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Practical challenges of model predictive control (MPC) for grid-interactive small and medium commercial buildings

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ABSTRACT

To the urgent call for mitigating climate change, substantial initiatives have been undertaken to deploy grid-interactive heating, ventilation, and air-conditioning (HVAC) controls, such as model predictive control (MPC) for buildings. These efforts typically aim to curtail peak energy demand, shift load and enhance overall energy efficiency. With the recent development of low-cost MPC technologies that don't require extensive instrumentation or manual modeling, small and medium commercial buildings (SMCBs), which rarely utilize advanced HVAC control systems, have become candidates for grid-interactive efficient buildings (GEBs). However, despite the potential benefits and maturity of the technology itself, several practical challenges remain in real-world implementation. In this paper, we share the practical challenges that we have encountered in implementing and testing three types of MPC solutions (ON/OFF unit, dual-fuel, and VRF systems) on multiple SMCB sites. We describe the MPC deployment process and discuss the lessons learned. The site selection, eligibility, and retrofit availability (e.g., utility price structure, thermostat communications, etc.) are the main discussion points at the beginning of the project. Also, the modeling automation and the best practices for interacting with end-users and handling erroneous situations are presented for successful operations.

Introduction

With the urgent need to mitigate climate change, efforts to transition to a carbon-neutral society are gaining significant momentum, especially, for building sectors, which account for over 70% of U.S. electricity consumption and around 40% of CO2 emissions (Satchwell et al. 2021). While a complete transition of the building industry to renewable energy sources would require significant financial investments, grid-interactive efficient buildings (GEBs) can cost-effectively support decarbonization by enabling demand flexibility of various distributed energy resources (DERs) through controls such as load shifting and load shedding (Neukomm et al., 2019). Furthermore, a combination of energy efficiency technology and demand flexibility can result in a 91% reduction in carbon emissions from buildings by 2050 (Langevin et al. 2023).

While traditional building control research has focused on the energy efficiency of building heating, ventilation, and air-conditioning (HVAC) systems (ASHRAE 2021), more recent studies have explored advanced control methods aimed at facilitating grid services through dynamic HVAC operations such as load shifting and peak demand (Ham et al. 2023). These controls can coordinate the operations of various resources (HVAC, Solar PVs, batteries) and take into account grid conditions, weather, and occupancy. They can use model-based optimal control techniques, such as model predictive control (MPC)(Kim et al. 2022a), or artificial intelligence, such as reinforcement learning (Touzani et al. 2021). Recent research in these advanced control strategies has shown significant potential to reduce energy costs (Touzani et al. 2021) and increase renewable energy utilization (Kim et al. 2022a) both in simulations and field demonstrations.

However, many factors are involved when deploying those advanced controls into real buildings. Using a simple but accurate and robust model has been a key part of MPC research. Numerous works have been conducted in the modeling including the development of modeling tools (Wetter et al. 2014) and software workflow (Jorissen et al. 2019), and the practical challenges are summarized by seven categories (building design, model structure, model order, data set, data quality, identification algorithm and initial guesses, and software tool-chain) (Blum et al. 2019). This research has helped automate the process of creating an accurate building model. However, every building has different characteristics, and the heterogeneity of building metadata and BAS configurations (i.e., naming conventions of measurable and controllable variables and database structure), remains a bottleneck of the modeling process. Recent progress in the application of semantic models to automate the deployment of portable control applications shows potential time reduction in applying demand flexibility (DF) in real buildings, but this approach has not yet been applied to MPC (de Andrade Pereira et al., 2024).

Despite the development of automation in the modeling process, it is still challenging to apply MPC to SMCBs because they are usually conditioned by packaged systems that are controlled by off-the-shelf thermostats based on simple setpoint schedules without a centralized BAS. This type of system provides limited data points, such as indoor temperatures and operational signals of packaged systems. Having an accurate building thermal model with these limited data points is challenging due to various unmeasured disturbances (e.g., internal gains, infiltrations, etc.), which significantly deteriorate the accuracy of the model (Kim et al., 2016).

To overcome this limitation, a scalable MPC solution for SMCBs was developed in our previous study (Kim 2022b). This MPC solution is specifically designed for SMCBs equipped with ON/OFF rooftop units (RTUs) in a scalable and practical manner because it can be implemented without additional sensors other than WiFi-enabled thermostats. This makes the solution well-suited for SMCBs, where the expensive BAS is not typically installed, and its installation for retrofit is prohibited due to cost. The core idea of this approach is to include the effect of unmeasured disturbances such as human heat gains as a disturbance model term in the building model, resulting in a robust model that captures the building's thermal characteristics without additional sensors other than thermostat temperature and HVAC operating signals. Furthermore, the MPC solution is further scalable and practical when it is integrated with open-source middleware software that manages drivers to communicate with edge devices (e.g., thermostats) and collects data and control devices (Paul et al., 2023). As a result, our previous studies (Kim et al. 2022b, Ham et al., 2023, Ham et al., 2024a) have shown the scalable and practical MPC solutions for SMCBs without hardware retrofit for demand flexibility showing significant peak demand reduction (20-30%) and load shifting (10-15%) in field deployment.

