholar: 47 (out of which 12 are self citations)

Journal statistics according to the Journal Citation Report®

Total Cites:	6634
Impact Factor:	5.106
5-Year Impact Factor:	4.456
Immediacy Index:	0.952
Citable Items:	558
Cited Half-life:	2.5
Citing Half-life:	5.7

Annotation:
This paper follows the previously published work dealing with the identification of a thermodynamical model of the CTU university building and first experience with deployed MPC [64]. This paper deals mainly with the description of the implementation of the MPC controller (development of a grey-box model, the formulation of the optimization problem to be solved, the development of the software platform for the optimization problem solving and the communication of optimal control moves to the BAS), validation of the MPC controller functionality (in terms of reasonable predictions the model gives and comfort violations the controller produces in closed-loop) and the evaluation of the energy savings (based on a cross comparison with well tuned state-of-the-art control strategy).
Contribution to the thesis:
This paper contributes mainly to the first goal of the thesis, i.e. it describes the implementation of the MPC controller on a pilot building and at the same time, the evaluation of the controller performance is presented.

In this paper, it is shown that the energy savings potential for using MPC with weather predictions for the investigated building heating system are between 15 % and 28 %, depending on various factors, mainly the insulation level and the outside temperature. Moreover, the power peak demand is lowered by 50 % and the thermal comfort in the building is kept on a higher level.

This paper is available at http://dx.doi.org/10.1016/j.enbuild.2011.06.030

4.2. BuildingLab: a Tool to Analyze Performance of Model Predictive Controllers for Buildings

Full citation:
J. Cigler, P. Tomáško, and J. Široký. "BuildingLab: a tool to analyze performance of model predictive controllers for buildings". In: *Energy and Buildings* 57 (2013), pp. 34–41. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.10.042

Co-authorship: 60 %
Citations:

- Web of Science: 0
- Google Scholar: 0

Journal statistics according to the Journal Citation Report®

Total Cites:	5508
Impact Factor:	2.386
5-Year Impact Factor:	2.809
Immediacy Index:	0.286
Citable Items:	434
Cited Half-life:	5.6
Citing Half-life:	6.6

Annotation:

Further investigations of MPC performance applied to the control of the CTU building gave motivation for the development of a tool that would make MPC strategy for buildings easier to debug/tune and at the same time more understandable for wide public. Therefore we created a web application entitled BuildingLab (`http://buildinglab.felk.cvut.cz/`) and summarized all the features in the paper.

This tool enables users to explore the controller behavior, tune controllers by the means of displaying and comparing simulation results based on arbitrary disturbance profiles, validate mathematical models of the particular building, etc.

Contribution to the thesis:

This paper contributes to the first goal of this thesis. Having the web application that enables controller tuning makes the process of deployment of MPC on a real building faster and reliable (one can validate controller functionality in advance in different weather conditions, occupancy profiles or in different thermal comfort regimes).

The whole application is licensed under the terms of a permissive free MIT license, therefore it can easily be used by other research teams focused on MPC for buildings.

This paper is available at `http://dx.doi.org/10.1016/j.enbuild.2012.10.042`

4.3. Optimization of Predicted Mean Vote Index Within Model Predictive Control Framework: Computationally Tractable Solution

Full citation:
J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "Optimization of Predicted Mean Vote index within Model Predictive Control framework: Computationally tractable solution". In: *Energy and Buildings* 52 (2012), pp. 39–49. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2012.05.022`
Co-authorship: 55 %
Citations:

- Web of Science: 2 (out of which 2 is a self citation)
- Google Scholar: 4 (out of which 4 are self citations)

Journal statistics according to the Journal Citation Report®

Total Cites:	5508
Impact Factor:	2.386
5-Year Impact Factor:	2.809
Immediacy Index:	0.286
Citable Items:	434
Cited Half-life:	5.6
Citing Half-life:	6.6

Annotation:
It was shown that by making use of PMV index in the MPC problem formulation, it is possible to achieve even higher energy savings [54, 67]. On the other hand, the price for the savings is the increased complexity of the resulting optimization problem that becomes a non convex constrained optimization problem. In this paper, PMV based formulation is stated at first, the main differences between typical MPC problem formulation and PMV based formulation are outlined, a computationally tractable approximation of the nonlinear optimal control problem is presented and its accuracy is validated.
Contribution to the thesis:
This paper contributes to the last point of the goals of this thesis, i.e. a computationally tractable MPC methods solving PMV based MPC problem is proposed and validated on a detailed BEPS model.
This paper is available at `http://dx.doi.org/10.1016/j.enbuild.2012.05.022`

4.4. On the Selection of the Most Appropriate MPC Problem Formulation for Buildings

Full citation:
J. Cigler, J. Široký, M. Korda, and C. Jones. "On the Selection of the Most Appropriate MPC Problem Formulation for Buildings". In: *Proceedings of 11th Rehva World Congress, Clima 2013*. Accepted, to appear. Prague, 2013
Co-authorship: 60 %
Citations:

- Web of Science: 0
- Google Scholar: 0

Annotation:
Based on *i)* observations from the long term MPC operation on the CTU building and *ii)* literature dealing with MPC for buildings, we specified four main issues that engineers are facing when formulating MPC optimization problem for a real building. These issues are described in detail in this paper and an alternative practical aspects motivated optimal control problem formulation is proposed there. It is shown that this formulation behaves in a better way especially in situations when there is some model mismatch (i.e. always except for MPC simulations), disturbance prediction errors, etc.
Contribution to the thesis:
This paper contributes to the second point of the goals of this thesis. The proposed optimal control problem formulation helps to achieve even better controller performance because the resulting performance *i)* is not oscillatory (in both open- and closed-loop operation) due to smoothing terms introduced in the cost function, *ii)* is sufficiently robust to disturbance predictions and model inaccuracies, *iii)* guarantees recursive feasibility of the optimization problem,

iv) respects user-defined comfort limits in such a way that it is high probable that high comfort violations do not occur, *v)* does not increase significantly the energy consumption, *vi)* does not increase the numerical complexity of the problem significantly – the problem stays in the same class of convex optimization problems.

