CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY
OF MECHANICAL
ENGINEERING

SUMMARY OF DISSERTATION

CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF MECHANICAL ENGINEERING
DEPARTMENT OF INSTRUMENTATION AND CONTROL ENGINEERING

Summary of Dissertation Thesis

Design and analysis of energy efficient indoor-climate control methods for historic buildings

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Doctoral Study Programme: Mechanical Engineering

Study Field: Control and Systems Engineering

Supervisor: *Tomáš Vyhlídal*

Dissertation thesis statement for obtaining the academic title of "Doctor" abbreviated to "Ph.D."

Prague *May, 2019*

Title in Czech language: *Návrh a analýza energeticky šetrných metod řízení vnitřního prostředí historických budov*

This doctoral thesis is an outcome of a part-time doctoral study programme at the Department of Instrumentation and Control Engineering, Faculty of Mechanical Engineering, Czech Technical University in Prague.

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Název práce: ***Návrh a analýza energeticky šetrných metod řízení vnitřního prostředí historických budov***

Anotace: Energeticky efektivní a šetrné řízení vnitřního prostředí v historických budovách je problémem s netriviálním řešením. Je nutné jednak zajistit akceptovatelný komfort pro návštěvníky a zejména pak vhodnost prostředí z pohledu ochrany interiéru budovy a objektů památkové péče. Následným problémem je technická implementace systému úpravy vnitřního prostředí s ohledem na neinvazivnost a energetickou úspornost. Tato práce je zaměřena na analýzu a návrh vybraných metod řízení prostředí v historických budovách z pohledu stanovené metodiky a její technické implementace. První analyzovanou metodou je krátkodobé vytápění historických budov s masivní konstrukcí. Nejprve je navržen aproximativní hygro-termální model dané třídy budov včetně parametrizace modelu na základě neměřených průběhů teploty a relativní vlhkosti. Hlavním výsledkem je návrh algoritmu pro postupné zvyšování tepelného výkonu tak, aby byl eliminován nebezpečně rychlý pokles relativní vlhkosti. Daná metodika je validována na měřených datech a simulačních modelech tří historických kostelů. U nevytápěných historických objektů lze často pozorovat zvýšené hodnoty relativní vlhkosti, které mohou vést k nežádoucímu růstu plísní. Jednou z energeticky šetrných metod, kterou lze dané riziko snížit je adaptivní ventilace. Z analýzy této metody provedené v práci vyplývá její efektivnost ve významném snížení rizika vzniku plísní. Při dlouhodobém provozu je ale možné indikovat časové intervaly, kdy vlivem nevhodných podmínek venkovního prostředí není metoda zcela efektivní. Z analýzy naměřených dat též vyplývá zvýšení rizika poškození objektů hygroskopické povahy následkem zvýšení variability relativní vlhkosti. Následně je v práci provedeno vyhodnocení tříletého experimentu na barokním zámku Skokloster ve Švédsku, s cílem porovnat tři různé metody úpravy vnitřního prostředí: sorpční odvlhčování, vlhkostně řízené vytápění, a adaptivní ventilaci. Z výsledků analýzy vyplývá, že pro daný typ interiérů s absencí vnitřních zdrojů vlhkosti, je nejvhodnější aplikovat odvlhčování pomocí sorpčních odvlhčovačů. Analýza též poukazuje na důležitost zajištění vzduchotěsnosti jako primárního opatření pro zachování bezpečného prostředí dané třídy historických interiérů.

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

Abstract: Indoor climate in historic buildings pose both practical and scientific challenges. Firstly, establishing a proper indoor climate with respect to both comfort and conservation. Secondly, achieving the desired indoor climate in a non-invasive, sustainable, and energy efficient way. This thesis aims to explore the link between technical equipment and target ranges for indoor climate, i.e. control strategies and algorithms based on the hypothesis that smarter and more effective control of the indoor climate, based on an understanding of the specific characteristics of the building in question can be a cost effective way to achieve a sustainable indoor climate. The first addressed method is intermittent heating of massive historic buildings. To control the change rate of relative humidity at a heat-up event, a simplified model for heat and moisture transfer together with a method to derive the hygrothermal parameters and the time constant of the building from measurements is presented and validated. The study considers a feedforward control algorithm that uses the model to predict and control the change rate of relative humidity during the heat-up event. The method has been validated on measurements and models of three historic churches. Unheated historic buildings often face problem with mould growth. Adaptive ventilation is a candidate for being an energy efficient method to decrease mould growth risk. The research questions are if the measure is sufficient to limit the risk, how it influences the stability in relative humidity, and if it is an energy efficient measure. The present research shows that adaptive ventilation significantly lowers the risk for mould growth on an annual basis, but there is still an increased mould growth risk during short periods when it´s not a sufficient measure. It also was shown that adaptive ventilation increases the risk of mechanical damage on objects due to increased fluctuations of relative humidity. Finally, in a three year study of Skokloster Castle, three climate control measures are compared: dehumidification, conservation heating, and adaptive ventilation. This comparison includes efficiency to prevent risk for mould growth, indoor climate stability, and energy efficiency. The investigation shows that dehumidification had the best result regarding all three criteria. However, the draught proofing of the rooms prior to the study improved the indoor climate significantly.

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1. Introduction

Indoor climate in historic buildings such as museums, castles and churches pose both a practical and a scientific challenge. There are two fundamental challenges that must be addressed

1 What is the proper indoor climate with respect to human comfort and with respect to conservation of the building itself and its interiors: artworks, furniture etc.?
2 How do we achieve the desired indoor climate in a sustainable way?

This thesis aims to explore the link between technical equipment and target ranges for indoor climate, i.e. control strategies and algorithms based on the hypothesis that smarter and more effective control of the indoor climate, based on an understanding of the specific characteristics of the building in question can be a cost effective way to achieve a sustainable indoor climate [12].

2. State of the art

In a conservation perspective, the indoor climate in a historic building is mainly determined by the air temperature and humidity. Common climate related problems in occasionally used historic buildings are high values of relative humidity causing biodegradation, such as mould growth. [13,14].

Large variations in temperature and relative humidity (RH), often related to heating, can cause mechanical damage to the building and objects [15,16,17,18,19].