The success of these field demonstrations does not mean that this advanced control technology is ready for deployment in the market. The U.S. Department of Energy (U.S. DoE) proposes the concept of adoption readiness level (ARL) as a supplementary concept to the technology readiness level (TRL) for technology deployment (Tian et al. 2023). The ARL includes comprehensive concepts such as value proposition, market acceptance, resource maturity, and license to operate. In consideration of the concept of ARL, besides the market and policy sides, the technology itself needs to be designed based on multiple stakeholders for market-ready deployment regardless of the completeness of the technology itself. For instance, when the end-users (such as occupants and building operators) keep overriding the MPC-generated setpoints for their thermostat, the MPC controller cannot achieve its demand flexibility goals (Ham et al. 2023). Also, the coordination of responsibilities, liability, troubleshooting, and safety needs to be discussed with the facility operator, end-users, facility owners, etc. (Kim et al. 2022a). These factors are often presented as practical challenges in research based on the specific research and the projects.

These steps are even more pronounced for small and medium commercial buildings (SMCBs, floor area less than 50,000 ft^2), which account for 50% of the total floor area of all commercial buildings in the U.S. (U.S. Energy Information Administration (EIA). 2018). Typically, these buildings lack a building automation system (BAS) for modeling automation and trained building managers to enable the deployment of advanced controls. Despite the significance of these stages, there remains a gap in research addressing the design and deployment of technology, particularly in integrating the perspectives of diverse stakeholders and considering their viewpoints throughout the deployment process.

The main purpose of this paper is to identify the stakeholders and provide a holistic pipeline for the deployment of advanced HVAC control, specifically MPC. The design choices and proposed workflows to deploy these advanced control technologies presented in this paper have been informed by our experiences leading several recent field demonstrations of MPC projects. We have also incorporated the perspectives of various stakeholders based on our interactions with both on-site and off-site entities. One benefit of designing this process is to present the big picture of the entire deployment process to the public, allowing them to use it as a checklist or a best practice guide for their projects. This study will first present an overview of MPC and our implemented project to give a basic idea of MPC's goals and expected benefits. This is followed by a description of the different stages of technology deployment and the stakeholders involved in each stage. Finally, we present practical challenges encountered in each stage.

Background

MPC for Grid-interactive SMCBs

MPC, one of the advanced HVAC controls, optimizes the operation of an HVAC system to minimize the objective (e.g., energy cost) with given constraints such as comfort boundaries by utilizing mathematical models for buildings and disturbance forecasts (e.g., weather). It can provide demand flexibility through peak demand reduction and load shifting as shown in Figure 1. In the schedule-based control (Figure 1 (a)), the heat pumps (HPs) operate based on the thermostat setpoint schedule. Typically, the night setbacks are programmed during the unoccupied times to save energy. However, when the occupied time starts, all the rooms need to be cooled down to the occupied cooling setpoints, resulting in high demand for HP powers, especially when there are multiple thermal zones served by multiple HPs. Also, regardless of the peak price time, the HPs operate to maintain the cooling setpoint. Alternatively, the MPC starts the cooling earlier than the occupied time to pre-cool the space and alternates the operations of multiple HPs to prevent the simultaneous operations of multiple devices. By doing so, it can smooth the HP peak demand at the beginning of the occupied time (peak reduction). In addition, the advanced control leverages forecasts of price information to shift the cooling load from the peak price time to the non-peak price time (load shifting) via pre-cooling.