This paper is available at `https://support.dce.felk.cvut.cz/pub/ciglejir/data/Clima_OCP.pdf`

5. Conclusions

5.1. Summary and Contribution

Model predictive control for buildings is a very large research area and therefore in this thesis, we focused on three main goals only. Solving of the goals contributed to the state-of-the-art both from a theoretical and practical point of view. We briefly remind the main contributions of this thesis.

- The main practical achievement of this thesis is the implementation of MPC on a pilot building of the CTU in Prague. Assessing the energy savings potential, it was shown that the potential for using MPC with weather predictions for the investigated building heating system were between 15 % and 28 % depending on various factors, mainly insulation level and outside temperature. Moreover, the peak energy demand was lowered by 50 %.

  For tuning and testing of MPC controller applied for CTU building, we also developed a tool called BuildingLab. The tool is not limited for CTU building only, but can be used for any building described by a linear time invariant model.

  We did not implemented MPC only on the CTU building, but there are two other buildings that we have been dealing with.

  - The first one is a new office building in Munich, Germany. Performance of MPC was compared in simulations to the performance of a well-tuned rule-based controller very similar to the one currently deployed in the real building. MPC yielded similar energy usage (to within 5 %) as the reference controller at a comparable amount of thermal comfort violations. This result was mainly because of the building's relatively light construction (that provided little scope for predictive thermal storage management) and the high quality of the original control [69].
  - The other one is a new office building in Hasselt, Belgium. The building itself is a light façade but in the core, both the floors and the ceilings are equipped with so-called double layer Thermally Activated Building Systems (TABS), where water piping circuits are integrated into the concrete core itself. Our proposed two-level control algorithm reduces energy consumption by $15 - 30\,\%$ in average (depending on the methodology used for the comparison) and simultaneously significantly reduces comfort violations, when compared with the previously applied non-predictive control strategy [70].

- The long term operation of MPC did not always go well. Therefore over the time, we had a chance to analyze MPC behavior and point out the main issues. Subsequently, we proposed an alternative MPC problem formulation that tackles these issues and results in a better performance in situations when there is some model mismatch, disturbance prediction errors, etc.

- Finally, we proposed a tractable method for solving PMV based MPC problem for buildings, which translates the original general constrained optimization problem into QP that can be solved in polynomial time. The accuracy of this approximation was analyzed, showing only a small difference between the real value and approximation that can be neglected for control purposes. The application of this control scheme requires, however, sensors that are not available in buildings we control, therefore this methods has not been tested on a real building yet.

The two above mentioned alternative MPC formulations are the main theoretical achievements of this thesis.

We showed that MPC application results are very encouraging, nevertheless, for commercial transferring of the technology, one has to keep two issues in mind. First, each building is unique and the MPC saving potential depends on many factors like HVAC system, building construction or weather conditions to name a few. Second, the complete cost benefit analysis should not include just energy savings but also the cost of the MPC implementation, i.e. the modeling effort in particular, that presents the most time consuming part and MPC integration into a BAS. These aspects are discussed in detail in the author's recent paper [69].

5.2. Future Research

The most recent work has been focused on the selection of the most suitable MPC formulation for buildings. This part can even be more extended by performing a sensitivity analysis of the resulting optimization task. Basically, two methods are at hand.

The first one is based on the techniques for sensitivity analysis in optimization, i.e. Lagrange coefficients associated with constraints can be analyzed. Then a high value of a Lagrange coefficient indicates a possible high increase of the overall cost and thus it should be related to the sensitivity of the particular equality/inequality constraint to e.g. model mismatch, prediction error and so on. Lagrange coefficients can be obtained for all typical initial states, reference trajectories and disturbances (either by means of a sampling of the state-space or by multi-parametric programming) and further compared. In addition, it can be extended and the structure of the dual problem can be studied in detail.

Moreover, with the computational power now available, we can run exhaustive large-scale Monte-Carlo MPC simulations with various MPC formulations, under various operating conditions and with models of various complexity for simulations setup where there is a model mismatch and/or a disturbance prediction error.

Bibliography

[1] *Communication from the commission to the European Parliament, the Council, the European Economic and Social Comittee and the Comittee of the regions*. Brussels, 2010.

[2] R. K. Dixon, E. McGowan, G. Onysko, and R. M. Scheer. "US energy conservation and efficiency policies: Challenges and opportunities". In: *Energy Policy* 38.11 (2010), pp. 6398–6408. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2010.01.038.

[3] L. Pérez-Lombard, J. Ortiz, and C. Pout. "A review on buildings energy consumption information". In: *Energy and Buildings* 40.3 (2008), pp. 394–398. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2007.03.007.

[4] R. Radermacher. "Net-zero-energy technology for building retrofit". In: *HVAC & R Research* 17.1 (2011), pp. 1–1. DOI: 10.1080/10789669.2011.558460.

