Towards Enabling Continuous Integrated BIM2SIM Workflows with Model Augmentation Strategies

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Abstract

Enabling continuous integrated BIM2SIM workflows is as of yet a still open research area. One of the main reasons for that are interoperability challenges consisting of data, structural and exchange format mismatches between the BIM instance model, which describes the structure to be built, and the corresponding SIM instance model used for simulation. In this paper, we focus on tackling the issue of data mismatches by augmenting BIM models to enable model interoperability and transformation for arbitrary simulations. A specification of such a model augmentation system is presented. We elicit requirements of the system, outline the architecture and describe a conceptual workflow. A preliminary version of the proposed system has been implemented within a research project, and we provide an initial scenario-based evaluation. Our findings demonstrate the feasibility of enabling BIM2SIM workflows through our approach. We conclude this paper by summarizing our results and presenting future work.

Keywords

BIM2SIM, Model augmentation, Model transformation

1. Introduction

Simulation (SIM) models in the Architecture, Engineering, Construction, and Operations (AECO) domain serve a wide range of purposes, including energy simulation, lighting simulation, and structural analysis. These models encompass not only buildings but also infrastructure projects such as bridges and tunnels. Each type of structure and simulation requires distinct, domain-specific data within the model to accurately simulate the relevant tasks. For example, daylight simulation requires the *solar radiation* to be given, whereas the *heat transfer coefficient* is essential for energy simulation. The most substantial impact of simulations is observed when they are conducted during the early design phases of a project, where the positive impact of changes is high and their costs are low [1, 2].

In recent years, much research has been done in the area of using a structures' Building Information Modelling (BIM) model as the foundation for these simulations [3, 4, 5]. A BIM model is a digital representation of a building design with geometric information and alphanumeric attributes that serves as a central information source for all project participants. The contained data attributes, commonly referred to as properties, serve as metadata that describe both specific geometrical elements (e.g., thermal resistance of windows) as well as broader concepts related to the project (e.g., construction phase). Typically, a BIM model is developed prior to any SIM models, making it logical to leverage the existing BIM model rather than reconstruct the entire structure within the SIM tool.

However, historically, BIM and SIM models and tools have been developed independently of each other. This separation arises primarily because the functionalities provided by each tool cater to distinctly different user groups [6]. BIM authoring tools are predominantly used by architects and engineers, who focus on the design and documentation of buildings and structures. In contrast, SIM tools are utilized by building engineering physics specialists who are adept at conducting detailed building performance

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simulations. Architects typically lack the expertise to perform complex simulations, just as simulation specialists are generally not trained in the comprehensive design of buildings from the ground up [7].

Likely also due to this separation, the makeup of a *structural* BIM model, which requires detailed building geometry, often differs significantly from that of an *analytical* SIM model, which is tailored for specific performance analyses [8]. For example, an energy simulation may necessitate a thermal perspective that is not inherent in a *structural* BIM model, requiring geometrical simplifications and modifications for simulation use [3].

Therefore, interoperability between BIM and SIM models is still an open issue and challenges are manifold [9, 1, 5, 4, 10]:

- `Data loss`
  - BIM authoring tools may not export all relevant data, even if it is contained in the BIM model.
  - SIM tools may not be able to correctly import all data from a BIM model.
  - Data may have been mapped falsely between a BIM and a SIM model.
- `Missing data`
  - BIM model might not be able to store all data needed for a SIM model
  - BIM model is able to store relevant data, but the data is still not contained in the model.
- `Model structure differences`
  - Fundamental structural differences exist between *structural models* used in BIM and *analytical models* used in SIM.
- `Model standards`
  - Missing or not fully implemented interoperable BIM and SIM model standards.

One strategy for addressing these challenges is the *open BIM* approach [1]. It promotes interoperability and collaboration across various software platforms and stakeholders by using standardized, open file formats to share and manage models seamlessly throughout the project lifecycle. The two most notable standards are the Industry Foundation Classes (IFC)[1] and Green Building XML (gbXML)[2][1]. Unfortunately, neither standard is fully accepted or implemented on the BIM authoring tool side nor on the SIM tool side [5, 4, 9]. In order to circumvent these shortcomings, middleware tools can be used to correct and enrich models adhering to these standards [9].