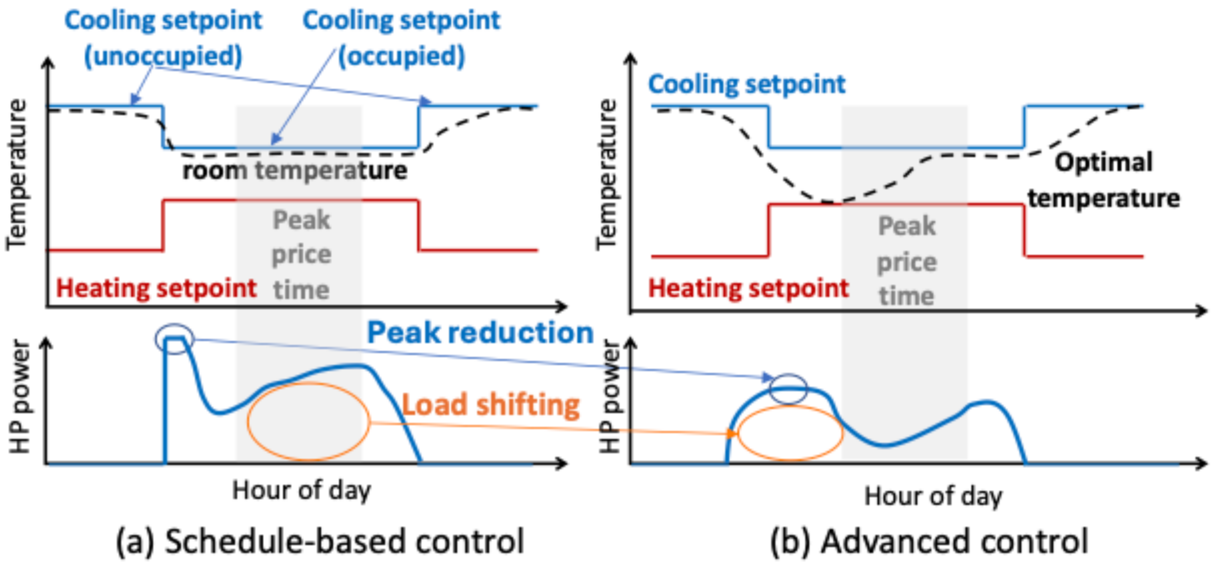


Figure 1. Conceptual diagram of advanced control (MPC) for demand flexibility.

Field Demonstrations for Deployment Process Development

Throughout the multiple MPC deployment projects, we have experienced various practical challenges and proposed a deployment process based on the lessons learned. To provide a better understanding of the process, we provide a summary of the field demonstration sites. The scalable MPC solution has been implemented in three sites as shown in Figure 2: a laboratory (Site 1), a small business (Site 2), and an office building (Site 3). The original MPC solution is designed for ON/OFF RTUs (Ham et al., 2023), but the MPC formulation has been improved to adopt various HVAC systems such as mini-split HP, dual-fuel system (Ham et al., 2024a), and variable refrigerant flow system (VRF) (Ham et al., 2024b), by scaling the operational signals, modeling gas furnace (GF) as an inefficient HP, and including a VRF performance map.

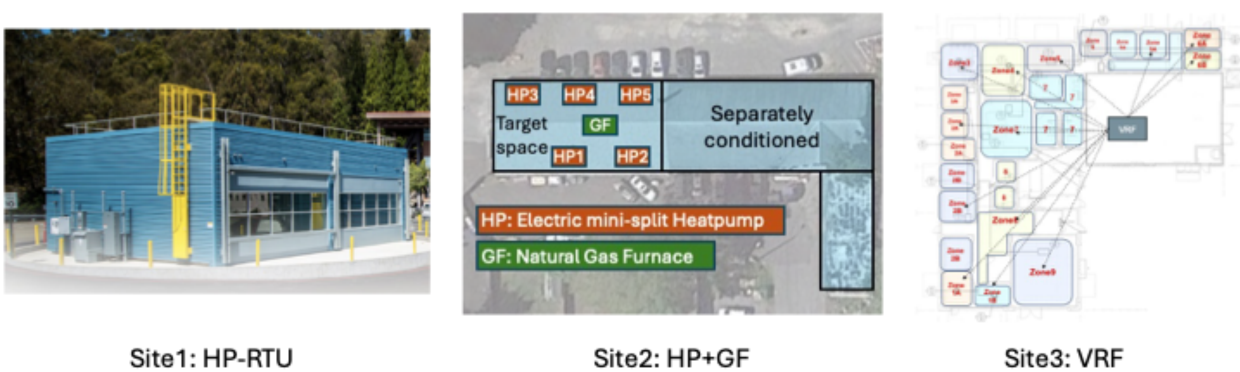


Figure 2. Field demonstration sites.

One example of the MPC solution results is presented in Figure 3 for description purposes. Two types of MPC solutions were implemented and are compared with the schedule-based control in Site 1. One is a traditional MPC solution (MPC_{ideal}) that requires additional sensors in addition to thermostats to monitor internal heat loads. The second one is a practical solution (MPC_{hybrid}) that does not require additional sensor retrofits and works with only typical WiFi-enabled thermostats. During this experiment, the utility prices had two peak price times: one in the early morning and another during the late afternoon. As can be seen from Figure 3, the baseline control had a high heating demand at the beginning of the occupied time, resulting in high power demand. Alternatively, both MPCs provided pre-heating earlier in the morning, showing significant load shifting from peak time to non-peak time (45-48%). As expected, the MPC reduces 27-30% of peak demand as the load shifts. In addition, it also shows 15-18% energy cost savings.