[5] J. Wong, H. Li, and S. Wang. "Intelligent building research: a review". In: *Automation in Construction* 14.1 (2005), pp. 143–159. ISSN: 0926-5805. DOI: 10.1016/j.autcon.2004.06.001.

[6] H. Han, Y. Jeon, S. Lim, W. Kim, and K. Chen. "New developments in illumination, heating and cooling technologies for energy-efficient buildings". In: *Energy* 35.6 (2010), pp. 2647–2653. ISSN: 0360-5442. DOI: 10.1016/j.energy.2009.05.020.

[7] D. S. Naidu and C. G. Rieger. "Advanced control strategies for HVAC & R systems–An overview: Part II: Soft and fusion control". In: *HVAC & R Research* 17.2 (2011), pp. 144–158. DOI: 10.1080/10789669.2011.555650.

[8] P. Ferreira, A. Ruano, S. Silva, and E. Conceição. "Neural networks based predictive control for thermal comfort and energy savings in public buildings". In: *Energy and Buildings* 55 (2012), pp. 238–251. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.08.002.

[9] A. Ruano, E. Crispim, E. Conceição, and M. Lúcio. "Prediction of building's temperature using neural networks models". In: *Energy and Buildings* 38.6 (2006), pp. 682–694. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2005.09.007.

[10] R. Z. Homod, K. S. M. Sahari, H. A. Almurib, and F. H. Nagi. "Gradient auto-tuned Takagi–Sugeno Fuzzy Forward control of a HVAC system using predicted mean vote index". In: *Energy and Buildings* 49 (2012), pp. 254–267. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.02.013.

[11] P. Bermejo, L. Redondo, L. de la Ossa, D. Rodríguez, J. Flores, C. Urea, J. A. Gámez, and J. M. Puerta. "Design and simulation of a thermal comfort adaptive system based on fuzzy logic and on-line learning". In: *Energy and Buildings* 49 (2012), pp. 367–379. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.02.032.

[12] R. Parameshwaran, R. Karunakaran, C. V. R. Kumar, and S. Iniyan. "Energy conservative building air conditioning system controlled and optimized using fuzzy-genetic algorithm". In: *Energy and Buildings* 42.5 (2010), pp. 745–762. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2009.11.014.

[13] R. L. Navale and R. M. Nelson. "Use of evolutionary strategies to develop an adaptive fuzzy logic controller for a cooling coil". In: *Energy and Buildings* 42.11 (2010), pp. 2213–2218. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2010.07.017.

[14] J. Maciejowski. *Predictive control with constraints*. Prentice Hall, 2001.

[15] J. Richalet, A. Rault, J. L. Testud, and J. Papon. "Algoritmic Control of Industrial Process". In: *Proceedings: Symposium on Identification and System Parameter Estimation*. IFAC. Tbilisi, 1976.

[16] J. Richalet, A. Rault, J. Testud, and J. Papon. "Model predictive heuristic control: Applications to industrial processes". In: *Automatica* 14.5 (1978), pp. 413–428. ISSN: 0005-1098. DOI: 10.1016/0005-1098(78)90001-8.

[17] W. Kwon, A. Bruckstein, and T. Kailath. "Stabilizing state-feedback design via the moving horizon method". In: *International Journal of Control* 37.3 (1983), pp. 631–643. DOI: 10.1080/00207178308932998.

[18] W. Grünenfelder and J. Tödtli. "The use of weather predictions and dynamic programming in the control of solar domestic hot water systems". In: *3rd Mediterranean Electrotechnical Conference (Melecon)*. Madrid, Spain, 1985.

[19] M. Snyder and T. Newell. "Cooling cost minimization using building mass for thermal storage". In: *ASHRAE Transactions* 96.2 (1990).

[20] G. Henze, C. Felsmann, and G. Knabe. "Evaluation of optimal control for active and passive building thermal storage". In: *International Journal of Thermal Sciences* 43 (2004), pp. 173–183. DOI: 10.1016/j.ijthermalsci.2003.06.001.

[21] J. E. Braun. "Load Control Using Building Thermal Mass". In: *Journal of Solar Energy Engineering* 125.3 (2003), p. 292. ISSN: 0199-6231. DOI: 10.1115/1.1592184.

[22] T. Chen. "Application of adaptive predictive control to a floor heating system with a large thermal lag". In: *Energy and Buildings* 34.1 (2002), pp. 45–51. ISSN: 0378-7788. DOI: 10.1016/S0378-7788(01)00076-7.

[23] S. Cho. "Predictive control of intermittently operated radiant floor heating systems". In: *Energy Conversion and Management* 44.8 (2003), pp. 1333–1342. ISSN: 0196-8904. DOI: 10.1016/S0196-8904(02)00116-4.

[24] M. Gwerder, C. Gaehler, N. Laubacher, and J. Tödtli. "Model-Based Predictive Regulation of a Building Energy System". WO2007096377 (A1). CIB: G05B13/04; F02C6/18; F02G5/00. 2007.

[25] P. Gruber and J. Tödtli. "Predictive apparatus for regulating or controlling supply values". US6439469 (B1). CIB: G05B13/04; (IPC1-7): G01M17/00; G06F19/00. 2002.

[26] M. Gwerder and J. Tödtli. "Device for Controlling the Room Temperature in a Building Using a Predictive Control Device". WO2007042371 (A1). CIB: G05D23/19. 2007.

[27] M. Gwerder, J. Tödtli, B. Lehmann, F. Renggli, and V. Dorer. “Control of thermally activated building systems”. In: *Proceedings: 9th REHVA World Congress Clima*. 2007.

