Strengths of Non-Linear White-Box MPC for Building HVAC Control.

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Abstract
Model Predictive Control (MPC) for building HVAC applications promises improved comfort and substantial energy savings. However, these are only achievable when MPC becomes sufficiently cheap to implement and maintain, which is often overlooked. We present an MPC approach that uses detailed white-box models and motivate the strengths compared to other approaches.

Key Innovations
- Economic scalability of MPC
- Detailed white-box MPC

Research Implications
We share important insights related to our MPC approach.

Introduction
Building HVAC accounts for 15% of the world final energy use (IEA, 2019). While building design standards become stricter, the building energy use is to a large extent determined during operation, when control and the available building flexibility play an important role. Model Predictive Control (MPC) is a methodology for controlling the building HVAC during this operational phase. It uses a model to compute the influence of the HVAC control options on the system operational cost and on building comfort requirements, though other objectives can also be selected. The goal of MPC is typically to find the HVAC control set points that lead to the lowest operational cost while keeping comfort violations to a minimum. MPC thus achieves system integration by optimizing the HVAC system control.

While MPC is a system integration tool, there exist many flavors of MPC and so the question remains “How to do it?”. MPC research too often focusses on one particular aspect of MPC and a coupled performance indicator for that particular aspect, while overlooking system integration aspects. Furthermore, the economic reality is often overlooked: MPCs will have to be developed at a sufficiently low investment cost. I.e. the MPC development workflow has to be robust against errors, fast to implement, easy to maintain and extend, generic for any type of HVAC device, low-demanding with respect to expertise to implement and operate, and systematically applicable to (a class of) buildings. The trend is to use simple models or grey-box and black-box techniques to achieve this, while we advocate detailed white-box models as a starting point.

Methodology
Years of MPC research within the Thermal Systems Simulation (The SySi) research group at KU Leuven have led to what we believe to be a viable MPC approach for well-documented buildings, which we present below.

Linear vs. non-linear models
We use non-linear models instead of linear programming, which uses linear models (constraints) and objective functions. The main reason is simply because the system physics are non-linear. E.g. fan and pump power are (in specific cases) cubic functions of mass flow rate. Linearized versions of these models that are accurate around some operating point can be developed, but that operating point tends to shift, and a good linearization depends on the building. E.g. a building ventilation system may be used for any combination of temperature, CO₂ and humidity control where each of the control objectives require a different mass flow rate and thus linearization. The linearization process is hard to generalize or automate and requires a lot of expertise. Moreover, linear models can lead to bang-bang control and they tend to shift heat production to the last possible moment with the risk of not reaching a constraint. These peak powers typically require large temperature differences and flow rates, leading to lower efficiencies.

An often-used argument in favor of linear models is that one can prove global optimality. Our experience is that a local minimum of a non-linear model is better than the global minimum of a linearized model.

Many of these disadvantages are mitigated when using Quadratic Programming (QP) but the question remains how to use QPs in a workflow that is economically viable.

Granularity
We use models with a granularity that corresponds to the system physics. Each pump, valve, air handling unit is modelled individually. Rooms are grouped such that they match the HVAC component control options. E.g. if 10 rooms have 1 individually controllable VAV per 2 rooms then we model 5 zones and 5 VAVs. The zones and components could be lumped, but then how should the MPC react when 3 zones are too warm and 2 are too cold? It will likely model some averaged temperature that is within the comfort constraints and thus lower the supply air flow rate and fan pressure, while in reality all zones require a large flow rate to compensate the discomfort. Furthermore, the aggregation and disaggregation require...
expertise on how to group the zones and different people may do the grouping in different ways, leading to unpredictable performance. Our philosophy is to do a 1-to-1 mapping where each physical device is mapped into one component model. That way the model is both accurate and easy to implement.

**Physics-based vs. measurement-based**

We use detailed physics-based (white-box) building envelope models instead of measurement-based (grey-box, black-box) models. White-box models are not calibrated using measurement data so clearly there must be some model mismatch? Yes. However, any model has a mismatch, and the (envelope) model does not need to be perfect to get decent control performance. We do plan to improve our model parameters using measurement data (grey-box). At the same time, model mismatch is an opportunity for detecting component malfunctions.

Still, why not train a model using only measurement data; it requires much less parameters. Right? Probably, but for new buildings the physical parameters are not hard to find in building schematics and data sheets. We developed a tool that generates Modelica/IDEAS (Jorissen et al., 2018) models from building schematics. It may even be faster to use than the time required for collecting measurements from a building. In any case, it is fast enough and white-box modelling need not be too slow, as is often claimed. An added bonus of white-box modelling: the model can already be developed at the design stage.

**Model scope**

We model both the building envelope and building HVAC in detail. Other approaches often only contain a building envelope model and the building HVAC emission devices are modelled in a simplified way using a lower and upper bounded heat flow rate. There are two problems with this approach. Firstly, it does not consider the influence of the heat flow rates on the HVAC system efficiency. Secondly, the $n$ heat flow rates have to be mapped to $m$ actuator positions of the actual system in some post-processing stage. When $n > m$, the problem is overdetermined and the solution found by the MPC cannot (in general) be physically achieved. When $n < m$ the problem is underdetermined and there may be an infinite number of solutions that lead to the desired heat flow rates, or zero. E.g. MPC may choose to heat in one zone and cool in another zone using a fan coil unit. If the fan coil unit uses a two-pipe system where the supply water temperature is chosen centrally, the system is unable to cool in one zone and heat in the other.

When an infinite number of solutions exist, the remaining degrees of freedom have to be determined somehow, ideally using a second optimization. When $n = m$, the solution may still be non-physical, as explained above.

This analysis shows that while simplifying HVAC may work in a simulation, it leads to challenges in real MPC implementations. The post-processing requires a lot of expertise and may be physically impossible. We choose to model the building HVAC and to optimize the building actuator positions directly. This avoids the post-processing and system efficiencies can be accounted for.

**Results**

We use a non-linear, detailed, white-box approach. We model fan/pump efficiencies, pressure-driven flow, temperature-dependent COPs, building shading and the position of the sun relative to each window, etc. This leads to complex models that are translated using an in-house developed Toolchain for Automated Control and Optimization (TACO) (Jorissen et al., 2019a).

TACO has been used to model a 10 000 m$^2$ office building, Solarwind (Jorissen et al., 2019b). The model has about 80 zones, 3000 state variables, 20 000 variables, 200 control variables, concrete core activation, 6 air handling units, supports CO$_2$, humidity and temperature constraints, etc. TACO generates efficient C-code that is able to perform the required optimizations, demonstrating the potential of the proposed approach.

**Conclusion**

The success of MPC for building HVAC applications partially depends on the ability to systematically implement MPC with limited time and expertise requirements. We present a workflow using detailed white-box models and use automation and efficient numerical algorithms for implementing and solving the resulting complex models. We believe and motivated that it has strengths compared to other approaches but of course there is room for improvement too.

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**References**