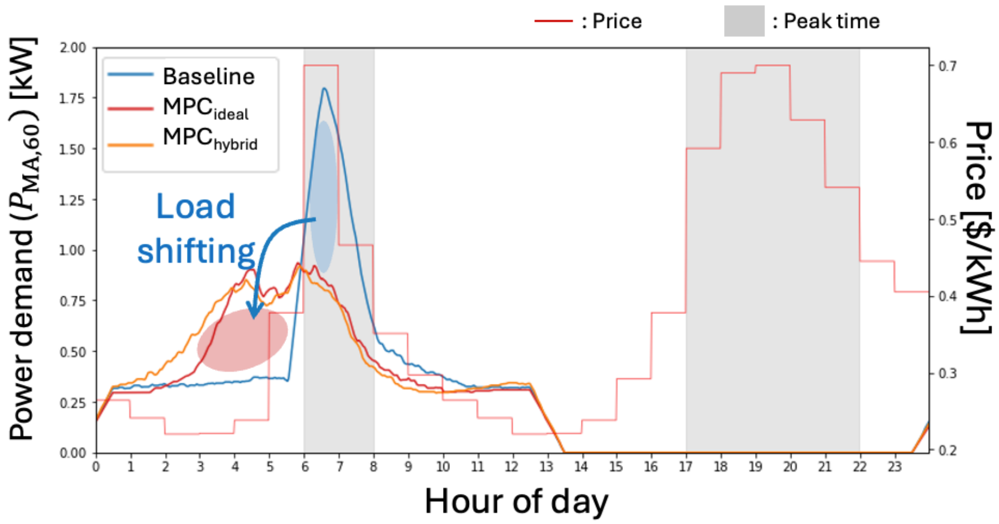


Figure 3. Load shifting and peak reduction performance of MPC in Site 1 ($P_{MA,60}$ indicates 60-minute interval averaged profiles).

Methods

Development of Deployment Process of MPC for SMCBs

Across these demonstrations, we have worked with different entities and multiple organizations, and the following sections are based on our collective experiences. These observations are from the perspective of a research organization that has worked with new and upcoming industry partners, who are entering the building control market. From this perspective, we have identified the different stakeholders involved in the deployment process.

- Service provider: an organization that has developed and is responsible for deploying the technology.
- Service engineer/software developer: engineers of the service provider organization.
- Building manager: engineers who operate the building facilities including HVAC.
- Building owners: building owners.
- End-users: occupants (tenants, residents, renters, etc.)
- Utility company: Utility company that provides utility services for the building.

Table 1 summarizes the MPC deployment process, and the stakeholders involved in each step. The identified practical challenges of each step will be presented subsequently.

Table 1. Roles and Responsibilities of MPC Deployment Stakeholders

Steps	Site acquisition/ Service agreement	Site inspection and retrofit	Software setup, Data collection/commissioning	Deployment details and education	Service run	Tech. transition
Service provider	- Distribute general marketing material - Provide investment/ benefit analysis - Prepare document for service	- Retrofit plan proposal - Subcontract for retrofit	- Decision on override policy - Lead malfunction repair process	- Deployment schedule (active test, education) - Survey active test boundaries - Deliver education and maintenance protocols	- Run MPC - Log any malfunctions / work orders and summarize them into lessons learned.	- Documenting educational materials for service run, trouble shooting, commissioning.
Service engineer/ software developer	- Analyze potential benefits and savings - Initial eligibility check	- Metadata collection - Determine eligibility of building and decision on retrofit - Conduct retrofit	- Software setup (sensor, database, control writes, override) - Control metadata and commissioning - Data processing (imputation)	- Develop education materials and maintenance protocol - Design comfort survey and M&V protocols	- Active test of system - System identification - Model validation	-Documenting technical materials for service run, trouble shooting, commissioning.
Building facility manager	- Provide initial site information to service providers for the analysis.	- Provide site information -Support retrofit including subcontract	- Malfunction repair	- Finalize the deployment schedule -Learn educational materials	- Log and share work orders from occupants	-Learn materials and summarize required items
Building owners	- Decisions from investment/ benefit analysis - Engage building occupants for the service	-Final retrofit decision making		- Finalize deployment schedule -Learn educational materials		-Learn materials and summarize required items
Occupants (end-users)	- Provide comfort requirements and sign the agreement			-Learn educational materials	- Report discomfort or atypical operations	
Utility	- Provide sharable utility data (utility price & usage)	- Provide any incentive programs				

Results

Based on the deployment process outlined in Table 1, we present the detailed tasks and practical challenges identified at each step below.

Practical challenges in Site acquisition/Service agreement

Given that the MPC market is quite unexplored, service providers often need to reach out to sites and make the case for these enhanced capabilities. Hence, the first step is site acquisition and agreement. During this process, the rough site characteristics and potential benefits of the MPC are investigated. If the building owner determines MPC would provide additional benefits, the technology is installed, and a service agreement needs to be produced and signed.

In our demonstration projects, the primary challenge in the site acquisition process lies in incentivizing stakeholders. Typically, building owners prioritize energy bill savings, while building managers are often hesitant to take on additional components to maintain and monitor. To address this, it is crucial to emphasize the benefits of transitioning to this technology, such as cost savings and decarbonization. Providing an initial investment/benefit analysis or highlighting other demonstration benefits can be helpful. However, it is also important to note that the savings may not be immediate, as they depend on weather conditions and other external factors.