[28] D. Rijksen, C. Wisse, and A. van Schijndel. “Reducing peak requirements for cooling by using thermally activated building systems”. In: *Energy and Buildings* 42.3 (2010), pp. 298–304. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2009.09.007.

[29] S. Katipamula, P. R. Armstrong, W. Wang, N. Fernandez, and H. Cho. “Efficient Low-Lift Cooling with Radiant Distribution, Thermal Storage and Variable-Speed Chiller Controls”. In: *Proceedings of 10th Rehva World Congress, Clima*. 2010.

[30] F. Oldewurtel, A. Ulbig, A. Parisio, G. Andersson, and M. Morari. “Reducing peak electricity demand in building climate control using real-time pricing and model predictive control”. In: *49th IEEE Conference on Decision and Control (CDC)*. 2010, pp. 1927–1932. DOI: 10.1109/CDC.2010.5717458.

[31] J. Ma, S. Qin, B. Li, and T. Salsbury. “Economic model predictive control for building energy systems”. In: *Innovative Smart Grid Technologies (ISGT), 2011 IEEE PES*. IEEE. 2011, pp. 1–6. ISBN: 978-1-61284-219-6. DOI: 10.1109/ISGT.2011.5759140.

[32] G. Platt, J. Ward, and J. Wall. “Optimal supervisory HVAC control: Experiences in Australia”. In: *HVAC & R Research* 17.3 (2011), pp. 297–308. DOI: 10.1080/10789669.2011.568318.

[33] Y. Zhang and V. Hanby. “Model-based control of renewable energy systems in buildings”. In: *HVAC & R Research* 12.S1 (2006), pp. 739–760. DOI: 10.1080/10789669.2006.10391196.

[34] P. D. Moroşan, R. Bourdais, D. Dumur, and J. Buisson. “Building temperature regulation using a distributed model predictive control”. In: *Energy and Buildings* 42.9 (2010), pp. 1445–1452. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2010.03.014.

[35] P. D. Moroşan, R. Bourdais, D. Dumur, and B. J. “A distributed MPC strategy based on Benders’ decomposition applied to multi-source multi-zone temperature regulation”. In: *Journal of Process Control* 21.5 (2011). Special Issue on Hierarchical and Distributed Model Predictive Control, pp. 729–737. ISSN: 0959-1524. DOI: 10.1016/j.jprocont.2010.12.002.

[36] Y. Ma, G. Anderson, and F. Borrelli. “A Distributed Predictive Control Approach to Building Temperature Regulation”. In: *American Control Conference*. IEEE. 2011, pp. 2089–2094.

[37] F. Oldewurtel, C. Jones, and M. Morari. “A tractable approximation of chance constrained stochastic MPC based on affine disturbance feedback”. In: *47th IEEE Conference on Decision and Control, CDC*. 2008, pp. 4731–4736. DOI: 10.1109/CDC.2008.4738806.

[38] M. Korda and J. Cigler. “On 1-norm stochastic optimal control with bounded control inputs”. In: *American Control Conference (ACC), 2011*. IEEE. 2011, pp. 60–65.

[39] Y. Ma, S. Vichik, and F. Borrelli. “Fast stochastic MPC with optimal risk allocation applied to building control systems”. In: *Decision and Control (CDC), 2012 IEEE 51st Annual Conference on*. 2012, pp. 7559–7564. DOI: 10.1109/CDC.2012.6426251.

[40] J. A. Orosa and A. C. Oliveira. “Software tools for HVAC research”. In: *Advances in Engineering Software* 42.10 (2011), pp. 846–851. ISSN: 0965-9978. DOI: 10.1016/j.advengsoft.2011.05.028.

[41] B. Coffey, F. Haghighat, E. Morofsky, and E. Kutrowski. “A software framework for model predictive control with GenOpt”. In: *Energy & Buildings* 42.7 (2010), pp. 1084–1092. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2010.01.022.

[42] M. Wetter. “Co-simulation of building energy and control systems with the Building Controls Virtual Test Bed”. In: *Journal of Building Performance Simulation* 4.3 (2011), pp. 185–203. DOI: 10.1080/19401493.2010.518631.

[43] S. Prívara, Z. Váňa, E. Žáčeková, and J. Cigler. “Building Modeling: Selection of the Most Appropriate Model for Predictive Control”. In: *Energy and Buildings* 55 (2012), pp. 341–350. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.08.040.

[44] S. Prívara, Z. Váňa, D. Gyalistras, J. Cigler, C. Sagerschnig, M. Morari, and L. Ferkl. “Modeling and Identification of a Large Multi-Zone Office Building”. English. In: *IEEE Multi-Conference on Systems and Control*. IEEE, 2011, pp. 55–60. ISBN: 978-1-4577-1061-2. DOI: 10.1109/CCA.2011.6044402.

[45] E. Žáčeková, S. Prívara, and Z. Váňa. “Model predictive control relevant identification using partial least squares for building modeling”. In: *Australian Control Conference (AUCC), 2011*. IEEE. 2011, pp. 422–427.

[46] J. Široký, F. Oldewurtel, J. Cigler, and S. Prívara. “Experimental analysis of model predictive control for an energy efficient building heating system”. In: *Applied Energy* 88.9 (2011), pp. 3079–3087. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2011.03.009.