2.1. Climate control for comfort

Intermittent heating is used to provide comfort in buildings that are occasionally used. The principle of intermittent heating is to heat quickly before use and in between periods of use, the building is kept cold or with background heating. Intermittent heating requires larger installed heating power as compared with installations for continuous heating [20]. Rapid intermittent heating is energy efficient but the fast changes in temperature and relative humidity may be harmful to objects and materials. Theoretical models for intermittent heating in massive monumental buildings have been developed since the end of the 19th century. The main outcome of the models is that when supplied with constant heat flux the increase in temperature during a heat-up event is proportional to the square root of time [21,22,23].

2.2. Climate control for conservation

This section describes low energy and low invasive climate control methods for occasionally used historic buildings in order to reduce humidity mostly to prevent mould growth.

2.2.1. Conservation heating

Conservation heating, also referred to as humidistatic heating, is a technique for climate control where heaters are controlled by humidistats rather than by thermostats. The temperature varies to adjust the relative humidity to the set value. Conservation heating is simple and cheap to implement if there is already a heating system installed in the building. A potential problem is that indoor air mixing ratio (MR) will increase due to evaporation from floors or walls which counteract the effect of reducing RH [24,25].

2.2.2. Adaptive ventilation

Adaptive ventilation (AV) systems has sensors for relative humidity and temperature both indoors and outdoors allowing the system to calculate the absolute humidity and compare the humidity levels and decide when to ventilate. The system ventilates only when the humidity is lower outside compared with indoors. AV is potentially a simple and low cost option but a number of case studies have shown different and sometimes contradictory results indicating a need for further investigation [26,27,28].

2.2.3. Dehumidification

Dehumidification works by reducing the absolute humidity in the air. In practise there are two techniques used to dehumidify air in historic buildings, sorption dehumidifying and condensing dehumidifying. Dehumidification is a well-established and reliable method to reduce relative humidity. To minimise energy use and ensure the right capacity, research is needed to assess the long-term performance of dehumidification systems installed to minimise the risk for mould growth under realistic conditions in massive historic buildings [24, 29].

3. Problem statement

Climate control of historic buildings is a complex task where the climate must meet a number of requirements, some of them contradictory. If humidity is too high, risk for mould growth increases; if humidity is too low, risk for mechanical damage increases. Similarly, if temperature is too high, energy consumption increases and if temperature and relative humidity fluctuations are too large, risk for mechanical damage increases.

Intermittent heating systems in historic buildings are often controlled manually. During a heat-up event, the system is turned on some arbitrary time before use and, as a rule, the maximum heating power is used to minimise the heat-up time and thereby energy use. Poor timing will lead to either insufficient heating or excessively high temperatures and energy use. By controlling the starting time as well as the heating power of a heat-up event, the temperature change rate can be controlled and thereby also the RH change rate.

When a building is not being used, energy efficient control of RH, mainly to prevent mould growth, is needed. Adaptive ventilation has been shown to be a cost effective option, but there are still questions about the method and whether it really is an effective measure to prevent mould growth. Thus, adaptive ventilation needs to be further validated, analysed and compared to other low energy and low invasive climate control measures.

Conservation heating, dehumidification and adaptive ventilation can be used to reduce RH in order to reduce mould growth. As energy costs may be excessive there is a need to compare these three methods in terms of energy efficiency and mould prevention effectiveness.

4. Thesis objectives

Based on the identified research gaps in the non-invasive control methods of indoor climate in historic buildings, the objectives of the thesis are defined as follows:

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.

The objective is to propose and validate a low-cost and energy efficient methodology for the heat-up procedure of intermittently heated massive historic buildings (typically churches) with regard to the safe indoor climate for deposited valuable historic objects. In the first stage, an approximate hygrothermal model of air temperature and relative humidity during a heat up procedure in such building is to be developed, together with a method for identifying the model parameters based on measured data. The subsequent and main task is to design a model-based control strategy for shaping the heating power so that the requirements on the indoor climate safety and low energy consumption are reached. In addition to achieving the desired indoor temperature in the predefined time, another objective is to avoid fast changes of relative humidity in the beginning of the heating procedure - as the fast changes of relative humidity were identified in literature as risky for the upper layers of historic objects of hygroscopic nature (wood, canvas, paper, etc.).

Objective 2 – Perform validation and analysis of adaptive ventilation method for relative humidity control in historic buildings

This objective is to perform case study based analysis of indoor climate control of historic buildings by adaptive ventilation. The particular task is to contribute to knowledge on whether the adaptive ventilation is an efficient alternative to other climate control measures for lowering relative humidity, in order to prevent mould growth in particular. Therefore, adaptive ventilation systems are to be designed, tested and be validate in real case studies in situ to find the practical and theoretical obstacles. Control methods are to be evaluated based on the analysis of measured data.

Objective 3 – Propose and validate improvements of indoor climate control methods in historic interiors with the focus at the mould growth prevention

The objective is to propose improvements of interior relative humidity control in historic buildings, taking into account recently quantified mould growth characteristics. The subsequent task is to evaluate three selected climate control measures in terms of energy efficiency, mould prevention effectivity and stability in relative humidity. This is to be done in a selected case study historic building.

5. Results

Objective 1, addressed in Section 5.1, analyses a hygrothermal model based on the heat conduction equation. The model is validated against measured data from three churches. A method for how to derive parameters to the model from a step response test is studied and further developed. Objective 2, addressed in Section 5.2, analyses a system for adaptive ventilation using two case studies. Objective 3, addressed in Section 5.3, analyses a three-year comparative study on climate control to prevent mould growth in Skokloster Castle. In the study, adaptive ventilation is compared with conservation heating and dehumidification.

5.1. Intermittent heating of massive historic buildings

Current systems for intermittent heating are often manually controlled with no control of the heat-up procedure. The lack of control is evident as the buildings do not reach a comfortable temperature during winter or are heated unnecessarily long time before use, ultimately wasting energy. The fast increase of temperature during a heating event induces a fast decrease in relative humidity that can be harmful for the building and its interior. This section will solve the problem stated in Objective 1 by developing a hygrothermal model for intermittent heating and designing a control method for limiting large fluctuations in RH at the beginning of the heating event. This section is an extension of a published paper [1] and [2] (the author of this thesis is the lead author of both papers).