Another approach involves using the Application Programming Interface (API) of a proprietary BIM authoring tool to facilitate the transfer of information between BIM and SIM models [4], minimizing data loss but leading to vendor lock-in. BIM and SIM tools can also be integrated through the use of plugins, wherein specific SIM tool plugins are developed for prominent BIM software applications. This approach eliminates the need for data transfer between software and ensures that design changes in the BIM model instantly affect simulation results. However, these plugins often provide only limited functionality [4].

Therefore, despite significant research efforts focused on enabling BIM2SIM model workflows, numerous unresolved issues persist. Consequently, the following research questions are proposed and addressed in this work: (RQ1) How can continuous integrated open BIM BIM2SIM workflows be enabled? (RQ2) How can the properties necessary for different kinds of simulation be managed in an efficient way? (RQ3) How can the different actors (architects, simulation specialists) be supported in their work?

The rest of this paper is structured as follows. In Section 2, related work is discussed. The methodology employed to generate the presented results is shortly introduced in Section 3. In Section 4, we discuss the identified issues in the area of BIM2SIM pertaining to the proposed research questions. Viable solution strategies for these challenges as well as requirements for a software system with the goal of enabling

[1]https://technical.buildingsmart.org/standards/ifc/
[2]https://www.gbxml.org/

BIM2SIM can be found in Section 5. In Section 6, the design of such a model augmentation system system is further specified and possible architectures as well as a conceptual workflow are presented. Sections 7 and 8 will present a prototype and preliminary evaluation of the proposed approach. Finally, we will conclude the paper in Section 9 by giving a summary of our work as well as a glimpse into future work.

2. Related Work

This section presents related work in the area of BIM2SIM and introduces the BIM2BEM-Flow research project, which serves as the foundation for all research discussed in this paper.

BEM (Building Energy Modelling) is a type of SIM focused on energy simulation, making BIM2BEM a special case of BIM2SIM. The *BIM2BEM-Flow* project emphasizes continuous energy efficiency planning from the early design phases to construction, integrating building physics analyses and simulations to maintain energy performance and automate changes. It addresses tool interoperability and develops a framework for BIM2BEM workflows based on exchange requirements. This involves refining BIM model elements with energy-related properties, such as heat transfer coefficients. Simulation results guide the design towards energy objectives. Leveraging established standards like Industry Foundation Classes (IFC) and open BIM principles, the project ensures well-defined data exchange and collaboration. The interdisciplinary team includes experts from civil engineering, computer science, and industry partners, supported by the Passivhaus Institut Innsbruck's expertise in BIM and BEM interoperability. A proof-of-concept will enable BIM2SIM workflows for tools related to daylight, artificial light, and energy balancing simulations.

BIM2BEM-Flow builds on previous work done in the area of BIM2SIM interoperability. In the *freeBIM* and *freeBIM2* research projects, the need for a single source of truth to manage property data has been recognized and addressed [11]. A so-called *property server*[3] has been developed, with the goal of keeping property data consistent and compatible with Austrian standards and the international standardization effort undertaken by buildingSMART[4], a global organization developing open standards for BIM with the goal of improving digital collaboration in the construction industry. However, the emphasis on strict adherence to national standards, characterized by comprehensive yet rigid and complex quality assurance processes, as well as a fixed structural framework has constrained its applicability. As a result, the anticipated adoption of this standardized data source by the industry has not materialized.

The importance of defining and managing properties necessary for different SIMs is widely recognized in the literature. Kamel and Memari address the need for various specialized properties for energy simulation in their BIM2BEM review [9]. Hauer et al. [12] propose a BIM2BEM approach centered on mechanical, electrical, and plumbing (MEP) planning, a key factor in a building's energy consumption. Their study outlines the essential properties required at each project phase and highlights the need for centralized management. To achieve this, they utilize the proprietary tool BIMQ[5]. Miller et al. in turn have focused on identifying which properties are necessary for day- and artificial light simulation [13]. These properties are have been made publicly available through the property server developed within the freeBIM projects.

BIM2SIM, especially BIM2BEM, has been the area of much research in recent years. Jansen et al. [14] present a semi-automatic BIM2SIM workflow using a BIM model of a dynamic hydraulic energy system (IFC file), *Modelica* as the simulation engine, and a middleware tool called *bim2sim*. *bim2sim* collects data, including properties from the IFC file, and transforms it into a format compatible with Modelica. It includes a simple model checker, supports additional Modelica-based SIM tools (requiring new plugins), performs unit conversions, validation checks, and prompts for missing properties during export.

