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Authors

Prakash, Anand Krishnan
De Andrade Pereira, Flavia
Bergés, Mario
et al.

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[1]Anand Krishnan Prakash, [2]Flavia De Andrade Pereira, [3]Mario Bergés, [1]Marco Pritoni, [3]Burcu Akinci

[1]Lawrence Berkeley National Laboratory, [2]University College Dublin, [3]Carnegie Mellon University

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Anand Krishnan Prakash
akprakash@lbl.gov
Lawrence Berkeley National Laboratory, Berkeley, CA
Carnegie Mellon University, Pittsburgh, PA
United States

Flavia De Andrade Pereira
flavia.deandradepereira@ucdconnect.ie
University College Dublin, Dublin, Ireland
University College London, London
United Kingdom

Mario Bergés*
marioberges@cmu.edu
Carnegie Mellon University, Pittsburgh, PA
United States

Marco Pritoni
mpritoni@lbl.gov
Lawrence Berkeley National Laboratory, Berkeley, CA
United States

Burcu Akinci
bakinci@cmu.edu
Carnegie Mellon University, Pittsburgh, PA
United States

Abstract

Model Predictive Control (MPC) has shown significant potential for improving energy efficiency, indoor air quality and occupant comfort of buildings. MPC-based control algorithms have also shown the ability to shift loads and optimize for multiple objectives, including but not limited to reducing the green-house gas emissions, energy costs and peak demand. However, one of the main implementation challenges of these control algorithms is the integration and configuration effort needed to deploy a supervisory MPC controller in a building. By assigning standardized references to information sources and control points in buildings, existing studies have shown that semantic ontologies and corresponding queries have the potential to ease the deployment of such controllers. Yet, the use of semantic information to ease the deployment processes of MPC controllers is still limited. In this paper, we review three MPC experiments and synthesize the information requirements of these optimization problems. We then turn to existing and upcoming semantic ontologies such as Brick, SAREF and ASHRAE Standard 223 to represent these requirements, evaluating their potential to support the implementation of an MPC controller. This investigation concludes with a discussion of existing opportunities and open questions that the community should explore to support more streamlined MPC implementations.

*Mario Bergés holds concurrent appointments as a Professor of Civil and Environmental Engineering at Carnegie Mellon University and as an Amazon Scholar. This paper describes work at Carnegie Mellon University and is not associated with Amazon.

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CCS Concepts

• **Information systems → Information systems applications**; **Graph-based database models**; • **Software and its engineering → Abstraction, modeling and modularity**.

Keywords

Model Predictive Control, Semantic Ontology, ASHRAE S223, Brick, SAREF

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1 Introduction

In order to curb the impacts of the ever-increasing climate crisis around the globe, nations and organizations are setting ambitious targets to achieve reduced or zero carbon emissions from diverse sectors, including buildings. As one example, the United States has set a target for 2030 to reduce energy consumption in all federal buildings by 30% and completely decarbonize them by 2045 [11]. One approach to meet these targets is by incorporating intelligence in buildings and supporting communication with the utility grid through "Grid-Integrated Energy Efficient Buildings" (GEBs) [14]. Transitioning to GEBs will enable buildings to reduce their energy use and shift their power demand to periods when the utility energy mix is cleaner and less reliant on fossil fuel-based sources, with minimum disruption to the service they are providing. This also makes them a valuable resource to the utility grid by providing a clean option of "flexibility".

One of the promising techniques to provide demand flexibility is Model Predictive Control (MPC). MPC is a control technique that generates control actions over a finite horizon, optimizing system performance into the future. Multiple studies have demonstrated MPC applied to GEBs, resulting in improvements in energy efficiency up to 40% and reduction in peak demand by 30% [9, 18, 20, 21].

However, integrating an MPC controller into a building, still requires significant time and expertise, due to the lack of interoperability between building systems. For example, [3] allocated 29% and [6] spent 20% of the total implementation time on system integration. This time is spent in identifying and connecting inputs and outputs of the MPC controller to the right data sources and control points in a building. Therefore, it is imperative that we identify alternative workflows to enable the plug-and-play development and deployment of MPC controllers.