5.1.1. Simplified model for intermittent heating of massive buildings

In Figure 1, the main heat fluxes at a heat-up event are shown schematically. The supplied heat from the heaters, P_s (W), is mainly divided in two main fluxes. The large part, $P_W(W)$, heats the walls and interiors via the air. The smaller part, $P_L(W)$, represents losses due to infiltration and conductive losses. Irradiation, $P_{IR}(W)$, also contributes to the temperature in the building. The increase in air temperature at the heat up event, $\Delta\vartheta_a$ $(°C)$, can be expressed by

$$T_1 \frac{d\Delta\vartheta_a(t)}{dt} + \Delta\vartheta_a(t) = a_1 P_s \sqrt{t} + b_1 P_s, \tag{1}$$

where T_1 is the time constant, $a_1 P_s \sqrt{t}$ represent the wall surface temperature and $b_1 P_s$ is the static gain. The constant a_1 includes material parameters, effective wall surface area and the heat losses. The constant b_1 includes heat losses, effective wall area and heat transfer coefficient between air and wall surface.

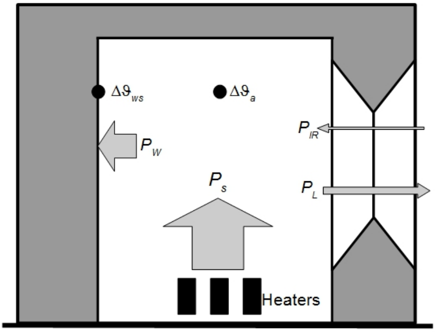

Figure 1. Major heat flux and temperatures during intermittent heating according to the simplified model, where ϑ_{ws} is the surface temperature (°C), ϑ_a is the air temperature (°C), P_s is the supplied heat (W), P_{IR} is the irradiation (W), P_L is the losses (W), and P_W is the heat transferred to the walls (W)

Equation (1) has the following solution for a step input in P_s.

$$\Delta\vartheta_a = P_s\left(a_1\left(\sqrt{t} - \sqrt{T_1}\cdot\frac{\sqrt{\pi}}{2}\operatorname{erfi}\left(\sqrt{t/T_1}\right)e^{-t/T_1}\right) + b_1\left(1 - e^{-t/T_1}\right)\right)$$
$$= P_s K_\vartheta(t). \tag{2}$$

As it is difficult to determine the thermal parameters of a historic masonry wall the parameters can be estimated from measurements of the temperature during a step response test (i.e., a heat-up event) [22]. The task is to determine parameters T_1, a_1 and b_1 to define the dynamic equation (1) and its solution (2). According to equation (2), after the first stage, where the effect of the time constant dominates, the increase in air temperature is very close to a linear function of the square root of time ($\sqrt{t}$).

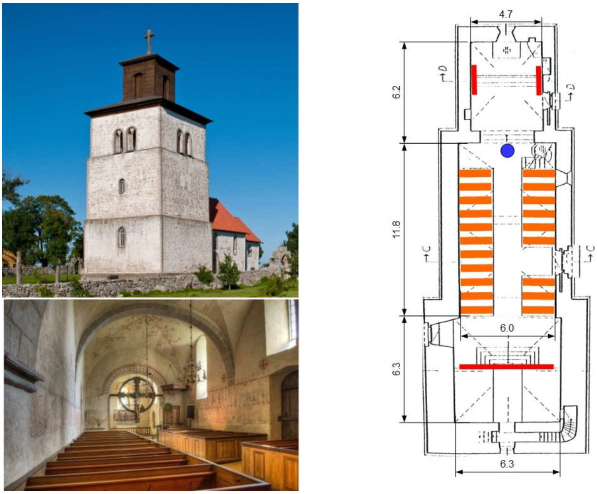

Figure 2. Fide Church. The blue spot indicates the location of temperature and RH sensors, the orange area shows the location of the pew heaters, the red shows the location of the radiators. (Photo A. Söderlund).

Parameters a_1 and b_1 can be determined by linear regression of air temperature measurements at the step response test. The regression must be conducted on the latter part of the data, where the influence of time constant accumulation has none or very little impact. From the equation of the regressed line, parameters a_1 and b_1 can be derived. The time constant T_1, for the indoor air and interiors can then be found by signal integration of equation (1) [31]. The model identification procedure described above was tested on data collected from three 13th century churches. Figure 2, shows a photograph of Fide church and its floor plan with dimensions and heater types and positions. The church is equipped with pew heaters (orange) and radiators (red). The total heating power of the heating system is 32 kW. In Fide Church, the walls and floor are made of sandstone and rendered with lime mortar both inside and outside. The roof is constructed with two cross vaults without a central pillar. The total indoor volume is approximately 1000 m^3. Temperature and RH were measured hourly by data loggers located approximately 2.5 m above the floor in the middle of the church (see the blue circle in Figure 2). Testo 175 H1 data loggers were used. Step response tests were carried out during winter from March 8, 9:00 to March 9, 14:00.

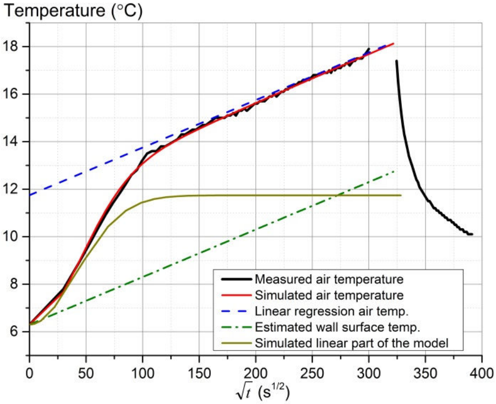

Figure 3. Heat-up event in Fide Church – measured versus simulated responses by the model (2) with identified parameters from measured data

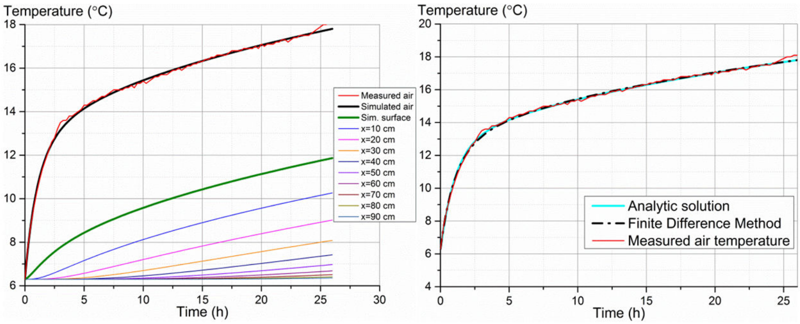

Figure 4. Fide Church: Left – measured versus simulated data by higher order numerical model. Right – Measured data compared with both simulated by model (2) and numerical model.

Model parameters from Fide Church: $a_1 = 5{,}7 \cdot 10^{-4}\ (°C/kW/s^{1/2})$, $b_1 = 1{,}7 \cdot 10^{-1}\ (°C/kW)$, $T_1 = 3400\ (s)$.

