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# Generalized model-based predictive weather control for the control of free cooling by enhanced night-time ventilation

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## HIGHLIGHTS

- Free cooling of a building by night-time ventilation decreases energy demand for cooling.
- Generalized model-based predictive weather control algorithm (G-MPWC) was developed.
- G-MPWC enables forecasting of free cooling system operation and efficiency for the next day.
- G-MPWC is presented in the form of control matrixes for a specific building.
- Experimental validation of G-MPWC confirmed the accuracy of the predicted building thermal response.

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## ABSTRACT

Free cooling by enhanced night-time ventilation could be an efficient technique for decreasing the energy demand for the cooling of buildings. Such systems use the ambient cold of surrounding air, which is transported into buildings by mechanical fan-driven ventilation systems. Only carefully designed and operated systems can be efficient enough to compete with other free-cooling techniques, such as evaporative cooling or even compressor-driven mechanical cooling systems. The efficiency of free cooling by enhanced night-time ventilation could be significantly improved if a model-based predictive weather control algorithm is used for operation control. The aim of this article is to present a generalized model-based predictive weather control (G-MPWC) algorithm that was developed with a detailed short time step numerical simulation of the thermal response of the building and free cooling system and simplified weather forecast data. The result of the G-MWPC is a set of control matrixes that includes data on the forecast required night-time air exchange rate and forecast daily coefficient of the performance of the free cooling system regarding the forecast daily average ambient air temperature and amplitude and the pre-set free cooling system on/off temperature difference. An additional matrix that includes data on forecast maximum indoor air temperature is developed for the case of the free cooling system being unable to fulfil pre-set thermal comfort requirements. A unique set of G-MWPS control matrixes must be developed for specific buildings and building operation conditions; afterwards, that control matrix can be used for the predicted controlling of the free cooling system by night time ventilation for the whole range of summer time meteorological conditions. In this article, the method and numerical model for developing a G-MPWC algorithm is presented as well as an example of a control matrix developed for a typical office room. The G-MPWC algorithm was validated for the case of a free-cooled office room.



## 1. Introduction

Regarding forecast climate changes, it can be expected that energy demand for the cooling of buildings will increase [1–3]. This will cause not only higher emissions of greenhouse gasses due to increasing electricity demand but also less healthy and pleasant indoor conditions. Increased electricity demand for cooling is expected particularly in urban areas as a consequence of increasing population and anthropogenic heat sources there [3–7]. In addition to other measures, free cooling by enhanced night-time ventilation could be used for decreasing the energy demand in buildings. Such systems use the ambient cold of surrounding air, which is transported into the buildings by mechanical fan-driven systems. The advantages of free cooling with enhanced night-time ventilation has been studied widely recently. Inard et al. [8] analysed 14 office

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**Nomenclature**

| | |
|---|---|
| $A$ | surface area ($m^2$) |
| $A_o$ | amplitude of outdoor air temperature (°C) |
| $a_0$, $a_k$, $b_k$ | coefficients of Fourier series |
| $c_p$ | specific heat of air (W h/kg K) |
| $C$ | building thermal capacitance (J/K) |
| COP | coefficient of performance (–) |
| $G$ | solar radiation ($W/m^2$) |
| $g$ | solar energy transmittance of glass (–) |
| $g_{tot}$ | total solar energy transmittance of glassing and shading (–) |
| $n$ | air change rate ($h^{-1}$) |
| $P$ | fan power (W) |
| SF | shading factor (–) |
| $T$ | temperature (°C) |
| $\overline{T}$ | average daily temperature (°C) |
| $t$ | time (s) |
| $U$ | overall heat transfer coefficient ($W/m^2$ K) |
| $V$ | volume of building ($m^3$) |

*Greek letters*

| | |
|---|---|
| $\Delta$ | interval or step changes |
| $\eta$ | efficiency (–) |
| $\rho$ | density of air ($kg/m^3$) |
| $\tau$ | solar time (h) |