Recent advances in semantic ontologies for building applications can help alleviate some of these challenges. The work of [2] published in 2015 emphasized the potential of a semantic standard to address the challenge of interpreting unclear and ad-hoc point names in building automation systems. It highlighted how semantic ontologies could facilitate the discovery, mapping, and integration of data sources and control points, enabling scalable and portable applications. Since then, multiple ontologies have been proposed, leading to the development of an ecosystem of tools and applications built around them [16]. Software frameworks such as Mortar [10], SeeQ [13] and OpenBOS [7, 15] have leveraged semantic ontologies to develop scalable fault detection and diagnostics algorithms and rule-based demand flexibility control sequences. However, they have not investigated the use of semantic information to ease the deployment of MPC controllers. A recent study [5] proposes an information model that uses a combination of semantic ontologies, to aid the design of an MPC controller. However, from the proposed approach, it is not evident how the individual ontologies fare in representing all the information requirements of an MPC controller and how much overlap is present across these different ontologies. Additionally, this study did not consider the emerging industry-driven ASHRAE Standard 223P [17]. In this paper, we build on existing literature to evaluate three semantic ontologies aimed at streamlining the development of an MPC controller. We then present the gaps and research questions that need to be addressed to enable MPC deployments at scale.

2 Methodology

The evaluation of ontologies for meeting the information requirements of a MPC controller necessitates the extraction of these requirements from existing MPC implementations. We used recent publications from the Annex 81 and the Annex 82 subgroups of the International Energy Agency's Energy in Buildings and Communities Programme to construct three case studies and synthesize the list of information required by these MPC implementations. Then, we identify concepts and associate properties from the different ontologies under evaluation to formally represent the requirements. These requirements have also been categorized into different components of an MPC problem formulation based on the framework presented in [8].

2.1 Case Studies

In this section, we introduce the three MPC case studies, from which we will extract the information requirements.

Case Study 1 (NEST) describes an MPC controller that was developed to reduce the greenhouse gas emissions associated with energy consumption in the NEST demonstrator at Empa in Switzerland [4]. This controller managed the operation of a heat pump for space heating, another heat pump for domestic hot water heating, an electric battery and a simulated electric vehicle. It minimized the carbon emissions while maintaining the required space and water temperatures.

Case Study 2 (B59) presents an MPC controller field tested in Building 59 on the main campus of Lawrence Berkeley National Laboratory in Berkeley, California [3]. The controller manages an HVAC system that conditions two floors of office space in the building, which includes four roof-top units (RTUs) with water-cooled direct expansion (DX) coils. It also controls an underfloor air distribution system with 50 fan-powered underfloor terminal units (UFTs), each fitted with water heating coil to provide heating and reheat. The MPC controller aims to minimize the total power consumed by the HVAC system while maintaining the zone temperature within acceptable bounds and ensuring a minimum air flow rate in the space.

Case Study 3 (VLB) employs an MPC controller to optimally utilize the thermal energy generated by a building integrated photovoltaic/thermal (BIPV/T) system [19]. The MPC controller and the BIPV/T system in this case study were deployed in the Varennes Library, a net-zero building in Varennes, Canada. Thermal energy from the BIPV/T system can be recovered using a Energy Recovery Ventilator and either supplement the heating/cooling supplied to an air handling unit (AHU) or boost the performance of an air-to-water heat pump (AWHP). The AHU supplies conditioned air to the building and the AWHP is responsible for space heating through a hydronic radiant slab.

2.2 Components of MPC Problem Formulation

For each case studies, we decompose the MPC problem formulation into distinct components and describe the information required for each one. Based on the general MPC framework presented in [8], in this paper, we aim to capture and represent using the three different semantic ontologies, the information needed to represent the different "types" of objectives, constraints and models. For each type, different information from the building systems are needed by the MPC controllers. The "forms" of these components (such as hard v/s soft constraints, linear v/s quadratic objectives) are also critical factors in the MPC problem formulation. However, as our focus is solely on the inputs and outputs of the controllers, the details of the optimization function (such as prediction horizon, solvers etc.) are beyond the scope of this paper. Similarly, the algorithms, tools and problem classes are very specific to an MPC problem formulation and, hence, go beyond the scope of building-specific ontologies.