Although there are only three parameters in the simplified model parametrised at the single step response test, very good conformity between models and measurements has been achieved as can be seen in Figure 3. The conformity is also confirmed in Figure 4, where results of the approximative low order model (1) fit very well results obtained by higher order numerical model arising from solving the heat equation PDE by finite difference method.

Parameter a_1 can change during the year depending on the wall moisture content. Static gain b_1, includes the heat transfer coefficient and is therefore temperature dependent. However, step response tests, which were conducted under different seasons in different churches, showed that the variations in these parameters are relatively small and not much influenced by seasonal changes [22]. If the seasonal differences in responses are substantial, design models can be identified and used for the design for each season.

The air temperature at the end of the heat-up process as a function of elapsed time is relevant for practical calculations. The time constant has a significant impact only at the first part of the heat-up process, but at the final temperature its impact is only a few tenths of a centigrade. If the heat-up time is larger than five time constants ($5T_1$) and constants a_1 and b_1 are known from the step response test, the final temperature can be approximated with the following simplified equation:

$$t_f = \left(\frac{\vartheta_{af} - \vartheta_{a0} - P_s b_1}{P_s \cdot a_1}\right)^2, \tag{3}$$

where ϑ_{af} is the target temperature at the end of the heat-up time, t_f.

5.1.2. Simplified hygric model for intermittent heating of massive buildings

Similar to the thermal balance model, in this section an approximate hygric model for air humidity an in a massive building in response to the heat input step is developed. The coupled thermal and hygric models will then be useful for planning a safe heat-up procedure. During a heat-up event, with the increase in temperature, the indoor air mixing ratio (MR) increases as moisture evaporates from the indoor walls and interiors. Due to capillary action, RH at the wall surface can be considered 100%. Therefore, MR at the wall surface can be assumed to be dependent only on the wall surface temperature [22]. As the wall surface temperature at the intermittent heat-up event is a function of square root of time (equation (1)), a similar equation for humidity is applied.

$$T_2 \frac{d\Delta x_a(t)}{dt} + \Delta x_a(t) = P_s\left(a_2\sqrt{t} + b_2\right), \tag{4}$$

which has the same type of solution for a heating-power step as for temperature:

$$\Delta x_a = P_s\left(a_2\left(\sqrt{t} - \sqrt{T_2}\cdot\frac{\sqrt{\pi}}{2}\operatorname{erfi}\left(\sqrt{{}^{t}/_{T_2}}\right)e^{-{}^{t}/_{T_2}}\right) + b_2\left(1 - e^{-{}^{t}/_{T_2}}\right)\right)$$
$$= P_s K_x(t) \tag{5}$$

To determine the parameters a_2, b_2, and T_2, the same approach as used for air temperature can be applied, using measured data from a step response test.

Model parameters from Fide Church:$a_2 = 230 \cdot 10^{-6}\ (g/kg/kW/s^{1/2})$, $b_2 = 36 \cdot 10^{-3}\ (g/kg/kW)$, $T_2 = 3600\ (s)$.

The identification procedure has been tested on the data measured in the three churches of which one is given in Figure 2. MR is calculated from measured data of relative humidity and temperature using standard psychrometric formulae [17]. The calculated MR, its slope, and its intercept are shown in Figure 5. As seen from the simulation results, model (5) fits the data very well for the church.

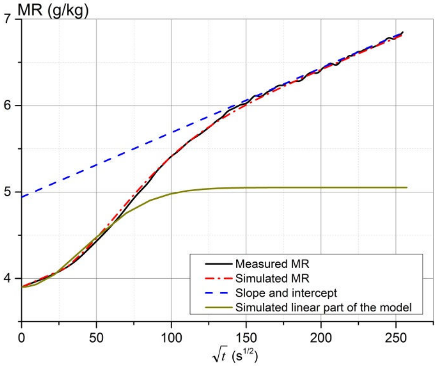

Figure 5. Air mixing ratio at a heat-up event in Fide Church – measured versus simulated responses by the model (4) with identified parameters from measured data

5.1.3. Control of the heat up procedure

The primary objective of deriving the approximate hygrothermal models above is to involve them in the optimisation of the heat-up procedure in intermittently-heated massive buildings. The control strategy should have the following requirements:

- **RH change**: To minimize the risk associated with fast variation of RH, the heating power should be adjusted so that the magnitude of RH change rate associated with temperature increase does not exceed a specified value.
- **Energy consumption**: The longer the heating lasts, the larger the heat losses due to heat accumulation in the wall, conduction and infiltration. Thus, to keep the energy consumption low, the heater should be turned on just in time before using the building and with as much power as possible considering safety constraints on the RH change rate requirement.
- **Comfort temperature:** The predefined comfort temperature needs to be achieved at a specific time.

With respect to preservation, the RH change rate at the beginning of the heating period should be kept in a limited range. In this case, an hourly RH change rate limit $\Delta\varphi_{a,s} = 2\%$ / hour was used. However, other values for both the change rate limit and period can be defined. In the following, the step-wise adjustment of the heating power in the time intervals Δt is determined to satisfy the given maximum RH change per Δt. A step-wise adjustment of heating power in time intervals $i\Delta t, i = 0, 1, 2, \ldots$ is determined by satisfying the given maximum change of RH per Δt. The overall response is then derived as a superposition of the partial responses to the heating-power steps $\Delta P_{s,i}$, taken at $t = i\Delta t, i = 0,1,2,$. The magnitude of the heating power step can be determined by following algorithm:

Algorithm 5.1: Determining the power increment $\Delta P_{s,i}$ at $i - th$ step

1. Values $x_a(t)$ and $\vartheta_a(t)$ at $t = i\Delta t$ are determined as

   $$\vartheta_{a,i} = \vartheta_{a,0} + \sum_{k=0}^{i-1} K_\vartheta\big((i-k)\Delta t\big)\Delta P_{s,k} \text{ and} \tag{6}$$

   $$x_{a,i} = x_{a,0} + \sum_{k=0}^{i-1} K_x\big((i-k)\Delta t\big)\Delta P_{s,k}, \tag{7}$$

   where $\vartheta_{a,i}$ is the temperature and $x_{a,i}$ is the MR.

   The corresponding RH value is given by $\varphi_{a,i}(t) = f_\varphi\big(x_{a,i}, \vartheta_{a,i}\big)$ determined e.g. by Magnus formula [17].

