Model-Based Auto-Commissioning of Building Control Systems

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Abstract: Digital twins are valuable instruments for model-based design, commissioning, and operation, with significant applicability potential in the construction industry. Whereas with Building Information Modeling (BIM) a standard for the representation of building models has been established, these models lack (i) modeling support for building control systems, and (ii) tool-based automation support for model-based auto-commissioning of building automation systems, an instrumental factor in putting a digital twin in operation. In this paper, we present a domain-specific language (DSL), its modeling methodology, and tool support to augment and condition BIM models for auto-commissioning. Preliminary results from an early prototype evaluation using the *Technology Acceptance Model* demonstrate the feasibility of our proposal in contributing to the improvement of building operations by facilitating auto-commissioning of building control systems and subsequent commissioning of digital twins.

1 INTRODUCTION

Digital twins (DT) represent virtual replicas of cyber-physical systems (CPS) comprising (Grieves and Vickers, 2017)

- a virtual entity, i.e., the assemblage of models describing the CPS' manifestation,
- a physical entity, i.e., the *running instance* of the ,CPS, and
- interchanged data and connection between the virtual and physical instance, respectively,

and represent valuable instruments the for model-based design and operation of CPSs. DTs provide increased planning and operational efficiency, decreased interruption, improved product quality, optimized resource utilization, and enhanced innovation through simulation and analysis of real-time data (Semeraro et al., 2021). Due to their capacity to automate building operations, the architecture, engineering, construction, and operation (AECO) domain is increasingly interested in adopting DTs to improve project design, planning, construction management, resulting in improved collaboration, cost savings, schedule optimization, and better asset performance throughout the entire lifecycle of buildings (Ozturk, 2021). A DT for automating building operations leverages a virtual representation of a building that incorporates building control system (BCS) data to produce an accurate digital model. It enables building planners and operators to design, simulate and optimize BCS in the planning phase and during operation by auto-commissioning the BCS from the DT during initial building operation and later re-commissioning. Specifically, the integration of DTs, Building Information Modeling (BIM), and building automation enables stakeholders to create a model-based, dynamic, high-fidelity digital representation of a building for building operations and Computer-Aided Facility Management (CAFM). BIM and BCS are two distinct, yet interdependent technologies and methodologies that perform complementary roles in the design, construction, and operation of buildings, viz., during the

- *design phase*, BIM can provide valuable and detailed information for planning and simulation so that calculations, system dimensioning and specifications can be substantiated and optimized. Information that subsequently informs design decisions for the BCS;

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- *construction phase*, coordination between BIM and BCS trades ensures that BCS components are installed and configured per design specifications;
- *operation phase*, BCS are auto-commissioned from the BIM model and are responsible for the surveillance, control, and optimization of the building in real-time. They utilize sensors, controls, and data analytics to manage HVAC, lighting, and security systems, among others. Beneficially, this auto-commissioning substantially can reduce costs and errors during initial on-site operations.

The relationship between BIM and BCS is becoming increasingly important as organizations seek to create smart and connected buildings (Vieira et al., 2020). BCS data can be integrated with BIM, allowing working with a dynamic digital representation of the building. This integration enables better real-time monitoring and control of BCS and can facilitate predictive maintenance and contribute to the traceability of decisions across all construction phases (Ozturk, 2021).

While BIM has led to the standardization of the representation of building models (cf. Industry Foundation Classes (ISO, 2018); IFC), these models lack (i) collaborative modeling support among different trades, which encompasses BCS, and (ii) tool-based automation support for model-based auto-commissioning (and re-commissioning, respectively) of BCS, an instrumental factor in automatically putting a digital twin in operation (Ozturk, 2021). Specifically, BIM models lack

- modeling support for BCS,
- tool support for the processing of BCS trades in BIM models, i.e., BCS information is locked inside closed tools, and
- tool support for collaborative work among different trades over the building lifecycle.