[47] Y. Ma, A. Kelman, A. Daly, and F. Borrelli. “Predictive Control for Energy Efficient Buildings with Thermal Storage: Modeling, Stimulation, and Experiments”. In: *Control Systems, IEEE* 32.1 (2012), pp. 44–64. ISSN: 1066-033X. DOI: 10.1109/MCS.2011.2172532.

[48] D. Gyalistras, M. Gwerder, and (Eds.) *Use of weather and occupancy forecasts for optimal building climate control (OptiControl): Two years progress report*. Tech. rep. ETH Zurich, Switzerland and Siemens Building Technologies Division, Siemens Switzerland Ltd., Zug, Switzerland, 2009.

[49] C. Verhelst, F. Logist, J. V. Impe, and L. Helsen. “Study of the optimal control problem formulation for modulating air-to-water heat pumps connected to a residential floor heating system”. In: *Energy and Buildings* 45 (2012), pp. 43–53. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2011.10.015.

[50] D. Sturzenegger, D. Gyalistras, M. Morari, and R. S. Smith. “Semi-automated modular modeling of buildings for model predictive control”. In: *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*. BuildSys ’12. Toronto, Ontario, Canada: ACM, 2012, pp. 99–106. ISBN: 978-1-4503-1170-0. DOI: 10.1145/2422531.2422550.

[51] *ISO7730:2005, Ergonomics of the thermal environment-analytical determination and interpretation of thermal comfort using calculation of PMV and PPD indices and local thermal comfort criteria*. Internation Organization for Standardization. 2005.

[52] *ASHRAE Fundamentals, ASHRAE Handbook Series*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, USA. 2005.

[53] *Standard 55-2004, Thermal environmental conditions for human occupancy*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. 2004.

[54] R. Freire, G. Oliveira, and N. Mendes. "Predictive controllers for thermal comfort optimization and energy savings". In: *Energy and Buildings* 40.7 (2008), pp. 1353–1365. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2007.12.007.

[55] M. Castilla, J. Álvarez, M. Berenguel, F. Rodríguez, J. Guzmán, and M. Pérez. "A comparison of thermal comfort predictive control strategies". In: *Energy and Buildings* 43.10 (2011), pp. 2737–2746. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2011.06.030.

[56] J. Woods. "Cost avoidance and productivity in owning and operating buildings". In: *Occupational medicine (Philadelphia, Pa.)* 4.4 (1989), p. 753.

[57] O. Seppanen and W. Fisk. "Some quantitative relations between indoor environmental quality and work performance or health". In: *HVAC & R Research* 12.4 (2006), pp. 957–973.

[58] F. Oldewurtel, D. Sturzenegger, and M. Morari. "Importance of occupancy information for building climate control". In: *Applied Energy* 101 (2013), pp. 521–532. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2012.06.014.

[59] G. Henze, D. Kalz, S. Liu, and C. Felsmann. "Experimental analysis of model-based predictive optimal control for active and passive building thermal storage inventory". In: *HVAC & R Research* 11.2 (2005), pp. 189–213. DOI: 10.1080/10789669.2005.10391134.

[60] Y. Ma, F. Borrelli, B. Hencey, A. Packard, and S. Bortoff. "Model Predictive Control of thermal energy storage in building cooling systems". In: *48h IEEE Conference on Decision and Control, CDC* (2009), pp. 392–397. DOI: 10.1109/CDC.2009.5400677.

[61] Y. Ma, F. Borrelli, B. Hencey, B. Coffey, S. Bengea, and P. Haves. "Model Predictive Control for the Operation of Building Cooling Systems". In: *IEEE Transactions on Control Systems Technology* PP.99 (2011), pp. 1–8. ISSN: 1063-6536. DOI: 10.1109/TCST.2011.2124461.

[62] J. Figueiredo and J. S. da Costa. "A SCADA system for energy management in intelligent buildings". In: *Energy and Buildings* 49 (2012), pp. 85–98. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.01.041.

[63] W. Bernal, M. Behl, T. X. Nghiem, and R. Mangharam. "MLE+: a tool for integrated design and deployment of energy efficient building controls". In: *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*. BuildSys '12. Toronto, Ontario, Canada: ACM, 2012, pp. 123–130. ISBN: 978-1-4503-1170-0. DOI: 10.1145/2422531.2422553.

[64] S. Prívara, J. Široký, L. Ferkl, and J. Cigler. "Model predictive control of a building heating system: The first experience". In: *Energy and Buildings* 43.2-3 (2011), pp. 564–572. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2010.10.022.

[65] J. Cigler, P. Tomáško, and J. Široký. "BuildingLab: a tool to analyze performance of model predictive controllers for buildings". In: *Energy and Buildings* 57 (2013), pp. 34–41. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.10.042.

[66] J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "Optimization of Predicted Mean Vote index within Model Predictive Control framework: Computationally tractable solution". In: *Energy and Buildings* 52 (2012), pp. 39–49. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.05.022.

[67] J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "On predicted mean vote optimization in building climate control". In: *Control Automation (MED), 2012 20th Mediterranean Conference on*. 2012, pp. 1518–1523. ISBN: 978-1-4673-2530-1. DOI: 10.1109/MED.2012.6265854.

[68] J. Cigler, J. Široký, M. Korda, and C. Jones. "On the Selection of the Most Appropriate MPC Problem Formulation for Buildings". In: *Proceedings of 11th Rehva World Congress, Clima 2013*. Accepted, to appear. Prague, 2013.