*Subscripts*

| | |
|---|---|
| fc | free cooling |
| $i$ | indoor, iteration step |
| min | minimum |
| max | maximum |
| o | outdoor |
| on/off | on–off switch temperature |
| wall | wall |
| win | window |

rooms in low-energy buildings to evaluate energy savings by free cooling by enhanced night-time ventilation. They reported that the highest indoor thermal comfort category could be achieved in 70–95% of working hours during the summer time conditions. Wang et al. [9] reported on research on night ventilation strategies in office buildings. They analysed how indoor operative temperatures decrease in response to the duration of night-time ventilation and air exchange rates. Air exchange rates up to 10 $h^{-1}$ were assumed. Shaviv et al. [10] determined the decreasing of maximum daily indoor air temperature in response to the outdoor daily temperature amplitude and reported that up to 6 °C lower indoor temperature can be reached at air exchange rates up to 20 $h^{-1}$. Free cooling efficiency can be improved, for example, with the integration of heat storage into the ventilation system. Zhou et al. [11] and Arkar and Medved [12] studied the free cooling of a building using phase change materials (PCM) as cold storage integrated into the ventilation system. Both studies have shown the advantages of PCM storage even in the case of low daily outdoor temperature amplitude.

One of the most commonly used indicators of the efficiency of free cooling by night-time ventilation is the coefficient of performance (COP), which is defined as the ratio between the cold delivered into the building and auxiliary electricity demand for operation of the system in the same time interval, most often as an average daily value. The value of COP must be high enough to compete, on the primary energy demand level, with mechanical cooling and other free-cooling techniques such as evaporative cooling. In addition to the careful planning process, advanced control algorithms are needed to ensure that the COP value remains as high as possible. Recently, many studies have focused on the predictive operation of building systems using weather forecast data to increase energy savings in the winter as well as in the summer. Such modelling is called model-based predictive weather control (MPWC). Petersen and Svendsen [13] investigated the MPWC concept in the early stage of building design to predict future needs for cooling or heating. The same authors [14] investigated energy savings and overheating hours in light-, medium- and heavyweight buildings to show the effect of weather forecast uncertainty for Danish weather conditions. They concluded that despite the uncertainty in the weather forecasts, MPWC has an advantage in comparison to a conventional rule-based control. May-Ostendorp et al. [15] calculated that by using MPWC for the free cooling of a small office building in Boulder, USA, the electricity demand for the backup mechanical cooling can be decreased by 40%. In similar research for the Danish climate, Wittchen et al. [16] found that the annual cooling demand decreased by 36% if weather forecast control is used for night-time cooling. Candanedo et al. [17] presented a comparison between on/off and MPWC algorithms of an ice storage device in a small commercial building. The MPWC algorithm could provide annual savings from 5% to 20% with regard to the modified storage-priority algorithm and from 20% to 30% with regard to the chiller-priority strategy. Dovrtel and Medved [18] presented the optimization of cold storage integrated into a mechanical ventilation system using MPWC. They showed that by using the weather forecast controlling algorithm the cold store process increased the COP of ventilation process in comparison to the preselected on/off controlling.

There are two main approaches to developing MPWC control algorithms: the white-box and black-box approaches. The white-box models are based solely on physical parameters of the building and are most often developed with simulation software tools, such as TRNSYS or EnergyPlus [14,17,18]. The black-box models are based on the historical data gathered from monitoring of the building's thermal response without insight into physical properties of building and building service systems [19–21]. The white-box models are generally more convenient and could be used in the building design phase, but such models require pre-set boundary conditions of building use and could be more complex and time-consuming, especially in the case of a complex building.

In all the above-presented research, the benefits of MPWC for a free-cooling system with enhanced night-time ventilation operation is proven. Common to all the research is the use of complex methods or a large historical database to predict the thermal response of the buildings and to adjust the operation of a free-cooling system for the upcoming day(s). Despite the complexity of such approaches, COP and low morning indoor air temperatures are often not considered in the development of MPWC despite their crucial influence on thermal comfort and energy savings.

In this article, the developing of a generalized MPWC (G-MPWC) for controlling of free-cooling system by night time ventilation is presented. The G-MPWC includes data on the forecast night time air exchange rate required to fulfil the indoor thermal comfort criteria during the following 24-h period and the forecast average daily energy efficiency of a free-cooling system