In other words, the immediate bill savings may not appear within a few weeks according to the weather conditions. Additionally, building managers need to perceive MPC as robust, and the service providers and engineers must commit to supporting them in troubleshooting, especially at the beginning of the deployment. Their active participation and trust are critical to the success of the deployment. Therefore, documenting all these factors in a service agreement for technology implementation is essential.

The initial investment/benefit analysis is a critical part of the site acquisition step because the analysis result is a key driver for the building owner's technology adoption. In this study, we provide one example analysis of electricity load profiles from a demand flexibility viewpoint. Figure 4 shows the load profiles of Site 3 with its utility prices. Each day's profile is expressed with a dimmed gray line, while the average profile of the entire analysis period (two weeks of the heating season) is visualized with a thick black line. While all days showed high heating demand in the morning, zig-zag patterns of heating demands were found during the daytime. This is because all indoor units were simultaneously turned on during the morning start-up time, but their simultaneous operations were more stochastic during the daytime. In this site, given that the peak price period starts at 4 PM, flexibility is achieved by shifting the load via pre-heating during the 2 PM-4 PM time window. However, considering the ratio between peak/off-peak price ratio (1.1), the expected energy savings are minor. On the other hand, the current load profile (Figure 4) showed a significant morning heating demand due to the simultaneous operations of multiple VRF systems during the 7-8 AM time window. Hence, the investment/savings need to be analyzed based on the benefits that can be obtained from the peak demand reduction (i.e., demand charge reduction).

In certain instances, the utility price structure may be outdated, rooted in old contracts like flat rates or the absence of demand charges. In such cases, delivering benefits to both building owners and the grid becomes challenging because MPC cannot bring any energy cost savings from peak demand reduction and load shifting. Then, the site is less ideal for implementing the technology until the utility program undergoes updates toward a more decarbonization-friendly approach.

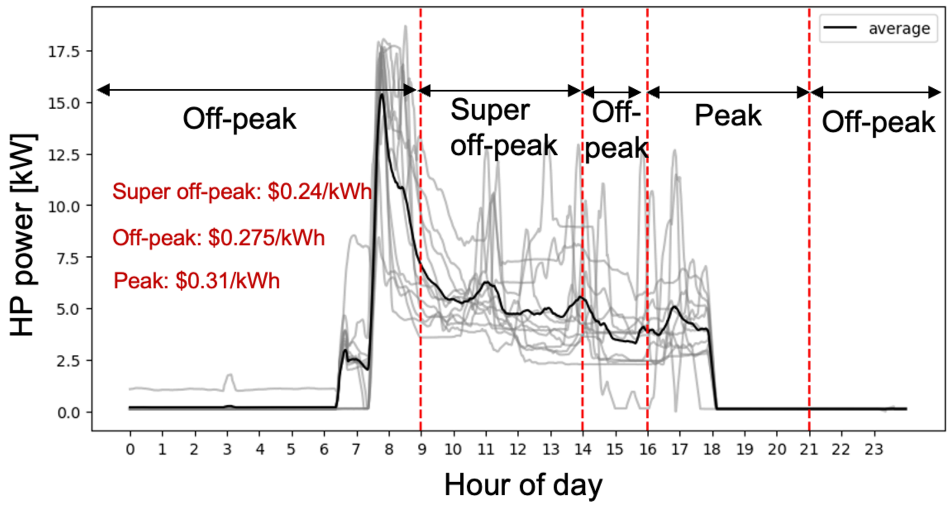
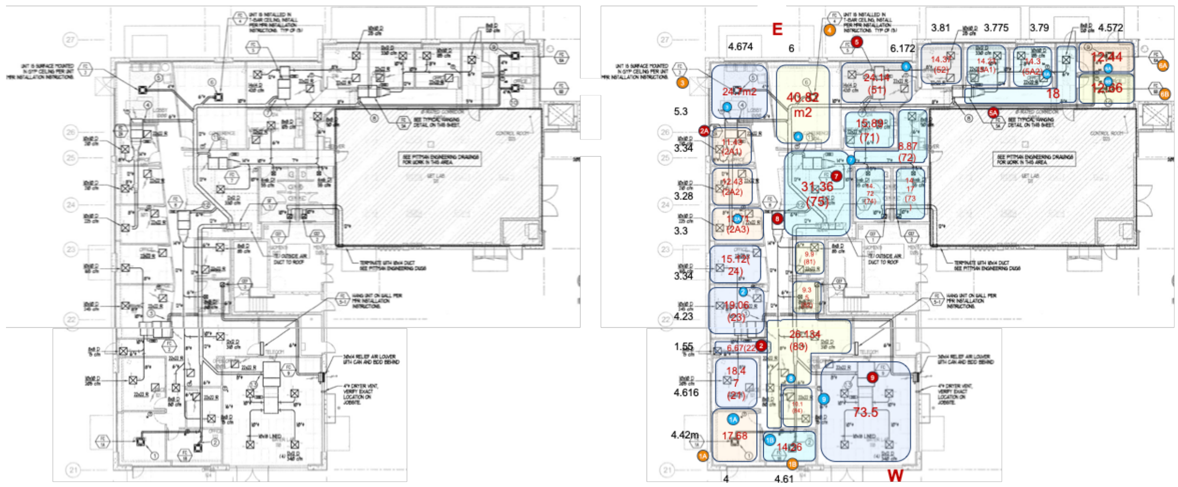


Figure 4. Load analysis example (grey: each day profile, black: average profile, two-weeks of the heating season).