[69] J. Cigler, D. Gyalistras, J. Široký, V. N. Tiet, and L. Ferkl. "Beyond Theory: the Challenge of Implementing Model Predictive Control in Buildings". In: *Proceedings of 11th Rehva World Congress, Clima 2013*. Accepted, to appear. Prague, 2013.

[70] J. Hoogmartens and L. Helsen. *GEOTABS Final report*. Tech. rep. 2013. URL: http://geotabs.eu/Publication/final/view.

Appendix A.

Contents of the Attached CD

`thesis/`
Directory containing the PDF versions of this document, doctoral thesis statement, list of author's publications and curriculum vitae.

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Directory containing all author's journal papers referenced in this thesis

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Directory containing all author's conference papers referenced in this thesis

Publications of the Author

Publications Related to the Thesis

Publications in Journals with Impact Factor

[Dis-A1] J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "Optimization of Predicted Mean Vote index within Model Predictive Control framework: Computationally tractable solution". In: *Energy and Buildings* 52 (2012). (co-authorship: 55%), pp. 39–49. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2012.05.022`.

[Dis-A2] S. Prívara, J. Široký, L. Ferkl, and J. Cigler. "Model predictive control of a building heating system: The first experience". In: *Energy and Buildings* 43.2 (2011). (co-authorship: 30%), pp. 564–572. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2010.10.022`.

[Dis-A3] J. Široký, F. Oldewurtel, J. Cigler, and S. Prívara. "Experimental analysis of model predictive control for an energy efficient building heating system". In: *Applied Energy* 88.9 (2011). (co-authorship: 25%), pp. 3079–3087. ISSN: 0306-2619. DOI: `10.1016/j.apenergy.2011.03.009`.

[Dis-A4] S. Prívara, J. Cigler, Z. Váňa, F. Oldewurtel, C. Sagerschnig, and E. Žáčeková. "Building modeling as a crucial part for building predictive control". In: *Energy and Buildings* 56 (2013). (co-authorship: 20%), pp. 8–22. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2012.10.024`.

[Dis-A5] J. Cigler, P. Tomáško, and J. Široký. "BuildingLab: a tool to analyze performance of model predictive controllers for buildings". In: *Energy and Buildings* 57 (2013). (co-authorship: 60%), pp. 34–41. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2012.10.042`.

Publications in Reviewed Journals

[Dis-B1] J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "Optimization of Predicted Mean Vote index within Model Predictive Control framework: Computationally tractable solution". In: *Energy and Buildings* 52 (2012). (co-authorship: 55%), pp. 39–49. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2012.05.022`.

[Dis-B2] S. Prívara, J. Široký, L. Ferkl, and J. Cigler. "Model predictive control of a building heating system: The first experience". In: *Energy and Buildings* 43.2 (2011). (co-authorship: 30%), pp. 564–572. ISSN: 0378-7788. DOI: `10.1016/j.enbuild.2010.10.022`.

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Patents

There are no patents related to the thesis.

Publications indexed in WoS

[Dis-D1] J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "Optimization of Predicted Mean Vote index within Model Predictive Control framework: Computationally tractable solution". In: *Energy and Buildings* 52 (2012). (co-authorship: 55%), pp. 39–49. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.05.022.

[Dis-D2] S. Prívara, J. Široký, L. Ferkl, and J. Cigler. "Model predictive control of a building heating system: The first experience". In: *Energy and Buildings* 43.2 (2011). (co-authorship: 30%), pp. 564–572. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2010.10.022.

[Dis-D3] J. Široký, F. Oldewurtel, J. Cigler, and S. Prívara. "Experimental analysis of model predictive control for an energy efficient building heating system". In: *Applied Energy* 88.9 (2011). (co-authorship: 25%), pp. 3079–3087. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2011.03.009.

[Dis-D4] J. Cigler and S. Prívara. "Subspace identification and model predictive control for buildings". In: *Control Automation Robotics & Vision (ICARCV), 2010 11th International Conference on*. (co-authorship: 60%). IEEE. Singapore, 2010, pp. 750–755. ISBN: 978-1-4244-7813-2. DOI: 10.1109/ICARCV.2010.5707821.

[Dis-D5] S. Prívara, Z. Váňa, J. Cigler, F. Oldewurtel, and J. Komárek. "Role of MPC in Building Climate Control". In: *21st European Symposium on Computer Aided Process Engineering*. Vol. 29. Computer-Aided Chemical Engineering. (co-authorship: 30%). Porto Carras, Greece: Elsevier Science BV, 2011, 728–732. ISBN: 978-0-444-53895-6. DOI: 10.1016/B978-0-444-53711-9.50146-2.

Other Publications

[Dis-E1] L. Ferkl, J. Cigler, and J. Rakušan. "Jak nastavit termostat na příjemně: Predicted Mean Vote". In: *TZB Haustechnik* 2 (2012). (co-authorship: 50%), pp. 44–46. ISSN: 1803-4802.

[Dis-E2] C. Sagerschnig, D. Gyalistras, A. Seerig, S. Prívara, J. Cigler, and Z. Váňa. "Co-Simulation for Building Controller Development: the Case Study of a Modern Office Building". English. In: *CleanTech for Sustainable Buildings – From Nano to Urban Scale*. (co-authorship: 20%). Lausanne, Switzerland: Solar Energy nad Building Physics Laboratory of the Swiss Federal Institute of Technology Lausanne, 2011, pp. 955–960. ISBN: 978-2-8399-0906-8.