Richter et al. [15] extend the middleware tool *bim2sim* developed by Jansen et al. [14] by introducing a new plugin, *PluginComfort*, which enables thermal comfort analysis. Existing thermal analysis property

[3] https://www.freebim.at/
[4] https://www.buildingsmart.org/
[5] https://www.bimq.de/en/

templates are extended and an evaluation of a use case has been presented, utilizing future weather scenario data.

A BIM2BEM approach supporting Revit[6] as BIM authoring tool and ModelicaBEM as SIM tool is presented by Jeong et al.[16]. A Model View Definition (MVD), a specification that defines the subset of data from an IFC schema required to support a specific use case in BIM, is used to minimize geometry-based interoperability issues between the BIM and SIM model. The same authors also propose a different approach [17], consisting of a two step process: 1.) expanding the data contained in the BIM model to include necessary properties for thermal simulation, 2.) transforming the BIM model to a SIM model compatible with Modelica by utilizing their Revit2Modelica prototype, running the simulation in an automated way and transferring the simulation results back into the BIM model, to facilitate assessment of the achieved results.

Guo et al. describe a multi-step semi-automatic BIM2BEM workflow using the gbXML exchange format [10]. This process involves several Revit plugins to clean and adjust geometry in the BIM model, which is then exported as a gbXML file. The gbXML file is verified and simplified with a custom tool, converted to the IDF format, and essential properties are added using their IDF checker. The final IDF file is compatible with EnergyPlus-based simulation tools.

3. Methodology

All research presented in this paper has been conducted in the context of the BIM2BEM-Flow research project, introduced in Section 2. We have decided to follow the Design Science Research Methodology (DSRM) [18] approach. DSRM is a rigorous research methodology that focuses on the systematic design, implementation, and evaluation of innovative artifacts to address complex, real-world problems, emphasizing both practical relevance and theoretical contribution. DSRM builds on the following activities [18]:

1. `Problem identification and motivation.` A model augmentation system is needed to enable continuous BIM2SIM workflows (see Sections 1, 2, 4).
2. `Definition of objectives for a solution.` Definition of requirements for such a system (see Section 5).
3. `Design and Implementation.` Definition of a conceptual workflow and the architecture of such a system; system implementation (see Sections 6, 7).
4. `Demonstration.` Continuous user tests and validation (see Section 7).
5. `Evaluation.` Scenario-based Proof-of-concept (PoC) evaluation (see Section 8).

A graphical representation of this process is shown in Figure 1.

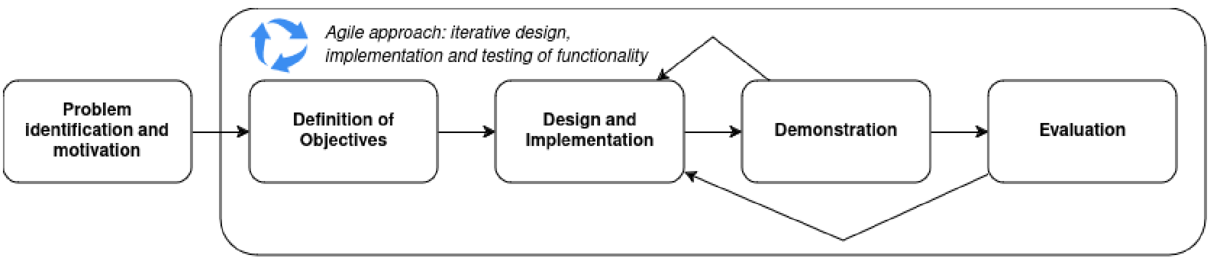

Figure 1: Graphical representation of the DSRM process utilized in the BIM2BEM-Flow project.

Numerous workshops and discussions have been held with the project partners, representing different stakeholders in the industry, with the goal of addressing these activities. Periodic bi-weekly meetings have been held between university partners, and a meeting between the full project consortium took place at least once every half year, often however as frequently as every six weeks to present new results

[6] https://www.autodesk.com/products/revit/

and gather fresh feedback. Additionally to the intra-project meetings, a workshop with Digital Findet Stadt (DFS) has been held, involving eleven companies working in the industry, where preliminary concepts were presented and invaluable feedback was gathered[7].

We have decided to follow these activities in an agile approach, iteratively building on preliminary results to create a comprehensive prototype. Every partial version has been tested and validated by all project partners.