Motivated by these conceptual and technological gaps, this paper explores the extension of BIM to include modeling and pre-configuration support of BCS for model-based auto-commissioning as a precursor for establishing a DT. We propose a modeling formalism with appropriate tool support for conditioning BIM models for model-based auto-commissioning of BCS. Specifically, we propose a graphical domain-specific language (DSL) and its implementation atop an existing BIM modeling tool that enables the aforesaid scenarios. The DSL is equipped with the necessary tooling regarding the extraction of BCS trades from the BIM model as required for auto-commissioning. The feasibility of our proposal is evaluated using a survey grounded in the Technology Acceptance Model (TAM).

Organization. Sec. 2 presents the challenges and contributions of our work. Sec. 3 introduces our proposed solution. Sec. 4 discusses our proposed modeling methodology and the tool implementation of our DSL. Sec. 5 evaluates our proposal and positions it w.r.t. related work. We conclude in Sec. 6.

2 CHALLENGES AND CONTRIBUTIONS

In light of our discussions in Sec. 1 we identify the following obstacles currently impeding model-based auto-commissioning of buildings for DTs, viz.:

1. Little to no interaction between stakeholders (e.g., building designers, building physicists, and building operators) as of lacking modeling formalisms for BIM-based configuration of BCS.
2. No tool support for model-based auto commissioning.
3. No foundation for establishing a BIM-based DT for tracing and optimizing a building's performance throughout its life cycle.

Commensurate with these, we introduce a DSL with an accompanying modeling methodology and appropriate tool support for the systematic conditioning of BIM models for model-based auto-commissioning of BCS. In synopsis, we deliver a model-based tool environment for

- modeling BCS components and their topology in buildings,
- describing runtime properties of BCS, and
- model-based auto-commissioning of BCS, i.e., automated deployment of runtime artifacts into BCS as a foundation for commissioning DTs

thereby targeting the following research questions:

RQ1. How can collaboration between experts in various trades for building design and building operation be improved?

RQ2. How to implement pre-configuration of BCS in BIM models?

RQ3. How to auto-commission BCS from BIM models for ultimately establishing BIM-based DTs?

We have structured our contribution as Design Science Research (DSR) (Wieringa, 2014) and produced a tool environment as an artifact. The development of our artifact follows a systematic process, starting with gathering requirements and ending with creating prototypes, tool evaluations, and obtaining feedback from experts. Our artifact is implemented as a solution to the following design science problem, outlined using the DSR template:

Improve *BIM-based DTs for building control* (context)
by designing *a modeling methodology for conditioning BIM models for building control* (artifact)
that satisfies *pre-configuration of BCS* (requirement)
to deliver *model-based auto-commissioning of BCS.* (goal)

DSR usually refers to an *artifact* as a prototype at Technology Readiness Level 3 (TRL3), representing a conceptual solution at an early stage of technology development. Using model-based engineering and a cyber demonstrator, our proposal achieves TRL5 (c.f. Sec. 3).

3 MODEL-BASED AUTO-COMMISSIONING

Our proposed solution has its roots in BIM-based auto-commissioning. Demand for BIM-based auto-commissioning is rapidly growing because of its benefits regarding enhancing efficiency, collaboration, compliance, and the overall quality of building operation processes (Vieira et al., 2020). In the following, we elicit actors and use cases in BIM-based auto-commissioning (denoted UC*X*), and their associated requirements (denoted R*X*) as to be delivered by our proposed solution (c.f. Sec. 3.3).

3.1 Use Cases, Actors, Requirements

Usually, *building designers* start with the design of the building [UC1] thereby creating the initial BIM model. During this early design phase, the model repeatedly is exchanged [UC4] among *building designers* and *building physicists* and *operators* to condition the model for auto-commissioning by extending it with BCS data [UC2] and necessary configurations [UC3]. Model exchange is done using the IFC which provide a vendor-neutral standard for the exchange of data and models in the AECO domain. A dedicated BIM model repository (Zech et al., 2024) provides the necessary technical infrastructure to realize such model-based collaboration. During the construction phase, the BCS-enabled BIM model provides *the* single source of truth regarding how to install and wire BCS components inside the building. Crucially, the BIM model allows *operators* to infer the BCS topology and wiring diagram [UC5] which acts as the blueprint for the aforesaid installation. Finally, at the beginning of the operation phase, *operators* deploy the BCS configuration contained inside the BIM model (cf. the *operating model*) into the BCS to auto-commission the building's initial operation [UC6]. During operation, any changes in the building's design and consequently the BCS readily can be re-commissioned. Tbl. 1 summarizes our discussion of use cases and actors.