[Dis-E3] J. Cigler, S. Prívara, Z. Váňa, E. Žáčeková, and L. Ferkl. "On predicted mean vote optimization in building climate control". In: *Control Automation (MED), 2012 20th Mediterranean Conference on*. (co-authorship: 60%). Barcelona, Spain, 2012, pp. 1518–1523. ISBN: 978-1-4673-2530-1. DOI: 10.1109/MED.2012.6265854.

[Dis-E4] J. Cigler, S. Prívara, Z. Váňa, D. Komárková, and M. Šebek. "Optimization of Predicted Mean Vote Thermal Comfort Index within Model Predictive Control Framework". English. In: *Proceedings of the 51st IEEE Conference on Decision and Control*. (co-authorship: 50%). Maui, Hawaii, US: IEEE, 2012, pp. 3056–3061. ISBN: 978-1-4673-2064-1. DOI: 10.1109/CDC.2012.6427051.

[Dis-E5] J. Cigler, J. Široký, M. Korda, and C. Jones. "On the Selection of the Most Appropriate MPC Problem Formulation for Buildings". In: *Proceedings of 11th Rehva World Congress, Clima 2013*. (co-authorship: 60%). Prague, Czech Republic, 2013.

[Dis-E6] J. Cigler, D. Gyalistras, J. Široký, V. N. Tiet, and L. Ferkl. "Beyond Theory: the Challenge of Implementing Model Predictive Control in Buildings". In: *Proceedings of 11th Rehva World Congress, Clima 2013*. (co-authorship: 60%). Prague, Czech Republic, Accepted, to appear, 2013.

[Dis-E7] J. Kubeček, Z. Váňa, J. Cigler, and S. Prívara. "Identification and Control of Large Multiple Input Multiple Output Systems". In: *Proceedings of 10th International Students Conference Poster*. (co-authorship: 25%). Prague, Czech Republic, 2010.

Publications Not Related to the Thesis

Publications in Journals with Impact Factor

[NonDis-A1] M. Korda and J. Cigler. "Nonquadratic stochastic model predictive control: A tractable approach". In: *Automatica* 48.9 (2012). (co-authorship: 50%), pp. 2352–2358. ISSN: 0005-1098. DOI: 10.1016/j.automatica.2012.06.053.

[NonDis-A2] S. Prívara, Z. Váňa, E. Žáčeková, and J. Cigler. "Building Modeling: Selection of the Most Appropriate Model for Predictive Control". In: *Energy and Buildings* 55 (2012). (co-authorship: 10%), pp. 341–350. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.08.040.

[NonDis-A3] S. Prívara, J. Cigler, Z. Váňa, F. Oldewurtel, and E. Žáčeková. "Use of partial least squares within the control relevant identification for buildings". In: *Control Engineering Practice* 21.1 (2013). (co-authorship: 10%), pp. 113–121. ISSN: 0967-0661. DOI: 10.1016/j.conengprac.2012.09.017.

Publications in Reviewed Journals

[NonDis-B1] M. Korda and J. Cigler. "Nonquadratic stochastic model predictive control: A tractable approach". In: *Automatica* 48.9 (2012). (co-authorship: 50%), pp. 2352–2358. ISSN: 0005-1098. DOI: 10.1016/j.automatica.2012.06.053.

[NonDis-B2] S. Prívara, J. Cigler, Z. Váňa, and L. Ferkl. "Incorporation of system steady state properties into subspace identification algorithm". In: *International Journal of Modelling, Identification and Control* 16.2 (2012). (co-authorship: 20%), pp. 159–167. DOI: 10.1504/IJMIC.2012.047123.

[NonDis-B2] S. Prívara, Z. Váňa, E. Žáčeková, and J. Cigler. "Building Modeling: Selection of the Most Appropriate Model for Predictive Control". In: *Energy and Buildings* 55 (2012). (co-authorship: 10%), pp. 341–350. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.08.040.

[NonDis-B3] S. Prívara, J. Cigler, Z. Váňa, F. Oldewurtel, and E. Žáčeková. "Use of partial least squares within the control relevant identification for buildings". In: *Control Engineering Practice* 21.1 (2013). (co-authorship: 10%), pp. 113–121. ISSN: 0967-0661. DOI: 10.1016/j.conengprac.2012.09.017.

Patents

There are no patents related to the thesis.

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[NonDis-D1] M. Korda and J. Cigler. "Nonquadratic stochastic model predictive control: A tractable approach". In: *Automatica* 48.9 (2012). (co-authorship: 50%), pp. 2352–2358. ISSN: 0005-1098. DOI: 10.1016/j.automatica.2012.06.053.

[NonDis-D2] S. Prívara, Z. Váňa, E. Žáčeková, and J. Cigler. "Building Modeling: Selection of the Most Appropriate Model for Predictive Control". In: *Energy and Buildings* 55 (2012). (co-authorship: 10%), pp. 341–350. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2012.08.040.

[NonDis-D3] S. Prívara, J. Cigler, Z. Váňa, F. Oldewurtel, and E. Žáčeková. "Use of partial least squares within the control relevant identification for buildings". In: *Control Engineering Practice* 21.1 (2013). (co-authorship: 10%), pp. 113–121. ISSN: 0967-0661. DOI: 10.1016/j.conengprac.2012.09.017.

[NonDis-D4] S. Prívara, Z. Váňa, D. Gyalistras, J. Cigler, C. Sagerschnig, M. Morari, and L. Ferkl. "Modeling and Identification of a Large Multi-Zone Office Building". English. In: *IEEE Multi-Conference on Systems and Control*. (co-authorship: 25%). Denver, US: IEEE, 2011, pp. 55–60. ISBN: 978-1-4577-1061-2. DOI: 10.1109/CCA.2011.6044402.