4. BIM2SIM Model Interoperability Challenges

This section presents challenges pertaining to model interoperability and transformation in the area of BIM2SIM in more depth, based on the existing literature introduced in Section 1 and 2, complemented by insights originating from the BIM2BEM-Flow project and the workshop conducted with DFS[7]. Issues in model compatibility stem from various mismatches between BIM and SIM models:

- `Data`. Properties are missing in the BIM model, have no value / a wrong value set or are in a form that the SIM tool does not understand.
- `Model structure`. The geometrical composition of a structural BIM model often differs significantly from that of an analytical SIM model. SIM tools are mostly dependent on a certain way of geometrical modelling, which BIM authoring tools and actors do not enforce by default.
- `Exchange formats`. BIM models are typically stored in proprietary, company-specific formats, which are not understood by most SIM tools of other vendors. Model standards exist, but are not fully accepted or implemented on either BIM or SIM side.

4.1. Data Mismatches

As stated above, there are three types of possible *data mismatches* between a BIM model and the model necessary for a simulation:

1. Necessary properties are missing.
2. Properties have no value or a wrong value set.
3. Properties are semantically correct, but not in a form that is suitable for the SIM tool.

In the first case properties, which are necessary for simulation but not necessary for the design of the structure, are missing from the BIM model. Which properties are necessary is highly dependent on the kind of simulation that should be done as well as the tool used. Examples for such properties would be *conductivity* and *heat transfer coefficient*, which are necessary properties for energy simulation, and *reflexion*, which is a necessary property for lighting simulation. Since some SIM tools support different types of simulation, this is a necessary distinction.

In the second case, properties that are necessary for the simulation are included in the BIM model, but either no value or an incorrect value has been assigned. The most likely cause for this is missing domain knowledge of actors working on the BIM model. Additionally, the unavailability of certain value information during the early design stages may also contribute to this issue.

In the third scenario, a necessary property is included in the BIM model with a correct value assigned, but the property's format is not recognized by the simulation tool. There are two likely reasons for this: the property has a name that is not recognized by the simulation tool, or the property is in the wrong unit, e.g., meters (m) instead of centimeters (cm).

4.2. Structural Mismatches

SIM tools are often dependent on a certain way of geometrical modelling, which BIM authoring tools and actors do not enforce by default. For instance, accurately modelling the relationships between adjacent spaces is essential for correctly representing heat flows in a thermal simulation [19]. Architects

[7]https://www.digitalfindetstadt.at/news/news/anforderungen-an-eine-bim-basierte-gebaeudesimulation

Table 1
Example for a general property and property set definition, relevant for different kinds of simulations and SIM tools. Note: names have been translated from German and may not be exactly accurate.

Entity	Name	Relevant SIMs	Name DALEC	Name IES VE
Property	Heat transfer coefficient	Comfort	U-Value	Thermal transmittance coefficient
Property	Illuminance	Light	Illu_Close/Far	RadianceIES_Illuminance
Property set	Pset_Room	any	ASI_Room	IESVE_Room
Property set	Pset_Window	any	ASI_Window	IESVE_Glazing

typically design building components with extended boundaries, so to correctly simulate heat flows, it's necessary to intersect walls and ceilings to determine connections between rooms.

4.3. Exchange Format Mismatches

BIM models are typically stored in proprietary, company-specific formats, which are not understood by most SIM tools of other vendors. Model standards like IFC and gbXML exist, but are not fully accepted or implemented on either BIM or SIM side. For example, the BIM authoring tool Revit was unable to export space thermal zone information to gbXML in the study conducted by Kamel and Memari [9].

5. Strategies and System Requirements for enabling BIM2SIM: the BIM2BEM-Flow Perspective

Strategies for addressing BIM2SIM model mismatches are diverse and depend significantly on the involved tools, simulations, and specific project contexts. This section outlines strategies for managing model mismatches from Section 4 within the BIM2BEM-Flow project and presents software requirements for a BIM2SIM model augmentation system.