Table 1: Use cases and actors in BIM-based BEM.

	Use case	Actor
UC1	Design Modeling	Building designer
UC2	BCS Modeling	Building physicist, Operator
UC3	BCS Configuration	Building physicist, Operator
UC4	Model Exchange	Building designer, Building physicist, Operator
UC5	BCS Topology Extraction	Operator
UC6	BCS Configuration Deployment	Operator

3.2 Requirements

The use cases from Tbl. 1 readily define the basis for inferring the requirements our solution has to deliver. *Building designers* and *building physicists* need means to (i) create and evolve the building model, thereby conditioning it for auto-commissioning. This not only comprises the structural modeling of a building but in addition the placement of BCS controllers, sensors and actuators as well as their connectivity [RQ1]. This emphasizes the collaborative working aspect where *building designers* and *building physicists* work on the same model, yet using different tools, which implies the need for a tool infrastructure that allows for the seamless mapping and exchange of building models among involved actors' tools [RQ2]. Observe however that this exchange has to work in both directions, e.g., from *building designers* to *building physicists* and vice-versa, as BCS modeling may require design modifications. Given the fully BCS-conditioned BIM model, as a next step, wiring and topology diagrams are to be exported [R3] for that installation proceeds along the specified design. This is especially crucial for building automation. At present, this installation step is usually completely decoupled from any building design and done on a best-practice. This readily results in buildings not meeting their initial planning and design objectives. Crucially, for that this installation and subsequent initial building operation during auto-commissioning proceed without any issues, the validity of the modeled BCS pre-configuration needs to be checked inherently to ensure sound BCS pre-configuration [R4], i.e., only allowed devices are connected. Finally, as a last step with the building constructed and the BCS in place, *building operators* automatically deploy, i.e., auto-commission any runtime artifacts, e.g., control code or other parameterizations of the BCS, directly into the building [R5], rendering building-side commissioning superfluous. Tbl. 2 summarizes our requirements.

3.3 Proposal

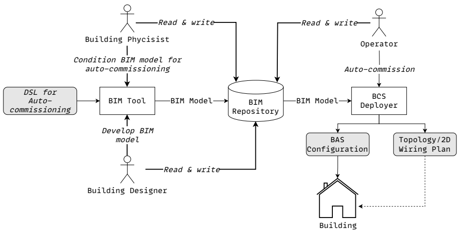


Figure 1: Conceptual model of our solution proposal.

Fig. 1 outlines our proposal. We employ DSLs for advancing BIM modeling towards the use case of model-based auto-commissioning of buildings. Specifically, we develop a graphical DSL for abstracting BCS and their components which is directly embedded into an existing **BIM tool** (cf. Autodesk Revitx). This readily enables *buildings physicists* the conditioning of a BIM model for auto-commissioning by augmenting it with BCS-relevant data [R1]. The **BIM repository** thereby enables collaboration [R2] by allowing for the seamless exchange of BIM models among different actors, e.g., *building designers* can share models which can then be retrieved by *buildings physicists* and vice-versa. *Building operators* on the other side retrieve the BIM model from the repository for both extracting a 2D wiring diagram and the BCS topology [R3] for installing the BCS as designed. Our proposal continuously checks and assures BIM model validity in that only sound configurations of BCS can be established [R4] (cf. Sec. 4). Finally, with the physical BCS in place, *building operators* eventually deploy any BCS runtime artifacts that are inferred from the BIM model (e.g., BCS configurations) [R5] into the building using a dedicated **BCS Deployer** which handles necessary conversion of BIM-based BCS data into runtime artifacts.