[NonDis-D5] S. Prívara, J. Cigler, Z. Váňa, L. Ferkl, and M. Šebek. "Subspace identification of poorly excited industrial systems". In: *Decision and Control (CDC), 2010 49th IEEE Conference on*. (co-authorship: 30%). Atlanta, US, 2010, pp. 4405–4410. DOI: 10.1109/CDC.2010.5717585.

[NonDis-D6] M. Korda, R. Gondhalekar, J. Cigler, and F. Oldewurtel. "Strongly feasible stochastic model predictive control". In: *Decision and Control and European Control Conference (CDC-ECC), 2011 50th IEEE Conference on*. (co-authorship: 15%). IEEE. Orlando, US, 2011, pp. 1245–1251. DOI: 10.1109/CDC.2011.6161250.

[NonDis-D7] M. Korda and J. Cigler. "On 1-norm stochastic optimal control with bounded control inputs". In: *American Control Conference (ACC), 2011*. (co-authorship: 40%). IEEE. San Francisco, US, 2011, pp. 60–65.

[NonDis-D8] Z. Váňa, S. Prívara, J. Cigler, and H. Preisig. "System identification using wavelet analysis". In: *21st European Symposium on Computer Aided Process Engineering*. Vol. 29. Computer Aided Chemical Engineering. (co-authorship: 20%). Porto Carras, Greece: Elsevier, 2011, pp. 763–767. DOI: 10.1016/B978-0-444-53711-9.50153-X.

Other Publications

[NonDis-E1] J. Cigler and V. Kučera. “Pole-by-pole shifting via a linear-quadratic regulation”. In: vol. 1. 9. (co-authorship: 50%). Štrbské Pleso, Slovakia, 2009.

[NonDis-E2] V. Kučera and J. Cigler. “Optimal control systems with prescribed eigenvalues”. In: *Communications, Control and Signal Processing (ISCCSP), 2010 4th International Symposium on*. (co-authorship: 50%). IEEE. Limassol, Cyprus, 2010, pp. 1–6. ISBN: 978-1-4244-6286-5.

[NonDis-E3] S. Prívara, Z. Váňa, J. Cigler, and L. Ferkl. “Predictive control oriented subspace identification based on building energy simulation tools”. In: *Control Automation (MED), 2012 20th Mediterranean Conference on*. (co-authorship: 20%). Barcelona, Spain, 2012, pp. 1290–1295. ISBN: 978-1-4673-2530-1. DOI: 10.1109/MED.2012.6265817.

[NonDis-E4] B. G. V. Lara, O. B. Padrón, J. Cigler, F. Oldewurtel, and M. Á. R. Borroto. “Model Predictive Control for a Tropical Island Hotel”. In: *Proceedings of 11th Rehva World Congress, Clima 2013*. (co-authorship: 15%). Prague, Czech Republic, Accepted, to appear, 2013.

[NonDis-E5] Z. Váňa, J. Cigler, and S. Prívara. “Modeling for Control of a Large Office Building”. In: *Proceedings of 11th International Students Conference Poster*. (co-authorship: 15%). Prague, Czech Republic, 2011.

[NonDis-E6] J. Cigler, J. Široký, M. Kulvejt, M. Chlupáč, and D. Gyalistras. “Web Services Based Data Acquisition from a Process Database”. In: *Proceedings of Technical Computing*. (co-authorship: 65%). Prague, Czech Republic, 2011.

[NonDis-E7] Z. Váňa, J. Cigler, and S. Prívara. “Wavelet filters in system identification”. In: *Proceedings of 11th International Students Conference Poster*. (co-authorship: 15%). Prague, Czech Republic, 2011.

Curriculum Vitae

Jiří Cigler was born in Pelhřimov, Czech Republic, in 1985. In 2007, he received the bachelors degree in the study branch of cybernetics and measurement at the Faculty of Electrical Engineering of the Czech Technical University in Prague. Two years later and at the same institution, he received a masters degree in the study branch of control engineering. Since 2009, he has been a Ph.D. student at the same university.

He has been involved in several research projects: before his Ph.D studies, he participated e.g. on *i)* the development of mobile robots for the international robot competition EUROBOT, *ii)* 3D reconstructions of photosynthetic activity of plants, *iii)* TORSCHE Scheduling toolbox. During his Ph.D. studies, he took part in the following projects: *i)* Research grant of the Czech Ministry of Industry "Integration of building systems, research and application of smart algorithms affecting energy consumption in buildings", *ii)* OptiPremier project, *iii)* European project GEOTABS (`http://geotabs.eu`), *iv)* Preseed project "MPC for buildings commercialization" of the University Centre for Energy Efficient Buildings of Czech Technical University in Prague.

His teaching activities at CTU cover courses on Theory of Dynamical Systems, Combinatorial Optimization and Mathematical Analysis. He has also supervised several students' projects and diploma theses.

During his Ph.D. studies, he stayed at the group of Prof. Morari at ETH Zurich for 5 month, where he participated on the OptiPremier project.

His scientific results were presented at several international conferences, mainly organized by IEEE. Among others, it was especially IEEE CDC 2010, 2011 and 2012, IEEE MSC 2011, IEEE ICARCV 2010, etc. The results were also published in multiple reviewed journal papers. Currently, he has 9 reviewed journal papers that have been cited by 41 publications indexed in the database of Web of Science.