Practical challenges in Site inspection and retrofit

The second step is site inspection and retrofit. In this process, we collect more detailed site characteristics and investigate the required retrofits for MPC to determine the eligibility of the technology. This includes (1) whether the current HVAC system is compatible with the MPC solution (e.g., ON/OFF unit vs. central multi-zone system) and (2) whether the building and its equipment (e.g.: thermostats) can provide the required data and control points. If the existing HVAC system is not compatible, the service provider must evaluate the effort needed to modify the existing MPC formulation to best fit the building and present the corresponding costs to the building owner. For example, the HPs in Site 2 were only controlled via infrared remote controllers. The minimum requirement of the MPC solution is to have WiFi-enable thermostats to collect current room air temperatures and HP operating signals. After retrofit cost analysis, we decided to install off-the-shelf WiFi-enabled infrared remote controllers and were able to implement the MPC solution (Ham et al. 2024a).

This process is manual and heavily relies on the service engineer's expertise, including analyzing HVAC characteristics from construction drawings and incorporating input from building managers. For example, as shown in Figure 5, we conducted a detailed site inspection at Site 3. Based on the architectural drawings, the details of HVAC's thermal zoning, thermostat locations, and eligibility of each zone are identified. Different rooms under the same unit are grouped and colored with a corresponding thermostat location as marked in Figure 5 (b). This process can potentially be automated by leveraging semantic models (Pritoni et al., 2021; de Andrade Pereira et al., 2024). This is an important research area, including providing eligibility criteria via a flowchart based on building metadata obtained from semantic models. Reducing the cost of site inspection is critical to increasing the adoption of this technology, as it lowers the upfront investment needed to determine site viability for MPC solution deployment. Adoption of semantic models and the reduction of these preliminary costs can expand the market for MPC solutions and increase value capture for stakeholders involved.



(a) Original drawing (b) Marked-up drawing

Figure 5. Detailed site inspection for Site 3.

Practical challenges in Software setup, data collection, and control commissioning

The third step is data collection and software setup. As shown in Figure 6, the MPC solution and middleware (Paul et al. 2023), which is running on a local machine or cloud server, can communicate and control the thermostats through WiFi or building communication protocols such as BACnet. This process could be complex when there are various thermostats from different vendors as it is necessary to collect their data in a single place. Connected thermostats are fairly diverse and have different methods for authentication and read/write operation. New device drivers are to be written for the middleware to enable connection with these thermostats. However, we implemented this middleware for a fairly large number of thermostats in the U.S. market, and the middleware is ready to be used for various sites with initial setup.

Also, if the thermostats do not support WiFi communication and communicate using other protocols such as BACnet, MSTP, or Modbus, the middleware needs to be installed on the local server. This is accompanied by cybersecurity processes that may change depending on site requirements and network configuration. Generally, the MPC and/or middleware requires access to the site's control network, and this is often supported through a VPN connection. The edge server can be configured as a DMZ[1] for the control network. Because of the potential cybersecurity threat created by IoT devices, some sites may prefer to deploy them with a completely separate control network and internet or cellular connection, but this increases costs.

[1] Originates from the term demilitarized zone. Increases the security of a private network by acting as a gateway between a private network and a public network (i.e. the internet), and controlling what is exposed.

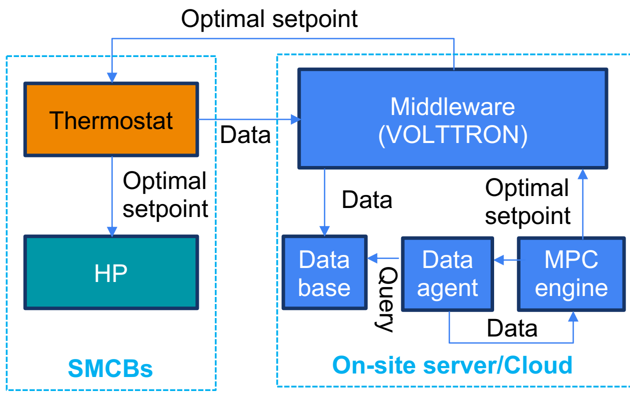


Figure 6. Schematic diagram of software platform (Paul et al. 2023).