2. The auxiliary values $\bar{x}_a(t)$ and $\bar{\vartheta}_a(t)$ are determined at $t = (i+1)\Delta t$:

$$\bar{\vartheta}_{a,i+1} = \vartheta_{a,0} + \sum_{k=0}^{i-1} K_\vartheta((i-k+1)\Delta t)\Delta P_{s,k} \text{ and} \tag{8}$$

$$\bar{x}_{a,i+1} = x_{a,0} + \sum_{k=0}^{i-1} K_x((i-k+1)\Delta t)\Delta P_{s,k}, \tag{9}$$

leading to the RH value $\bar{\varphi}_{a,i+1}(t) = f_\varphi(\bar{x}_{a,i+1}, \bar{\vartheta}_{a,i+1})$

3. The reduced RH decrement is given as

$$\Delta\varphi_{a,r_i} = \Delta\varphi_{a,s} + (\varphi_{a,i} - \bar{\varphi}_{a,i+1}). \tag{10}$$

4. The heating-power step at $t = i\Delta t$ is finally estimated as

$$\Delta P_{s,i} = \frac{1}{C_x(\vartheta_{a,i}, x_{a,i})K_x(\Delta t) + C_\vartheta(\vartheta_{a,i}, x_{a,i})K_\vartheta(\Delta t)}\Delta\varphi_{a,r_i}, \tag{11}$$

where $C_x(\vartheta_{a,i}, x_{a,i}) = \left.\frac{\partial f_\varphi(x_a,\vartheta_a)}{\partial x_a}\right|_0$ and $C_\vartheta(\vartheta_{a,i}, x_{a,i}) = \left.\frac{\partial f_\varphi(x_a,\vartheta_a)}{\partial \vartheta_a}\right|_0$

5. If the following inequality is satisfied,

$$\sum_{k=0}^{i} \Delta P_{s,k} \geq P_{s,m}\ , \tag{12}$$

then $\Delta P_{s,i}$ is reduced to $\Delta P_{s,i} = P_{s,m} - \sum_{k=0}^{i-1} \Delta P_{s,k}$ and the procedure stops; if not, then $i = i + 1$ and the procedure is repeated from step 1.

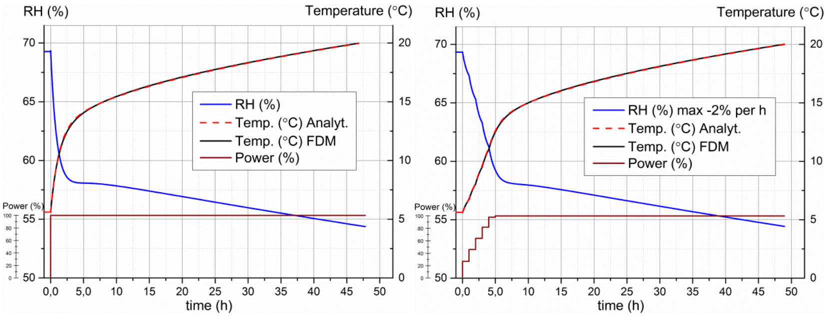

Figure 6. Fide Church: Simulation of heating event. Left – a single heating power step; Right – a stepped heating power distribution determined by the proposed control method with $i = 0,..,5$. (Temperature simulation performed with both FDM and analytical method).

For validation, the above algorithm was tested on the higher order numerical model. The stepped power signal generated by applying the above-derived control design procedure is considered as the input of model (1) coupled with FDM wall model. Figure 6 - Right shows the simulation results validating the control procedure for adjustment of the heating power by Algorithm 5.1 in the church. As can be seen, a considerable reduction of the RH change rate was achieved compared to the single step of the heating power, shown in Figure 6 – Left.

To sum up, a method of shaping the heating power and determine heat-up time of an intermittent heating event in massive historic buildings is proposed. The primary objective is to keep the RH change rate within a safe range, as a fast change rate of RH can damage cultural heritage objects. The method is based on simplified thermal and hygric analytical models, both derived from accumulation-type first-order nonlinear differential equations. Both models use an easy-to-apply parameter identification procedures based on in-situ measurements. The control method is applied and successfully validated on the models of three historic churches. The RH (hourly) change rate can be well controlled by the proposed sub-step procedure. As shown from the comparison with the single-heating power step response, the increase of heating time for the start-up step-wise power increase is relatively small. In addition, the heating power can be controlled manually at given times (e.g., every hour) based on tabularised values. Alternatively, the whole algorithm can be automated and implemented using a smart switch or a low-cost controller (e.g., Raspberry-Pi).

5.2. Validation and analysis of adaptive ventilation method

The primary objective of this chapter is to determine whether adaptive ventilation (AV) is an efficient alternative to other climate control measures for lowering RH to prevent mould growth. For this analysis, an AV system is designed and tested on real case studies in situ to find the practical and theoretical obstacles of the approach. The control methods are evaluated and refined. This section is an extension of previous studies ([3], [4], [5], and [6]) where the author of this thesis is either main author or a key co-author.

An AV systems attempts to lower the MR in the inside air by taking advantage of the natural diurnal and seasonal variations in the outside humidity. That is, the outside air is brought into a building only when MR is lower than indoor air [4]. The best drying effect is achieved if the building is air tight as the building should also be closed when it is more humid outdoors than indoors. In a leaky building, the intended effect will be counteracted if humid air enters the house by natural air infiltration [3].

As can be seen in Figure 7, a fan is controlled by a relay (on/off control) based on the value of the control error:

$$e = F_a - F_{out} - d, \tag{13}$$

where F_a and F_{out} are any of the quantities absolute humidity (AH), MR (x), or water vapour partial pressure (p_w) calculated using temperature and relative humidity, d is a bias for safety margin.

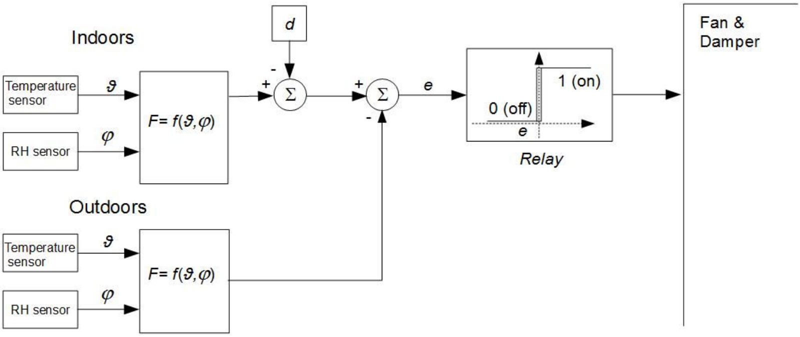

Figure 7. Adaptive ventilation system

To better understand how AV works in a real setting and how it should be designed within a control system an AV controller was developed in LabVIEW on a PC with an NI Compact DAQ I/O chassis.