4 MODELING METHODOLOGY

Commensurate to our solution proposal, the following sections provide an in-depth discussion of the artifacts developed to address our research problem (cf. Sec. 2).

Scope. The modeling methodology covers the pre-configuration of BCS in BIM models which includes the definition of devices and their connections. Model-based development of BCS control algorithms is out of the scope of this work and will be addressed in future extensions.

Modeling Languages. Eclipse Ecore is used for formalizing the abstract syntax of our DSL, whereas its concrete syntax, i.e., the graphical representation of the DSL, is implemented using Revit families (cf. Sec. 4.3).

4.1 Graphical DSL

To enable the model-based pre-configuration of BCS we have developed a graphical DSL for Autodesk Revit (cf. Sec. 4.3) for augmenting BIM models with BCS data (cf. Fig. 2). The top-level element of our DSL is a *Device*, e.g., a *sensor*, a *controller* (which houses the control logic), or an *actuator* (e.g., a motor to drive a blind), whereas sensors and actuators are further modeled as interacting devices, i.e., they measure or modify the environment. Crucially, each device has associated a unique *id* used for addressing it at runtime. Controllers can have attached up to N devices (where address ranges are bound in the interval $[1,N]$). Sensors and actuators can only be connected to controllers but not directly to each other. For each device, we also model its readable and configurable parameters that allow both monitoring the runtime state of the device and re-commissioning it at runtime by overwriting parameter values. We further model devices' specifications, e.g., *voltageType*, *resolution*, or *setpoint*. For both sensors and actuators, our metamodel provides predefined concrete classes, e.g., *BrightnessSensor* or *LedDriver* which describe common BCS components. Finally, our model also implements a *Gateway* that allows for interconnecting devices from different vendors in one BCS installation.

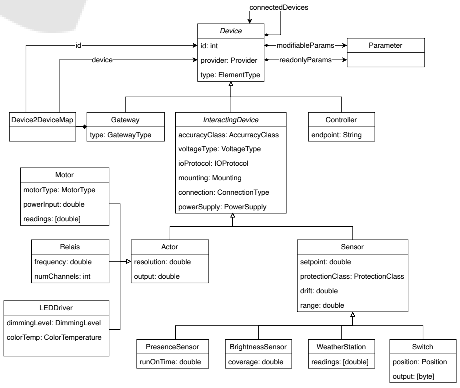


Figure 2: Metamodel specifying BCS components for BIM models.

Table 2: Requirements as prompted by the use cases from Tbl. 1.

	Requirement	**Prompting use case(s)**
R1	*Modeling and configuration support* to enable pre-configuration of BCS	[UC1], [UC2], [UC3]
R2	*Model exchange* to enable *building designers* the sharing of BIM models with *buildings physicists* and BCS experts for BCS modeling and configuration	[UC1], [UC2], [UC3], [UC4]
R3	*BCS topology/wiring diagram extraction* to enable general constructors to install the BCS according to the design	[UC5]
R4	*Model validity assurance* to establish sound and complete BCS pre-configurations	[UC2], [UC3]
R5	*BCS deployment* to enable *building physicists* and *BCS experts* model-based auto-commissioning of buildings	[UC6]

4.2 Modeling Steps

The modeling procedure for model-based pre-configuration of BCS comprises 3 steps: (1) specifying the BCS devices in the BIM model, (2) creating topology views for different stories, and (3) specifying inter-story (e.g., within a story) and intra-story (e.g., between stories) connections among devices. Crucially, the below steps need to be followed in order.

(1) Specifying BCS Devices. To begin, BCS devices (e.g., controllers, sensors, actuators, and gateways) are placed in the BIM model through the utilization of the provided Revit families whose implementation follows our metamodel (cf. Fig. 2). Fig. 3a shows a 3D view of a building with multiple modeled devices.

(2) Creating Topology Views. To draw connections between devices, the second step involves creating a topology through the `Create Topology` command which is part of the developed tooling for our DSL (cf. Sec. 4.3). The resulting *topology view* is created along the selected room, story, or the entire model which eventually determines the selection of displayed devices within the view. Room and story topologies are 2D views, whereas the full model topology is a 3D view allowing the establishment of connections between devices on different stories (cf. Fig. 3b).