After setting up the data collection software, the data commissioning step to detect peculiarities and errors in the configuration of the connected devices should follow. Some examples of these errors include incorrect building information, such as incorrect mapping of HVAC units to electrical meters, incorrect configuration of BACnet networks, leading to unexpected read or write results, or quirks in the read and write capabilities of different devices, such as rounding all written thermostat setpoints to whole number Celsius values, despite reporting data in Fahrenheit. Some of these errors can be identified through simple functional testing of the devices, reading and writing data to test communication integrity, measuring latency, and ensuring that devices perform as expected according to the data written. Functional testing is critical because it also identifies the policies that are required to read and write data. Additional software agents may be required to restore reading capabilities after a device goes offline. Different mechanisms for restoring data access are needed between each WiFi-enabled device as well as BACnet devices. To enable writing data, HVAC systems may require multiple modes and settings of the HVAC system to be changed, and these settings should be identified.

Figure 7 and Figure 8 illustrate one example of commissioning work. In this site, the zone air temperature was incorrectly configured as return air temperature in the BACnet system. Figure 8 provides the location of the return and room air temperature sensors. As the return air and room air are measured in different locations, these two temperatures are expected to differ. However, during cooling operation (Figure 7 (a)), the return air temperature and room temperature are similar due to the positioning of the sensors and supply cassettes, as well as the thermal dynamics of the space. Because of this, during the initial deployment of the MPC, the configuration error was imperceptible, and the temperature appeared to be well-regulated based on the set point. However, during the heating operation (Figure 7 (b)), both the room and zone temperatures significantly deviated from the heating setpoint, even with the heating coil valve (EEV) remaining open. This is mainly attributed to the buoyancy effect of the hot air as visualized in Figure 8. Subsequently, it was discovered that the room temperature had been incorrectly configured in the BACnet. Notably, this issue went undetected during the cooling season. This commissioning work is both time-consuming and labor-intensive. Similar to retrofit analysis, automation can streamline this process by utilizing an HVAC system-specific commissioning checklists. By using semantic models, the generation of checklist can be also automated.

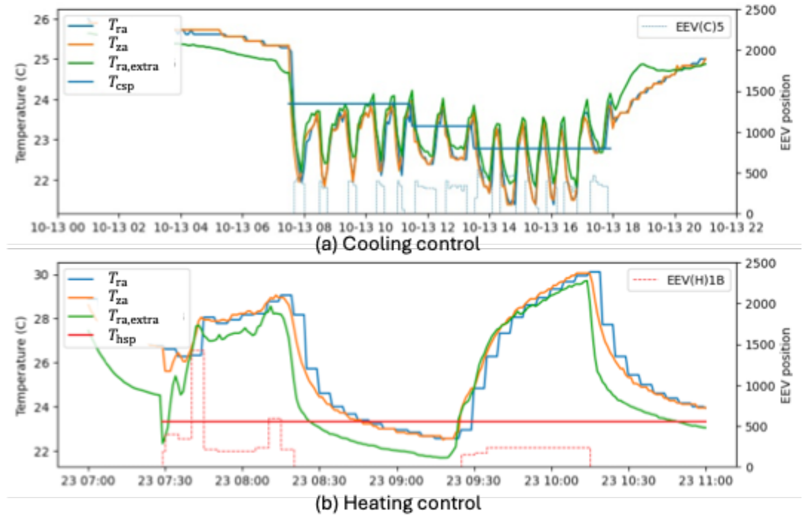


Figure 7. Commissioning example (incorrect sensor descriptions).

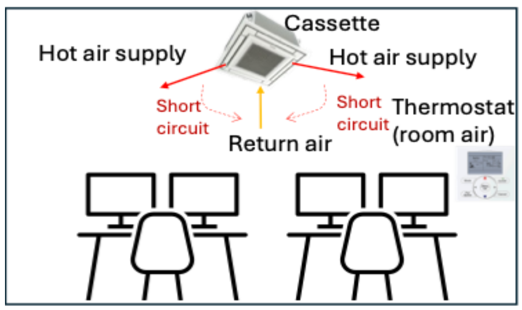


Figure 8. Short circuit issue in the air-heating system.

Practical challenges in Deployment details and education

The fourth step involves deployment setup and education. Before implementing the MPC in the actual building, it is essential to finalize deployment details. These details encompass operational constraints and communication processes for maintenance. Specifically, the operational constraints include comfort setpoint ranges, HVAC operational schedules, operable setpoint ranges, and potential control conflicts between end-users and the MPC. Additionally, if necessary, decisions regarding measurement and verification (M&V) protocols and occupant surveys need to be made. The communication process for maintenance is a critical part of keeping the trust between service providers/engineers and building managers. It is also important to notify the building representatives about the MPC schedule for testing and to set up weekly check-in meetings at the beginning of the real deployment. Additionally, maintaining records of communications and sharing them with other team members is crucial.