5.1. Dealing with Data Mismatches

To address data mismatches between BIM and SIM models, a Single Source of Truth (SSoT) is needed to manage properties which are necessary for simulations. Within this data source, it must be possible to define properties and for which SIM tools and what kinds of simulations they are relevant for. Additionally, associated entities, such as sets of properties and the model elements (corresponding to construction components) the properties are pertinent for, must be managed. Generally, one property is often relevant for different kinds of simulations and SIM tools. The basic semantic definition stays the same (e.g. data type, description), it may however exhibit a different name and/or unit in a different SIM tool. This multimorph nature necessitates a kind of mapping functionality between properties and simulation tools. The same holds true for property sets. Mapping functionality for model elements is an essential part as well, in order to be able to support augmentation of models of arbitrary BIM authoring tools. Examples for this kind of multimorph nature of data entities can be found in Table 1 and Table 2. Providing the described functionality makes it possible to *automatically infer* which properties in what form are relevant for which SIM tools and which model elements they belong to. This constitutes the base for any (semi-)automatic model augmentation application.

Additionally, due to the highly specialized knowledge necessary to sensibly define values for properties, functionality to define sets of context-specific default values must be provided. These enable key BIM stakeholders, such as architects and engineers, to enhance a BIM model effectively without the need for highly specific domain knowledge. Additionally, default values facilitate meaningful simulations in the early stages of planning, when not all design decisions have been finalized and various assumptions about the project's future trajectory, such as material choices, are still being considered.

Table 2
Examples for a general construction component, its equivalent in the IFC as well as different BIM authoring tools. Note: names have been translated from German and may not be exactly accurate.

Construction component	IFC	Revit 2024	Allplan 2020
Wall	IfcWall	Walls	Wall
Space	IfcSpace	Rooms	Room
Roof	IfcRoof	Roofs	Roof

In order to actually augment a BIM model, a second software component is needed. A so-called model Augmentation Application (AA), leveraging the data and semantics defined in the SSoT, must be implemented to enhance a BIM model to yield a usable SIM model. An additional component should be implemented to check the BIM model for missing or incorrect values. This model checker will use the BIM model, context information, and default-value sets to verify successful augmentation and transformation into a viable SIM model.

5.2. Dealing with Structural Mismatches

What structural mismatches are encountered between a BIM and a SIM model is highly dependent on the tools used for managing each model, including specific tool versions, as well as the type of simulation being conducted. Depending on this context, the first step to addressing structural mismatches is establishing precise modelling guidelines that outline the necessary adaptations in the BIM model to produce a viable SIM model. These guidelines, which describe the geometric modeling of structures, must be developed by domain experts. They can be utilized directly by BIM practitioners to manually create models that align with specific SIM tools, or they can serve as the basis for (semi-) automated model transformation systems.

5.3. Dealing with Exchange Format Mismatches

Due to the prevalence of proprietary formats in both BIM and SIM tools, exchange format mismatches are inherent in any BIM2SIM workflow involving tools from different vendors. To address these mismatches in the context of openBIM, it is essential to utilize standard exchange formats such as IFC or gbXML. As previously noted, no standard is fully accepted or implemented across both BIM and SIM platforms. Nonetheless, IFC and gbXML are still under active development, and continued research into their use will promote their future acceptance and growth.

5.4. Requirements for a Model Augmentation System

Based on the solution strategies presented in this section, requirements for a software system capable of supporting model augmentation to achieve BIM2SIM can be synthesized.

Addressing data mismatches has so-far been the main focus of the BIM2BEM-Flow project. Specific functional requirements for both the Single Source of Truth as well as the Augmentation Application component have been extracted to satisfy the necessary functionality described in 5.1. A detailed listing of these can be found in table 3 and 4.

With respect to structural mismatches, modeling guidelines will be established by simulation experts as part of the BIM2BEM-Flow project. However, the presentation of these guidelines is beyond the scope of this paper. The development of (semi-)automatic model transformation systems based on these guidelines will be addressed in our future work.

In the context of adhering to openBIM principles, the issue of exchange format mismatches is best tackled by utilizing standard exchange formats like IFC or gbXML. In the BIM2BEM-Flow project, we have opted for the IFC, since it is dynamically extendable, able to handle complex models and most commonly used in practice.

Table 3
Functional requirements for the Single Source of Truth.