AV was tested in two case studies. The first case study was carried out in the first floor of an 18th century stone building. The study showed that AV has a significant effect. During one year some 1600 kg of water were removed from the building. However, in a typical diurnal cycle the temperature will be lower outside when AH is higher inside and the fan is running which means that the ventilation has a cooling effect that would tend to increase RH even though moisture is removed simultaneously. Further investigations will aim to investigate if and how control can be improved with respect to this effect.

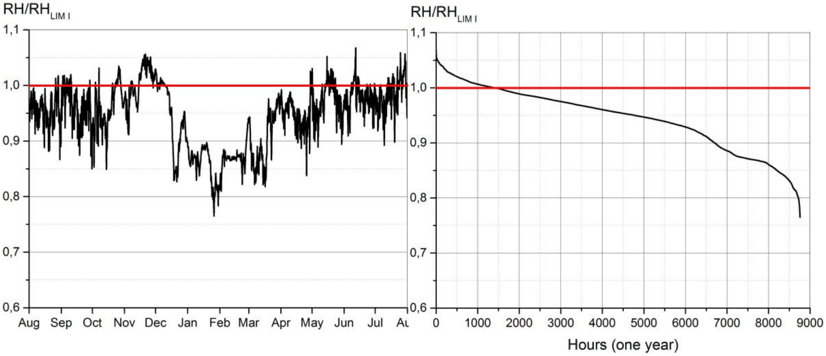

Figure 8. Left – mould risk during the test period. Right – mould risk represented as a duration graph.

Mould risk assessment is based on a mould risk potential defined as RH divided by the critical RH – i.e., the critical combination of temperature and RH for mould to start growing. The critical limit is expressed as an isopleth called LIM I [14]. Theoretically, mould growth is possible when $RH/RH_{LIM\ I} > 1$, but the mould risk potential must be larger than one for some consecutive time (days) before mould starts to grow. However, the number of hours when $RH/RH_{LIM\ I} > 1$ can be used to assess risk for mould growth and mould control measures. The mould risk potential for the case study is shown in Figure 8 - Left. The mould growth potential stays below one for most of the year except for short periods. To keep $RH/RH_{LIM\ I}$ below 1, auxiliary climate control would thus be needed for around 1400 hours (Figure 8 - Right).

However, as single periods shorter than 24 hours with mould potential larger than one are still considered safe, a deeper analysis shows that only on nine occasions did the risky events ($RH/RH_{LIM\ I} > 1$) last longer than 24 hours. If an auxiliary climate control would have been run only during those nine occasions, the number of hours would be reduced to 907. The longest period of dangerous mould risk potential was 328 hours, which is too long to be acceptable.

The second case study was carried out in a Swedish 13th century stone church. From the previous case study in the farmhouse, it was shown that the ventilation often has a cooling effect, which would tend to increase RH, even though moisture is simultaneously being removed from the building. The obvious mitigation measure is to heat the inlet air to decrease RH, thereby decreasing the mould risk. The new concept applied in this case study was to heat the inlet air with energy produced by solar panels (Figure 9 - Left)

The heaters were controlled by a control system developed in the LabVIEW environment on a PC with an NI Compact DAQ I/O chassis. The LabVIEW system was designed to keep records of energy produced by the voltaic panels and the energy consumed by the heaters. Therefore, the amount of stored energy produced by the photovoltaic panels could be compared with the amount of energy consumed by the heaters.

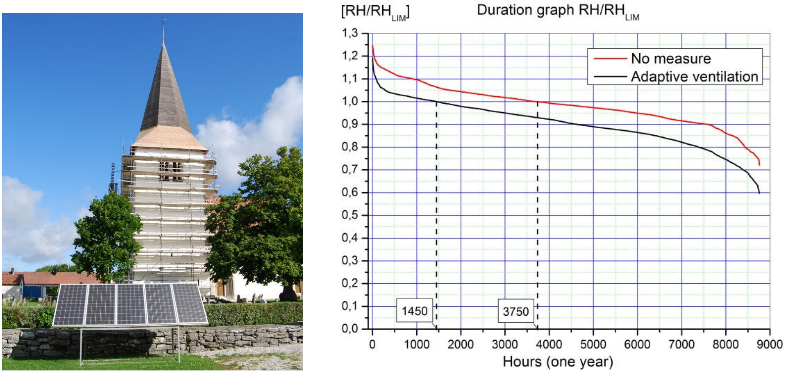

Figure 9. Left – Hangvar Church and the photovoltaic elements panels outside the church fence. Right – Duration graph of RH/RH_{LIM}.

In the first year, without climate control, the average duration above LIM was 72 hours and the longest period was 826 hours. In the year with AV, the average was 32 hours and longest period was 134 hours. In the latter case, the extended periods were in the summer. Consequently, the overall duration graph in Figure 9 - Right shows that even small changes in RH levels have a significant impact on climate control requirements. The time of mould risk was 1450 hours in combination with AV, but 3750 hours the year without climate control. Therefore, the numbers of hours with mould risk were reduced by 2300 hours.

In the two case studies, AV has had a significant drying effect, removing about 1600 kg of water from the farmhouse and 1100 kg of water from the Church in one year. The mould risk was kept at an acceptable level except for a few periods. Concerning the RH fluctuations, AV considerably increased a number of events when the short term fluctuations were outside of the limits proposed in the standard EN 15757 [30]. This can be dealt with by adjusting the control algorithms. A control method based on the standard EN 15757 is presented in [9].

In the above case studies, AV is not sufficient to eliminate mould risk throughout the whole year; however, it does significantly reduce the operational time and energy demand for auxiliary measures such as dehumidification or additional heating. The results presented in these studies are from one year of operation. Over a longer period, the massive structures can be expected to slowly become drier thus reducing indoor RH levels.

The preheating of the inlet air in the Church counteracted the cooling effect, which was reported in the farmhouse study and previous studies. Both case studies confirmed that AV is particularly useful when there are internal moisture sources in the building. This situation is quite common in historic buildings due to evaporation of moisture from the floor or through the walls.