Objectives: The objectives of an MPC controller are expressed as a cost function that the optimization aims to minimize. These could be, for instance, minimizing greenhouse gas emissions, or minimizing energy cost for the building. Each objective often requires information about the states of the system (e.g.: indoor temperatures, energy consumption, peak demand) and specific additional information such as utility tariffs or greenhouse gas forecasts.

Constraints: Every setpoint or action generated by an MPC controller must be or produce results within acceptable bounds. These bounds could originate from the physical constraints of an

Table 1: Using semantics to represent information needed for objectives

Case Study	Variable	S223	Brick	SAREF
NEST	grid carbon intensity	X	X	X

Table 2: Using semantics to represent information needed for the inequality constraints

	Asset	Variable	S223	Brick	SAREF
NEST	HP for space heating	room temperature bounds	✓	✓	X
		max thermal power	✓	✓	X
	HP for domestic hot water	DHW tank temperature bounds	✓	✓	X
	Electric Battery	max charge/ discharge rate	X	X	X
		min SOC	X	X	X
	Electric Vehicle	max charge/ discharge rate	X	X	X
		min SOC	X	X	X
		grid connection status	X	X	X
	Building	power export status	X	X	X
B59	RTU	supply air temperature bounds	X	✓	✓
		supply air flow rate bounds	X	✓	✓
VLB	Thermal system	air flow rate bounds	X	✓	X
	AWHP	air flow rate bounds	✓	✓	X

actuator, the comfort levels of a zone or the safety limits of the equipment itself. Hence, to ensure the safe and comfortable operation of the building equipment, it is important to incorporate these constraints in the MPC problem.

Models: Developing models to capture the system dynamics of a building or a system is a critical part of developing an MPC controller. These models are included as equality constraints and they help estimate the states of the building in the future based on actions generated by the controller. While there are different methods to create these models, each with varying information requirements, in this paper, we limit our analyses to support the case studies under consideration.

3 Evaluation and Results

Incorporating references to the information required by MPC controllers within semantic models enables control developers to use semantic queries without the need for hard-coding data point names. Semantic models of buildings also contain network addressing information and hence using semantic queries to configure the controller streamlines the process of linking the appropriate data sources to the right component of an MPC controller.

In this paper, we will evaluate two published ontologies for building applications: Brick [1] and Smart Applications REFerence (SAREF) [12]. Additionally, we will include the upcoming ASHRAE Standard 223P (S223), based on the publicly available information as of September 2024 [17][1]. Brick and SAREF have been gaining significant traction in the US and European research communities, respectively, and initial adoption in commercial applications. Brick focuses on representing the physical, logical and virtual assets in buildings, as well as the relationships between them. SAREF facilitates the matching of existing assets (standards, protocols, data models, etc.) in the smart appliances domain. The industry-led effort under ASHRAE to develop Standard 223, with its goal of providing more detailed information about equipment layout and system composition, justifies its inclusion in this evaluation.

Tables 1, 2, 3 describe the different assets and variables that the three case studies of MPC controllers require. The last three columns in these tables indicate whether S223, Brick or SAREF contain concepts that can be used to explicitly model the respective asset, variable and their relationship, directly using concepts that exist in the ontologies. When all three ontologies were able to represent certain information requirements, they were excluded from the tables[2]. For example, all three ontologies were able to represent the power consumption of the uncontrollable lighting and plug loads for NEST and B59, as well as all the data points from the energy recovery ventilator (recovered thermal energy, air flow rate and fan power) in VLB. Correspondingly, those requirements have not been included in Table 3. The results presented in the tables indicate that each ontology exhibits varying levels of completeness, reflective of its primary purposes, and all ontologies share overlapping concepts. They further reveal that the Brick ontology is the most comprehensive, meeting approximately 76% of the specified requirements. In comparison, the S223 and SAREF ontologies support 52% and 47% of the requirements, respectively