ID	Name	Description
SSoT-FREQ1	Management of core data entities	The system must support the management of properties, sets of properties (for organizational purposes) and model elements. Additionally, properties may be added to / removed from property sets, and properties or property sets may be associated / disassociated from model elements.
SSoT-FREQ2	Management of related entities	The system must support the management of supported SIM tools, simulation types and users. Furthermore, the system must provide means to define which properties are relevant for which simulation types.
SSoT-FREQ3	Mapping functionality	The system must offer functionality to define mappings, name and unit, for properties and different SIM tools. Additionally, it must be possible to map property sets across different SIM tools, and map model elements to various BIM authoring tools.
SSoT-FREQ4	Property inference algorithm	To support automatic model augmentation, the system must provide an algorithm that is capable of automatically inferring what properties are relevant for which simulations / SIM tools.
SSoT-FREQ5	Default value management	The system must support the management of sets of default values for properties.
SSoT-FREQ6	Data import	In order to access external data sources as well as for reasons of user friendliness, the import of data (properties, property sets, model elements as well as associations between them and mapping data) needs to be provided.
SSoT-FREQ7	Data export	The defined data must be accessible from outside the system in order to enable model augmentation applications. This may be done by offering a file export and/or an API.
SSoT-FREQ8	Versioning	To ensure consistency as SIM and BIM tools evolve, the system must implement versioning for data entities, including properties, property sets, model elements, and their mappings.
SSoT-FREQ9	User role mangement	Different roles for users should be supported. Identified meaningful roles are: *System Administrator* (User and role management), *Editor* (data management), *Viewer* (read-only access to the data) and *Reviewer* (responsible for managing and publishing versions).

6. Architecture and Conceptual Workflow of a BIM2SIM Model Augmentation System

Building on the solution strategies and requirementes discussed in Section 5, we present possible architectures of a model augmentation system able to solve the issue of data mismatches in the BIM2SIM domain. The proposed architectures combined with a conceptual workflow of a BIM2SIM model augmentation system can be found in Figure 2.

At the heart of the system is the aforementioned Single Source of Truth. This component defines and manages properties as well as associated entities such as property sets and model elements. It includes mapping functionality to handle differences in properties, property sets and model elements across various BIM and SIM tools. A property inference algorithm is implemented, which allows to automatically determine what properties are relevant for which workflow. Workflow meta data consists of the used BIM authoring tool, SIM tool and type of simulation. Additionally, it provides functionality to manage context-specific default values to enhance BIM models without requiring specialized domain knowledge.

The second part of the system is constituted by the model Augmentation Application. Here, the BIM model will be augmented to yield a model usable by a SIM tool, using the data and semantics defined in the SSoT. Additionally, a model checker module is needed to ensure that an augmented model is ready

Table 4
Functional requirements for the Augmentation Application.

ID	Name	Description
AA-FREQ1	Model import	The system should import BIM models efficiently by supporting open exchange formats like IFC or gbXML.
AA-FREQ2	Model export	After augmenting the BIM model, it must be exportable for use in SIM tools.
AA-FREQ3	Workflow definition	The system must allow users to create workflows defining metadata for model augmentation, including the BIM authoring tool, SIM tool, and simulation type, which is then used by the SSoT to identify relevant data.
AA-FREQ4	SSoT Connector	The system must be able to access the data defined in the SSoT. Depending on the SSoT implementation, this may be done by importing data exported by the SSoT or accessing its API.
AA-FREQ5	Basic model augmentation	The imported model is augmented by creating necessary properties, property sets and associating them with the correct model elements.
AA-FREQ6	Extended model augmentation	Functionality to provide values for the properties created in AA-FREQ5 needs to be implemented, with default values from the SSoT made available.
AA-FREQ7	BIM model synchronization	It must be possible to merge changes in the underlying BIM model, even after model augmentation has begun.
AA-FREQ8	Model checker	The basic version of this component should verify that all necessary properties are included and assigned values, with extended versions adding semantic checks.
AA-FREQ9	User and user role management	Different users and roles for users should be supported. Identified meaningful roles are: *System Administrator* (User and role management), *Workflow Manager* (import/export of the model, workflow management, access to model checker), *Model Augmenter* (augments the model with the necessary data and defines values for the created properties, access to model checker) and *Viewer* (read-only access to workflows and models)

to be transferred to the SIM tool. As depicted in Figure 2, there are two options this application can be implemented, both with their own advantages and disadvantages.

In *Option 1*, the AA is implemented as a part of a BIM authoring tool. Typically, this will be done in the form of a plugin, which most notable non open-source BIM authoring tools allow (e.g. Revit, ArchiCAD, Allplan). Export of the model in an open exchange format must be supported, either natively by the BIM authoring tool itself or by the plugin. The advantages of this approach inlcude offering the user working on the BIM model a familiar environment and functionality, greatly reducing the learning curve and increasing acceptance. Another notable benefit is real-time synchronization: changes in the BIM model can be integrated into the SIM model in real-time. Disadvantages of this approach include that the application is BIM authoring tool dependent, and a new plugin is needed for each BIM authoring tool that is to be supported.