A general problem with AV in historic buildings is achieving sufficient air tightness. The air tightness measurements in the Church indicate that the air leakage may be of the same order of magnitude as the fan air flow. In the farmhouse, air leakage was larger. The effect of the ventilation can be improved by increased fan capacity and improving air tightness to reduce leakage when the fan is not in operation.

Given the complex interaction between the thermal inertia and the RH and temperature of the incoming air, control by water vapour partial pressure rather than AH has proven to be a robust method. Further research will investigate the effect of the hygrothermal inertia of the building, long-term effects on the moisture balance, the potential for improving performance, and the further integration of heating or dehumidification.

The two case study experiments reveal several pros and cons of the AV. These are presented below.

Positive aspects:

- substantial reduction of mould risk;
- low-cost and low energy demand;
- non-invasive technical installations;
- improved indoor air quality as perceived by people;
- reduction of indoor temperature during hot periods.

Negative aspects:

- increased RH short-time fluctuations,;
- function is highly dependent on outdoor conditions;
- decrease of indoor temperature in winter months;
- needs auxiliary measures (i.e. heating or dehumidification) to fully prevent mould risk.

5.3. Comparison of control methods with the emphasis on mould growth

One significant climate-related problem in massive historic buildings is high levels of relative humidity that cause mould growth. To mitigate these high humidity levels, conservation heating and dehumidification of the indoor climate have been used with good results. Additionally, adaptive ventilation (AV), which is analysed in the previous chapter, has emerged as an energy-efficient measure that could be a candidate for mould growth prevention. Studies on AV and dehumidification have been carried out before as outlined in the state-of-the-art section. A new aspect of the presented analysis is cross-comparison of the methods with respect to mould prevention. The applied measures will be controlled in a way to mitigate mould growth while keeping the energy demands as low as possible. The objective of this section is thus to evaluate these three climate control measures for lowering RH to prevent mould growth in massive historic buildings in terms of energy efficiency, mould prevention effectiveness, and stability. This requires a case study in a real massive historic building where the three climate control measures can be compared and evaluated. This section is an extension of a published paper [7] where the author of this thesis is the main author. This section also includes results presented in 'Built Cultural Heritage in times of Climate Change' [8] and Deliverable report D7.1.2; 'New algorithms for optimal control of relative humidity' [11] of the FP7 European project Climate for Culture, which the author contributed to.

5.3.1. Mould growth climate control using isopleths

Traditionally, when a climate control measure is installed to mitigate mould growth, the RH set-point is often a constant level with some safety margin to 75%. This approach is unnecessarily restrictive and will cause higher energy consumption than needed. By using a predictive criterion for mould growth, the lowest boundary line of possible fungus activity, LIM (Lowest Isopleth for Mould, Figure 10) a set-point strategy can be developed for climate control [14].

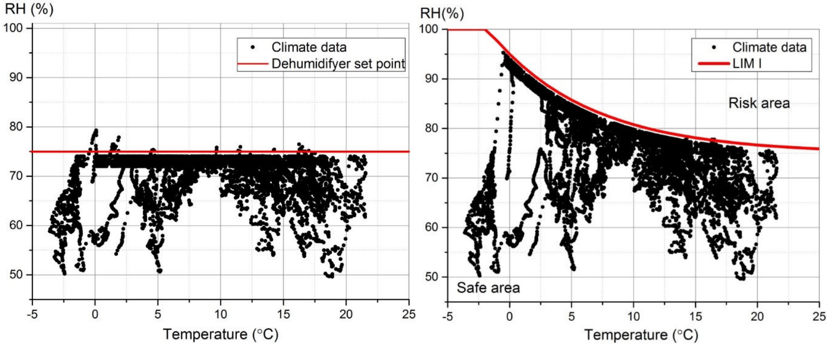

Figure 10. Simulated $[\vartheta, \varphi]$ data points for different control strategies. Left – simulation of traditional dehumidification with fixed set-point of 75%RH. Right – simulation of mould growth control with set-point according to LIM I.

One possible mitigation measure against mould growth is dehumidification. The control objective is to keep the microclimate conditions in the safe region below the LIM (Figure 10). This can be achieved by adjusting the set-point value of the dehumidifier, φ_{set}, based on the current (measured) temperature, ϑ_m, as

$$\varphi_{set}(\vartheta_m) = f_{\varphi}(\vartheta_m) = 75 + 20\mathrm{e}^{-0{,}1241\vartheta_m} - d, \tag{14}$$

The designed microclimate control method is demonstrated by simulation tests with the hygrothermal model for a Swedish church which was implemented in Hambase tool and parametrized based on the measured data. The simulations showed that mould growth control used 57 % less energy compared with a traditionally fixed RH set point control during the simulated year (Figure 10).

A case study on mould growth control was carried out in Fide Church for one year – from March 11 to March 11 the following year. The dehumidifier was controlled with the Culturebee system a wireless measurement and control system based on ZigBee-technology, which was evaluated and tested by the author of this thesis. Mould growth climate control was implemented according to equation (14). The in situ test showed the importance of the use of a safety margin to mitigate fast changes in indoor climate.

5.3.2. Comparative study in Skokloster Castle

The Skokloster Castle study compares three methods to control RH in order to minimise the long-term risk for mould growth with a minimum energy use [51]. Hence, the objective of this study is to evaluate and compare in situ the relative performance of these technologies in terms of mould prevention, energy consumption, and indoor climate stability of conservation heating (CH), dehumidification (DH), and adaptive ventilation (AV).

Due to a massive and relatively leaky building envelope, the indoor climate is characterized by high thermal inertia and high and unstable RH [10]. Three rooms known to have problems with bio-deterioration due to the indoor climate were chosen as case study rooms. Three similar rooms with no active climate control were used for reference. Before the first year of the study, all six rooms were draught proofed to make the active climate control more efficient: the windows were renovated, the doors were sealed, and dampers were closed and sealed. Temperature and RH were monitored in all six rooms for three years, and energy use was monitored in the three case study rooms. The three active measures were running for one year in each case study room and were then rotated annually. CH and DH were controlled according to the mould growth climate control described in section 5.3.1 and the AV-fan was controlled using the ratio between indoor and outdoor water vapour partial pressure. In this set up, the fan was on when the ratio was larger than 1.1.

The energy use for all three control methods was low. Dehumidification used the lowest amount of energy – in total, 534 kWh for all three years. Conservation heating used 957 kWh and AV used 742 kWh. The load for AV was more or less constant regardless of room and year, which is expected as the systems were controlled by the difference in indoor and outdoor climate. The load for conservation heating and dehumidification was highest in the leakiest room. Dehumidification and conservation heating successfully kept temperature and RH below the mould growth limit (i.e., below LIM I), except on one occasion during year one when the conservation heating one in room was unable to lower RH during a rapid weather change of warm and humid air.

