EVALUATION REPORT

Thesis title: **Design and analysis of energy efficient indoor-climate control methods for historic buildings**

Author: **Magnus Wessberg**

My collaboration with M. Wessberg started within the EU FP7 project Climate for Culture [P1], where he took a part in the team of prof. Tor Brostrom (Uppsala University). Taking into account engineering background of M. Wessberg and complementarity of research activities of mine (control engineering) and prof. Brostrom's (building physics) teams, M. Wessberg decided to apply for PhD position at CTU in the study field Control and systems engineering, and he was accepted. Despite he has fulfilled all the study duties well and in time during his studies, it took seven years to complete and submit the thesis. Such a long duration had two main reasons. The first one was due to the external form of PhD as M. Wessberg is among key tutors at the Uppsala University, Campus Gotland with relatively large teaching load. Nevertheless, he was able to spend couple of weeks at CTU in Prague almost every semester. The second and main reason for rather long duration of his PhD was in difficulties in shaping theoretically strong topic of the thesis from the control engineering point of view. The first attempts in this direction were aimed towards involving dynamical models of mould growth in model based control of indoorclimate of historic buildings. Unfortunately, after thorough analysis and intensive evaluation of existing models, this research topic has been identified as unfeasible. It was mainly due to the fact that the existing mould growth dynamical models are valid under specific conditions only. Due to their strong time dependence and low robustness against uncertainties, these models are not suitable for being involved in model based control at the moment. These findings lead to restarting research activities in slightly different directions. Taking into account the joint activities of research groups in the Climate for culture project and based on a thorough state of the art review he has performed, the following three objectives have finally been stated for the thesis:

> **Objective 1** – Propose and validate a methodology for shaping the heating power for intermittent heating in massive historic buildings with regard to heat-up time and change rate of RH.
>
> **Objective 2** – Perform validation and analysis of adaptive ventilation method for relative humidity control in historic buildings.
>
> **Objective 3** – Propose and validate improvements of indoor climate control methods in historic interiors with the focus of mould growth prevention.

As can be seen, the third objective still focuses on indoorclimate analysis and control design to prevent mould growth. However, the static models are considered for evaluation. From the mathematical modelling and control engineering points of view, the Objective 1 is the most challenging. It is solved in Chapter 4, which is based on a published journal paper [1]. The originality of presented research is mainly in developing low complexity thermal and hygric dynamical models of indoorclimate in massive historic buildings which can fit well the root-square of time dependent responses. Next to the model structure, parameter identification procedure is proposed and validated on indoorclimate data of three historic churches in Sweden. As the main result, a control method for intermittent heating is proposed and validated by simulations with the aim to limit the change rate of relative humidity during the first stage of the heat-up event.

The solution of the Objective 2 is in Chapter 5 and partially in Chapter 6 where thorough analysis of adaptive ventilation method for relative humidity control in historic buildings is performed. It benefits from wide practical experience of M. Wessberg in implementation of control strategies in historic buildings and his ability of thorough indoorclimate data processing taking into account various factors which can be risky for the indoorclimate in historic buildings. The case study based analysis is concluded by identifying positive and negative aspects of adaptive ventilation. Then, overall recommendation on adaptive ventilation implementation and its enhancement are proposed. The performed analysis confirmed that adaptive ventilation is a viable method, especially if the proposed adjustments are taken into account.

The final Objective 3 is fully solved in Chapter 6. First, a method to control mould growth based on isopleth model is proposed. The quantified mould growth characteristics are used to generate the set-point of relative humidity based on measured temperature. The method is then validated by simulations on Hangwar church hygrothermal model. Subsequently, the method is implemented within a real-time control system and successfully tested in Fide church. Next to minimization of the mould growth risk, significant energy savings can be achieved compared to traditional relative humidity control to a constant set-point. Finally, a comprehensive analysis of three indoorclimate control methods (adaptive ventilation, conservation heating, and direct dehumidification by sorption dehumidifier) is performed in Skokloster Castle. The direct dehumidification by sorption dehumidifier is identified as the best one concerning the indoor climate quality and energy consumption for the given historic interior type.

Research results presented in the thesis are of multidisciplinary character combining know-how, methods and approaches of mathematical modelling, control engineering, building physics and object conservation. M. Wessberg has shown a unique ability to tackle the problem of indoorclimate control in historic buildings in full complexity. In his research, particularly, he paid attention to analysis and redesign of non-invasive and energy efficient indoorclimate control methods being aware of budget and other limitations in the cultural heritage sector. Next to simulation based analysis and data processing and interpretation, he has designed and implemented real-time control systems in a number of case studies and performed wide measurement campaigns to support his theoretical findings. His results were published in two journal papers [1, 2] (indexed in WOS) and nine conference papers. As a PhD student of CTU, he was actively involved in the SGS project [P2].

Taking into account research independence, skills and results achieved and published by M. Wessberg, I **recommend the PhD thesis for defence**.

In Prague, June 25th 2019

prof. Ing. Tomáš Vyhlídal, Ph.D.

Thesis supervisor

Department of Instrumentation and Control Engineering,
Faculty of Mechanical Engineering,
Czech Technical University in Prague

Selected projects

[P1] Climate for Culture - Damage risk assessment, economic impact and mitigation strategies for sustainable preservation of cultural heritage in the times of climate change – 7FP EU project no. 226973

[P2] Algorithms and instrumentation for complex system of distributed nature, Grant agency of CTU in Prague No. SGS17/176/OHK2/3T/12

Journal publications

[1] Wessberg, M., Vyhlídal, T., & Broström, T. (2019). A model-based method to control temperature and humidity in intermittently heated massive historic buildings. Building and Environment, 159, 106026.

[2] Napp M, Wessberg M, Kalamees T, Broström T. Adaptive ventilation for climate control in a medieval church in cold climate. Int J Vent 2016;15:1–14. doi:10.1080/14733315.2016.1173289.