In *Option 2*, the AA is implemented as an independent system outside of the BIM authoring tool. One or more open exchange formats need to be supported for import and export. The advantages of this approach include platform independence - only one such application must be implemented to support any number of BIM authoring tools that provide a supported exchange format. Disadvantages of this approach include a higher learning curve for the users as well and a disjointed workflow. An additional significant drawback is the more challenging synchronization of changes in the BIM model with the already augmented model.

In the following, a conceptual workflow of the whole model augmentation process is presented to aid with understanding. The steps are visually represented in Figure 2.

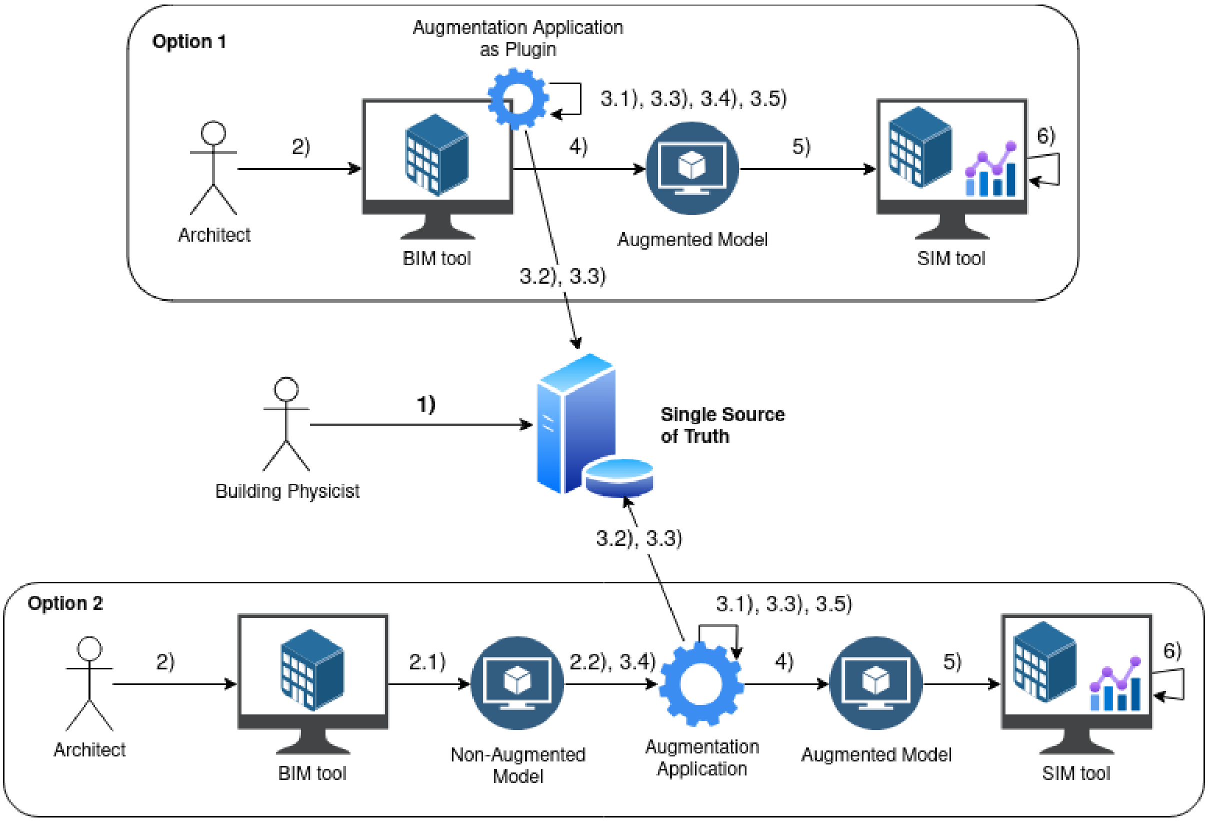

Figure 2: Basic schematic architecture of a BIM2SIM model augmentation system.

1) Properties, property sets and model elements as well as associations between those entities and mapping data are defined on the SSoT.

2) The BIM model is created / edited.

   2.1) and 2.2) The non-augmented BIM model is exported from the BIM authoring tool and imported into the AA.

3) Model augmentation is started.

   3.1) A workflow is created in the AA, defining which BIM authoring tool is used and for which type of simulation and SIM tool the model should be augmented.