AV lowered the MR in comparison to the reference rooms and to the other case study rooms, but the mould risk was not significantly lowered in comparison to the reference rooms; however, the mould risk was low in all rooms. The short time fluctuations were significantly higher (25-30%) in the rooms where AV was installed.

An important result of this case study is the effect of draught proofing. Two of the test rooms were well draught proofed but the third was adjacent to a tower room hard to draught proof. Comparing energy consumption per room for the whole three years shows that the two better draught proofed rooms consumed in total 512 kWh and 585 kWh, respectively, while the leakier room consumed the double amount of energy (i.e., 1135 kWh) for the three years. This result points out the importance of draught proofing when installing climate control measures in a historic building.

6. Conclusions

This thesis addresses questions connected to climate control in massive historic buildings with the focus on temperature and relative humidity. The research is motivated by the fact that many European cultural heritage objects – e.g., paintings, frescoes, sculptures, altars and organs – remain in historic buildings with no or limited indoor climate control.

Objective 1: Propose a methodology for non-invasive temperature and humidity control of intermittent heating of massive historic buildings

The main contribution is in performing the design of shaping the heating power increase at the beginning of the intermittent heating event in a massive historic building.

Applying model-based methods in the field of cultural heritage, simplified thermal and hygric analytical models of massive buildings were proposed. For both types of models, a two-step parameter identification procedure was proposed. The proposed models and identification procedures were successfully validated on measured data at three Swedish churches. The main contribution is in proposing an algorithm for stepped shaping of the heating power at the starting stage of the heating event so that the relative humidity change rate due to the heating is kept within a predefined range. In addition, a procedure to determine the overall heating time is proposed. The designed control procedure is then applied and validated on the models of all the three case study churches. For validation of the method, higher order dynamical models were proposed and parametrized from the available data, involving discretized heat equation. An almost ideal match with the results by the simplified models used to derive the control strategy shows that the stated simplifying assumptions were meaningful. Note that preliminary results presented have been published [1], and the final results are described in top journal paper [2], where the doctoral candidate is the main author. In summary, objective 1 of the thesis was fulfilled.

Objective 2: Perform validation and analysis of adaptive ventilation method for relative humidity control in historic buildings

The motivation for the given research lies in the fact that even though the adaptive ventilation has been implemented as a mitigation measure in a number of test historic buildings, it has not been investigated sufficiently in terms of mould growth prevention, relative humidity variability, control algorithms, and technical implementation. These perspectives were analysed and solved in the thesis. The main contribution is an analysis and validation of the measure regarding humidity control, energy performance, and stability of the indoor climate.

There is no doubt that adaptive ventilation lowers the humidity level. In the two case studies, the ventilation system transported out some 1600 kg and 1100 kg of water, respectively, during one year. The performed research shows that adaptive ventilation significantly reduces the number of hours of risk for mould growth on an annual basis, but there is still an increased risk during short periods when adaptive ventilation is not a sufficient. For these periods, a backup strategy is to be applied such as using portable dehumidifiers.

In summary, the performed case study analysis confirmed that adaptive ventilation is a viable method, especially if the proposed adjustments are taken into account. Hence Objective 2 has been fulfilled. The results of performed research are presented in [3], [4], [5], and [6], where the doctoral candidate is either the main author or a key co-author.

Objective 3: Propose and validate adjustments of indoor climate control methods in historic interiors with the focus on the mould growth prevention

The analysis of mould growth risk takes into account temperature and RH. This is then used to generate the relative humidity set-point based on measured temperature. By applying this approach, significant energy savings can be achieved compared to a constant set-point for RH. This conclusion has been made based on both simulation and case study experiments. The operation time for the proposed approach was only 57% of the run time for a fixed RH controlled dehumidifier. Applicability and benefits dehumidification with respect to mould growth were then confirmed via yearly experiment in Fide church (Gotland, Sweden).

The final contribution is a case study in Skokloster Castle comparing adaptive ventilation, conservation heating, and dehumidification. Dehumidification was found to be best concerning the indoor climate quality and energy consumption. However, a passive measure, drought proofing of the rooms performed before the first year of the study was a decisive factor in lowering the mould growth risk. The results presented in this part of the thesis was published in [7, 8] and [11].

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Curriciulum Vitae

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Education

2011 – 2018	PhD, CTU in Prague, Faculty of Mechanical Engineering, Department of Instrumentation and Control Engineering, Czech Republic.
1996 – 2001	Master Degree in Mechanical Engineering, Specialization Mechatronics, KTH, Royal Institute of Technology, Sweden
1988 –1991	Collage degree in Electrical Engineering, KTH, Royal institute of Technology, Sweden.
1986 – 1988	Upper Secondary School, Säveskolan Visby, Sweden. Adult education, university preparatory class.
1979 – 1981	Upper Secondary School, Säveskolan Visby, Sweden. Electricity programme, electronics.

Projects

2011 – 2018	Energy efficiency and preservation conservation through climate control. Swedish energy agency research program, save and preserve. Development of climate control strategies for historic buildings.
2009 – 2014	Climate for culture, European project funded by the European Commission. 27 partners. Responsible of measurements from case studies carried out by Uppsala University.
2007 – 2010	CultureBee, Measurements and control of indoor climate in historic buildings with wireless systems (zigee) funded by the Swedish energy agency. Responsible for integration in four historic buildings on Goland. Evaluation of climate data. Integration and test of mould growth control.

Publications

Author or co-author of 6 papers in conference proceedings and 3 papers in journals.

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Google Scholar: 12 records, *h*-index 4, 23 citations (without self-citations)

Work experience

2013 – 2018	Uppsala University, Campus Gotland Teacher in building materials, building physics, research engineer.
2003 – 2013	Gotland University Teacher in embedded systems, mathematics, programming basics, electronics, building materials, building physics
2001 – 2003	Hotswap Consultant in embedded systems, Med-Tech and instrumentation.
2001 – 2002	KTH/Berifors AB Master thesis, designing hardware and software for a debugging tool used for analysis of a J1708 - vehicle serial bus.
1992 – 2001	KTH-Visby Technical staff, responsible for a flexible manufacturing system lab.
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Courses

Higher education pedagogic 7,5 ETCS. Gotland University.

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