(3) Inter-Story and Intra-Story Connections. Once in the topology view, devices can be connected using the `Connect device` command and subsequently selecting the source and target device. Crucially, our tooling restricts selectable target devices to avoid erroneous connections, e.g., between two sensors. Only valid I/O connections between the individual devices are permitted. In the event of removing a connection, Revit automatically handles model updates. In addition, our tooling environment provides commands for managing connection visibility: (i) `Hide connections` to hide all connections in the view, (ii) `Show connections` to reveal existing but (yet hidden) connections, and (iii) `Highlight connection` to maintain visibility of connections among currently selected devices. Fig. 3c shows a reduced view on the building model (walls removed) from Fig. 3a with devices and their connections. The `Export topology` command generates a 2D topology plan of all devices and their directed connections from the BIM model (cf. Fig. 3d).

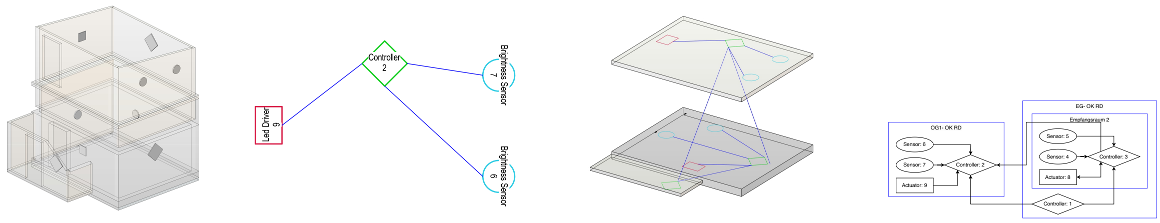
4.3 Implementation

Our prototype has been implemented as a series of Revit families and a dedicated plugin that implements the necessary tooling support. The choice for Autodesk Revit is due to both (i) our own experience in developing Revit plugins and (ii) our project partners' reliance on Revit as their commonly used planning tool.

Revit families – broadly spoken – allow the definition of a group of model elements with a common set of parameters, behavior, and graphical representation apart from what Revit innately offers. At this, Revit distinguishes between **system** and **component** families, whereas the latter are intended for our use case by extending Revit's innate modeling capabilities. Fig. 3 shows the graphical representation of our DSL as currently implemented in Revit.

Aside from the graphical syntax, dedicated tooling to support the modeling procedure was implemented in a Revit plugin. Specifically, this plugin implements the generation of topologies as part of the **BCS Deployer**, the checking of connection validity, and hiding and showing connections depending on the selected model view, e.g., in the 3D view of Revit, we deliberately hide connection as this would drastically congest the view on the model. Instead, connections are visible in the dedicated topology views. An exception to this are intra-story connections which also need to be visible in the 3D view, as they are not part of story-specific topologies.

Finally, the plugin implements a feature for generating a 2D topology diagram for BCS installation. We extract this plan directly from the BIM model inside Revit and store it as a graphviz file. Fig. 3d shows a sample 2D topology plan for the model depicted in Fig. 3.



(a) 3D view of a building with devices (lozenges denote controllers, circles sensors, and squares actuators) placed on different floors.

(b) 2D topology view of the first floor from the building from Fig. 3a.

(c) 3D view with walls and doors hidden showing inter- and intra-story connection between different devices from Fig. 3a.

(d) Exported topology for the building from Fig. 3d

Figure 3: Example 3D planning views of a building with devices.

5 EVALUATION

We evaluated our proposal using the Technology Acceptance Model (TAM) (Davis et al., 1989). The TAM holds considerable importance in the evaluation of tool utilization by providing a methodical structure for understanding user perceptions, attitudes, and intentions regarding the adoption of technology.