While the resolving complaints about MPC is important, it is also essential to have a better understanding of the technology for end-users, building owners, and building managers. Since the control actions are not everyday procedures, it is easy to forget the details if the stakeholders are not familiar with the MPC and demand flexibility. For example, as shown in Figure 9, when the MPC controls the thermostat, the end-user may want to have different setpoints due to thermal discomfort. Although the MPC is designed not to override the end-user's decisions, it is also recommended that the end-user does not override the thermostat unless it is required (i.e., no habitual override). This problem could be improved by providing education materials such as Figure 10. As discussed in the first step, it is also important to remind building owners that the bill savings are directly shown up in the beginning to the weather conditions. With education on the concept of bill savings, the service provider needs to continuously provide the bill-saving achievement by doing weather normalization to motivate the building owners to continue the adoption of the technology.

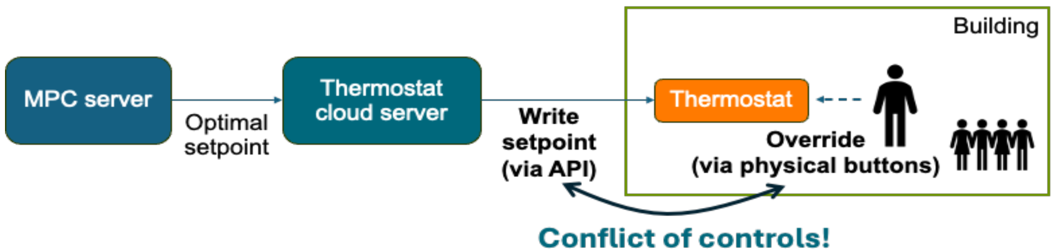


Figure 9. User-override issue.

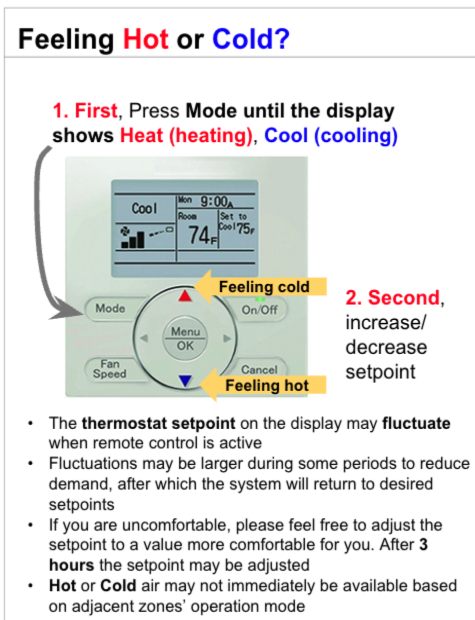


Figure 10. Education materials for thermostat usage.

Practical challenges in Service run

As discussed in earlier sections, the automation of model setup has been the focus of numerous studies, and our field demonstrations applied the typical workflow process, as illustrated in Figure 11. Upon data collection, the system identification for the building model is executed. Subsequently, model validation is performed to ensure the reliability of the model, and ultimately, the model is employed for the MPC solution. This process can be repeated when there are significant changes in the operation, such as a change in seasons. This is a typical process for MPC model building and service runs. We omit the details due to limited space, but further information can be found in our previous work (Ham et al., 2024a).

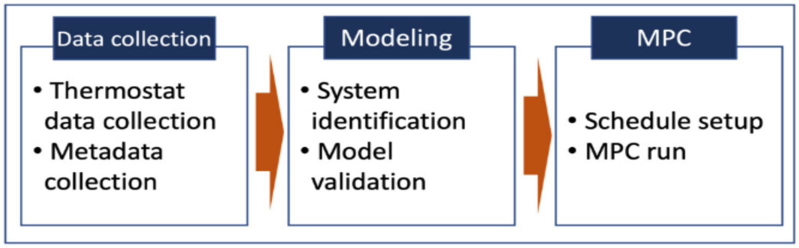


Figure 11. Modeling workflow (Ham et al., 2023).

Practical challenges in Tech Transition

After deployment of the MPC solution, the technology is transferred to site owners. The best practices, manuals, and troubleshooting procedures can be established for the complete tech transition. It is important to make the MPC service continue without the technology inventor. Therefore, the developed materials need to be delivered to the field facility operators via education. This is currently an ongoing project, we will update tech transition in our following research.

Conclusion

The urgent need to decarbonize electricity production and building end-uses has prompted significant efforts to implement grid-interactive HVAC controls. Particularly, research has been conducted on MPC development and demonstration to accelerate the technology transition from research to the real buildings. Promoting the scalable adoption of MPC in real building environments requires an understanding of the practical challenges MPC solutions will face, as well as the different roles market stakeholders will play in adopting this technology. This paper suggests a real-world deployment process for an MPC solution, including the roles of various stakeholders in key deployment processes. Based on the deployment process, we present various challenges encountered in the implementation and testing of MPC in SMCBs with a focus on typical HVAC systems such as RTU and VRF. The real-world insights and lessons learned about MPC deployment provide meaningful descriptions for early market providers interested in MPC as well as researchers commercializing MPC control technologies. Since the demonstration is going on for several projects of the authors, our future work will suggest the remaining parts such as the technology transitions and education parts.

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