Overview of model based control strategies for ventilation systems

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This overview focuses on model based control strategies for ventilation in nearly zero energy buildings (nZEB) where slower reactions towards disturbances are expected as a result of high insulation and air tightness of the building envelope (Killian and Kozek 2016). Furthermore, internal heat gains have a higher impact in these kind of buildings. In addition, occupancy pattern can be variable (e.g. in office- and school buildings) and HVAC control is consequently more challenging. In addition, there can be a discrepancy between the heating demand and ventilation demand with all-air ventilation systems. All these conditions imply that the internal environmental quality (IEQ) is a challenge to control in nZEB buildings. A model predictive control (MPC) approach could be a solution as it takes into account the current situation and the future disturbances and demand (Killian and Kozek 2016). Inside the MPC framework, state estimation is performed to predict the future states of a system and/or building. Based on these predictions the controller can set output values by solving an optimization problem. For the optimal control problem an objective is defined and constraints are set so also future disturbances are included. The objective is a cost function that minimizes typically the energy use with respect to the (thermal) comfort included in the cost function or defined as a constraint. The optimal control problem optimizes output values using the identified model to verify the solution.

Table 1 gives an overview of existing literature on MPC for ventilation systems. In total 14 studies are evaluated where MPC was implemented to control the ventilation system. Out of these studies, 6 use an all-air ventilation system of climatisation while in the other studies hydronic systems (e.g. a heat pump with a TABS system) are used for space heating. In 10 out of the 14 evaluated studies the developed MPC framework is implemented in a real operating building or a small experimental test building, the remaining studies are simulation studies. In these four remaining studies typically measurement data is obtained from the building to develop a virtual test model that is used inside the MPC framework to perform a co-simulation. The majority of real buildings is an office building (8 out of 10), one is a residential building and one an academic building.

The model that is needed inside the MPC framework is used to represent the actual building and system. Regarding the dynamic model used in the MPC framework there can be a wide variety identified in the used methods. From simple regression model (black box), over RC-models (grey box) to detailed white box models (e.g. in Modelica). Lately, also machine learning techniques such as random-forest or neural networks are being utilized for the model identification process. In literature a lot of attention is devoted to the model identification procedure since it consumes a major part of developing an MPC framework. The objective is to construct a simple but accurate dynamic models of the real building and HVAC system used for predictions in the MPC framework. A reduced order model, a model with less complexity, will significantly reduce the computation time needed to solve the optimal control problem.

In most cases the MPC for the ventilation system is used for temperature control of the supply air, only in 4 out of 14 studies the room CO_2 concentration was also controlled by the MPC. The MPC controls the VAV boxes in the ventilation system and provides input for the airflow rate and supply air temperature at each time step. The cost function for the ventilation MPC can be defined by minimizing the energy use with respect to the (thermal) comfort. Soft constraints are used on the (thermal) comfort constraints to penalize constraints violations for the minimum and maximum room temperature (and CO_2) set point. The weight factor used for the comfort cost is significant higher compared to the energy cost in order to give comfort a higher priority over minimizing the energy use of the HVAC system. Ventilation control is often non-linear resulting in an MPC that can be complex to solve, since it contains non-linear constraints. In all-air systems the airflow rate and supply air temperature are both variable in time. Therefore a non-linear optimization might be needed to have a better match with the real situation or a simplification in order to solve the non-linear constraints.

Total energy savings using an MPC for ventilation control range roughly between 17-55% compared to a rule based control (RBC). However, it is not always clearly defined what the baseline is. In addition, the effect of variability in input data or uncertainty is not always taken into account when energy savings are given. Finally, for future implementation also attention has to be drawn to the transferability of the developed MPC method to other buildings. One of the bottlenecks of the implementation of MPC in general for buildings is that high expertise knowledge is required to implement this type of control. A lot of data and fine-tuning is needed in the model identification process and the model identified is specific for one type of building or system.

Table 1; Literature overview of studies on MPC for ventilation systems

Study	**Control Airflow**	**Type model identification**	**Energy efficiency**	**Implementation**	**MPC**
(Bengea et al. 2014)	T+CO_2	RC model (grey box)	20% HVAC system	Office building	Non-linear
(Liang et al. 2015)	T	ARMAX (black box)	27,8% HVAC system	Office Building	Linear
(Yuan and Perez 2006)	T	linearized differential equation (grey box)	-	Office Building	Linear
(Parisio et al. 2014)	T+CO_2	grey box for Temp and ARX for CO_2 (black box)	-	1-zone experimental test	Linear
(Walker et al. 2017)	T+CO_2	linearized differential equation (grey box)	23.5-30% HVAC system	Office building (simulations)	Linear
(Afram et al. 2017)	T	ANN (black box)	6-73% operating cost	Residential building	Non-linear
(Niu and Neill 2016)	T	Non-linear regression (black box)	22,1% HVAC system	Data-driven simulations	Non-Linear

(Zacekova et al. 2015)	T	MPC relevant identification (black box)	-	Data-driven simulations	Linear and non-linear
(Erfani, Rajabi-ghahnaviyeh, and Boroushaki 2018)	T	NARX network (black box)	55,1% electrical 43,7% gas	3-zone experimental test	Non-linear
(West, Ward, and Wall 2014)	T	RC Model (grey box)	19-32% for the HVAC system	2 Office buildings	Linear
MPC also for TABS system					
(Sturzenegger et al. 2016)	T	Bilinear RC model (grey box)	17% HVAC, lighting and equipment	Office building	Bilinear
(Picard et al. 2016)	T	RC and Modelica model (grey and white box)	-	Office building (simulations)	Linear
(Jorissen 2018)	T+CO_2	Modelica model (white box)	82% electrical	Office building	Non-linear
(Hilliard, Swan, and Qin 2017)	T	Random forest regression model (black box)	10-29% electrical 63% thermal	Academic building	Non-linear

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