5.1 Method

From our research questions (c.f. Sec. 2) we created a user survey (cf. Riemenschneider and Hardgrave (2001)) to be administered to our sample. The sample in this case comprises representatives from the construction domain with both academic and industrial backgrounds. Specifically, after an interactive tool demonstration, we administered our survey to the 19 representatives, among them researchers (9), lightning planners and consultants (6), and building designers (4). The reported average age of participants is 39,5 years with an average of 9 years of experience. Two participants did not disclose their gender, among the remaining 19 participants, there were 14 males and three females.

5.2 Model Evaluation

To thoroughly assess the implementation of our suggested tool environment, we utilize a methodical approach to estimate and analyze the corresponding structural equation model (Hair Jr et al., 2021). Structural equation modeling (SEM) is a powerful tool for evaluating complex theoretical relationships, especially among latent variables. PLS-SEM is particularly beneficial in situations where the goal of the structural model is to predict and explain desired outcomes, such as technology acceptance (Hair Jr et al., 2021).

5.2.1 Measurement Model Evaluation

Starting with the evaluation of the dependability and accuracy of our reflective measurement, as per the approach outlined by Hair Jr et al. (2021), we analyze the reliability of each construct by analyzing respective indicator loadings, *(ii)* evaluate the reliability of the measurement instrument by calculating composite reliability (ρ_c), Cronbach's alpha (ρ_T), and the reliability coefficient (ρ_A), *(iii)* assess the convergent validity by calculating the average variance extracted (AVE), and *(iv)*, verify the discriminant validity by examining the Heterotrait-Monotrait (HTMT) ratios.

Concerning *(i)*, all the loadings of the four constructs, viz. *Training* (`TRA`), *Ease-of-Use* (`EOU`), *Usefulness* (`USF`), and *Use* (`USE`), which were measured reflectively, exhibit statistical significance at a confidence level of $\mathrm{CI}_\alpha = .05$ or below. Furthermore, being above the threshold value of .708 (Hair Jr et al., 2021), they suggest a sufficient level of indicator reliability. Concerning *(ii)*, all four constructs measured demonstrate a substantial level of internal consistency, with ρ_c, ρ_T, and ρ_A all surpassing .7 and slightly exceeding .95 (Hair Jr et al., 2021). Moreover, w.r.t. (iii), it is important to mention that all the Average Variance Extracted (AVE) values significantly surpass the threshold of .5, indicating a high level of convergent validity for the measures of the four constructs (Hair Jr et al., 2021). Concerning *(iv)*, all HTMT ratio values are below the liberal cut-off threshold of .85 (Hair Jr et al., 2021), indicating discriminant validity among the four constructs.

5.2.2 Structural Model Evaluation

Having proved the reliability and validity of the constructs, we investigate the structural component of our instance of the TAM. Following Hair Jr et al. (2021)'s recommendations, we *(i)* examine the structural model for collinearity issues based on the variance inflation factor (VIF), *(ii)* assess the significance and relevance of the structural model relationships, i.e., the path coefficients, using bootstrapping, and *(iii)*, assess the explanatory capability of the structural model using the coefficient of determination (R^2) and the effect size (f^2).

Regarding *(i)*, the VIF analysis reveals that our model does not exhibit any evidence of collinearity among the four constructs, as the greatest VIF values are well below the threshold of 5 (Hair Jr et al., 2021). Regarding *(ii)*, we assess the significance and the relevance of the structural model paths by bootstrapping the sampling distribution to test the structural model's relationship coefficients for statistical significance at $\mathrm{CI}_\alpha = .05$. Finally, concerning *(iii)*, the R^2 values for the endogenous constructs `USF`, `EOU`, and `USE` are moderate being located close to the moderate threshold of 0.5 (Hair Jr et al., 2021). This suggests that our instance of the TAM has a satisfactory ability to predict outcomes within the sample (Hair Jr et al., 2021).