4 Discussion and Conclusion

The evaluation conducted in this paper suggests that no single ontology can fully model the diverse data requirements of MPC controllers, given the specific needs arising from the heterogeneity of building systems. That being said, all the concepts required in the case studies which could be modeled by S223 and SAREF, could also be modeled by Brick. Nevertheless, while Brick has demonstrated better comprehensiveness in this analysis, the S223 and SAREF classes may be more suitable for other scenarios. For example, modeling comprehensive topological information within building HVAC systems would require S223 classes such as 'Ducts' and 'Pipes' which is abstracted in Brick through the 'feeds' predicate and not modeled explicitly. This consideration presents an opportunity for further exploration: *what are the overlapping and the distinct concepts across different building-specific ontologies and how and*

[1]https://explore.open223.info/.
[2]Full tables have been uploaded here: https://gist.github.com/anandkp92/6fc31bc58f5d541a67d9c77ab0fc4308

Table 3: Using semantics to represent information needed for system modeling

	Asset	Variable	S223	Brick	SAREF
NEST	HP for space heating	room temperature	✓	✓	X
		thermal power input	✓	✓	X
	HP for domestic hot water	tank temperature	X	✓	X
		water flow rate	✓	✓	X
		thermal power input	✓	✓	X
	Electric Battery	state of charge	X	X	X
		charge/discharge rate	X	X	X
	Electric Vehicle	state of charge	X	X	X
		charge/discharge rate	X	X	X
	PV System	solar irradiance	X	✓	X
	Building	building to grid power	✓	✓	✓
		grid to building power	✓	✓	✓
B59	Zone	zone setpoint	✓	✓	X
		solar irradiance	X	✓	X
	RTU	outside air flow rate	X	✓	✓
		supply air flow rate	X	✓	✓
		outside air temperature	X	✓	✓
		supply air temperature	X	✓	✓
		supply air temperature setpoint	X	✓	X
	Supply Fan	fan speed setpoint	✓	✓	X
	Return Fan	fan speed setpoint	✓	✓	X
	DX Coil	coil valve position command	✓	✓	X
	UFT	heating demand	X	✓	X
		air flow rate	X	✓	X
VLB	PV System	ambient temperature	✓	✓	X
		PV temperatures	X	X	X
		insulation temperature	X	X	X
	Thermal system	inlet temperature	X	X	X
		outlet temperature	X	X	X
		air flow rate	X	✓	X
		average air temperature	X	✓	X
	AWHP	electric heating load	✓	✓	X

when should an MPC controller leverage these distinctions to model its requirements?.

Delving further into the non-represented assets and variables, we noted that *none of the three ontologies were able to completely capture requirements pertaining to distributed energy systems (batteries, electric vehicles and PV systems) and utility signals (tariffs, emission rates).* Addressing this gap, either through extension of these schemas or inclusion of complementary ontologies, is essential to comprehensively represent and support the information requirements of MPC controllers that enable GEBs.

Formulating an MPC controller also requires information about certain non-time varying parameters that are not captured by these semantic ontologies (e.g.: prediction horizon, sampling time etc.). These parameters also depend on the "forms" the different components of an MPC controller take and finding a suitable solution to model these parameters requires further examination of a broader question: *how can we model the non-building dependent components (e.g.: algorithms and modeling approach) of an MPC controller in a modular and reusable way and how can this be incorporated with building-related and other complementary ontologies?.* Advancing this research prompts another compelling question: *Can semantic models be utilized to facilitate the development of system models (such as reduced-order resistance-capacitance model of a room) for an MPC controller?*

The literature clearly demonstrates that leveraging semantic models can bootstrap the integration of building analytic and control applications. Despite the current limitation in modeling all data requirements for MPC controllers, using existing ontologies such as Brick can still significantly speed up the MPC integration process in a variety of building types. By leveraging standard concepts, these ontologies help reducing time and labor to manually connect buildings' data sources and actuation points to the MPC software components. In a future where these ontologies comprehensively satisfy all data requirements for MPC, scalable deployment of MPC becomes closer to reality.

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