5.3 Interpretation of Results

The results of our data analysis have verified the accuracy of our implementation of the TAM and have shown a significant level of acceptability for the proposed tool environment. Our analysis suggests that the initial `TRA` has a significant influence on `EOU`. To put it succinctly, being trained in the utilization of a technology diminishes the level of proficiency needed to employ it efficiently. Nevertheless, it is crucial to acknowledge that `TRA` has an insignificant impact on `USF`. This implies that the mere benefit of adopting a new technology is sufficient for its implementation, even without any prior training, despite thereby raising the level of difficulty for newcomers. Based on these observations, it is evident that the impact of `EOU` on `USF` is considerable. This suggests that possessing the knowledge of how to utilize a particular technology enhances its utility, provided that it is advantageous for the task at hand.

When it comes to the concept of `USE`, it is evident that `USF` has a considerable impact. In addition, `EOU` has only a weak influence of `USE` implying that ease-of-use fosters technology acceptance but does not seem to be the driving force behind acceptance. This reinforces our prior assertion regarding the sole benefit of adopting a novel technology. Put simply, the weak impact of `EOU` on `USE` serves as more evidence that professionals are eager to embrace a new technology, regardless of the effort involved, as long as it is advantageous for their work. Overall, our analysis demonstrates a robust reception of our proposal and its modeling methodology.

Regarding RQ1, our proposal effectively showcases the utilization of model repositories for model exchange, model-based development, and language engineering to advance existing modeling formalisms towards novel use cases.

As for RQ2, our graphical DSL and its accompanying modeling methodology illustrate the process of pre-configuring BCS in BIM models. In our current work, we use this information to subsequently infer a 2D topology (cf. Fig. 3d) as a blueprint for the installation of the BCS.

Finally, in the event of RQ3, the combination of model-based development for BCS pre-configuration and the subsequent capitalization on models for automatically extracting relevant information thereof (cf. Fig. 3d) delivers the necessary foundation for establishing BIM-based DTs in the future.

5.4 Related Work

Tang et al. (2020) - similar to our approach - embed BCS-specific information into a BIM model. However, contrary to us, their approach does not support direct data extraction from the BIM model but instead leverages the IFC in combination with an additional tool, thus impeding an integrated workflow. The work of Dave et al. (2018) describes a concrete implementation of a framework that integrates IoT and BIM. Specifically, they export an IFC model from Revit which is subsequently extended with BCS data for further use (e.g., visualization). This heavy reliance on the IFC by *export-edit-import* however repeatedly results in errors due to information loss during export and import and the IFC not being designed for editing (Mirarchi et al., 2017). Louis and Rashid (2018) propose to leverage BIM models as operating systems for smart homes by extending the BIM model with relevant IoT-device data. By then loading the model into the Unity Game Engine, they create a platform for click-control of IoT devices in smart buildings. Contrary to our work, Louis and Rashid however only support locating IoT devices in BIM models but do not address the pre-configuration of BCS devices (e.g., establishing connections) as done in our work. Finally, the work of Tan et al. (2022) - similar to ours - also addresses the configuration of artificial lighting and daylighting. Yet, in their case models of the building and embedded BCS are established post factum only, thus not addressing initial model-based pre-configuration for initial building operations.

In the event of dedicated language extensions of

BIM, e.g., by DSLs, the only related work we were able to identify is by Alves et al. (2017). In particular, Alves et al. introduce a DSL for embedding real-time sensor data into BIM models. Yet, their work - similar to what was discussed previously - neither addresses pre-configuration nor subsequent model-based auto-commissioning of BCS.

6 CONCLUSIONS

In our paper, we have presented a metamodel with relevant tooling support for model-based pre-configuration of BCS for model-based auto-commissioning of BCS, a crucial precursor in establishing DTs of buildings. Our current implementation allows for both the configuration and extraction of a structural design plan for operators. The results of our evaluation using the TAM are promising in that – despite its for now limited functionality – our proposal is appreciated and will be used once it reaches the necessary TRL, e.g., TRL7.

In future work, we plan to extend our graphical DSL to capture further relevant information regarding *auto*-connecting, i.e., twinning, physical and virtual replicas by extracting a device configuration for a DT middleware that allows for the automated and seamless establishment of bidirectional data exchange with the physical entity. Further, we plan to extend our proposal by a textual DSL for model-based BCS programming thereby also delivering [R5] for eventually deploying such code-based runtime artifacts.

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