   3.2) The relevant properties and property sets are gathered from the SSoT, and are associated with the correct model elements. The workflow meta data (BIM authoring tool, SIM tool, type of simulation) is used as input for the property inference algorithm to determine what data is relevant.

   3.3) The user is defining values for the created properties. Default values defined on the SSoT may be used.

   3.4) Synchronize changes made in the BIM model with the augmented SIM model.

   3.5) Use the model checker to determine whether the BIM model has been fully and correctly augmented.

4) and 5) Export the augmented model using the AA and import into it the SIM tool.

6) Run the simulation.

7. Implementation

A prototype of the BIM2SIM model augmentation system was developed as part of the BIM2BEM-Flow project. This initial version serves as a technical proof-of-concept for preliminary evaluation, rather than a complete software application. The created prototype realizes the following requirements for the SSoT (see table 3):

- SSoT-FREQ1 Management of core data entities
- SSoT-FREQ2 Management of related entities
- SSoT-FREQ3 Mapping functionality
- SSoT-FREQ4 Property inference algorithm
- SSoT-FREQ5 Default value management
- SSoT-FREQ7 Data export

As of the latest version, SSoT-FREQ6 (Data import), SSoT-FREQ8 (Versioning) and SSoT-FREQ9 (User and user role management) remain future work. Additionally, to simplify the mapping process, it is currently not possible to map property units. The SSoT has been implemented as a Spring Boot web application with an Angular frontend and a REST-API is offered to access data from outside the SSoT. The software is called YAPS (**Y**et **A**nother **P**roperty **S**erver). An overview of the architecture can be found in Figure 3.

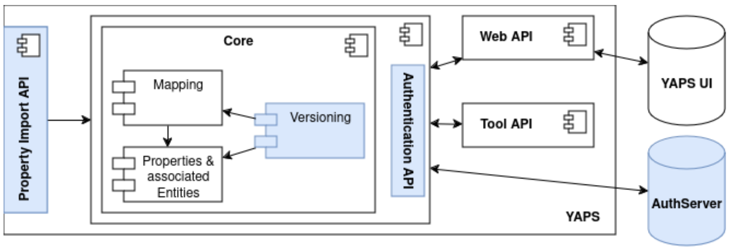

Figure 3: Architecture of the YAPS system. Components in blue remain future work.

The *Core* component encapsulates the main business logic. Properties, necessary adjacent entities and default sets can be created and managed. Most importantly, however, flexible mapping functionality is offered for all core entities. The *Tool API* component is responsible for offering the data stored on the YAPS via a REST API to external applications, such as our AA application. Complementing the Tool API, a *Web API* is offered, which provides the functionality to create and edit data. This API is used by our YAPS Angular UI.

We have decided to implement the AA as a plugin to the BIM authoring tool Revit, which corresponds to implementation option 1 as introduced in Figure 2. This has the advantage of providing requirements AA-FREQ1 (Model import), AA-FREQ2 (Model export) and AA-FREQ7 (BIM model synchronization) out of the box. Further implemented requirements encompass (see table 4):

- AA-FREQ3 Workflow definition
- AA-FREQ4 SSoT Connector
- AA-FREQ5 Basic model augmentation system
- AA-FREQ6 Extended model augmentation
- AA-FREQ8 Model checker

As of the latest version, AA-FREQ9 (User and user role management) remains future work. A simplified model checker has been implemented to verify that all relevant properties are present and assigned in the BIM model, without performing further semantic checks. The AA is called RWM (**R**evit **W**orkflow **M**anager) and connects to the YAPS via the Tool API.

Functional correctness of the YAPS and RWM has been ensured by comprehensive unit testing as well as periodic user test. The group of test users included all project partners.

8. Evaluation

To evaluate the usefullness of our proposed system, we have conducted a scenario-based evaluation, comparing our approach to previous work published by some of the authors.

8.1. BIM2BEM with Revit2DALEC

Miller et al. describe a BIM2BEM approach using Revit as the BIM authoring tool and DALEC[8] as the SIM tool, which supports integrated day- and artificial light simulation as well as energy calculation as simulation type [20]. A plugin for Revit, called Revit2DALEC, has been implemented to assist users in augmenting the BIM model and exporting it as an IFC file compatible with DALEC. Relevant properties and property sets have been provided by domain experts in a reusable format. Additionally, DALEC itself provides default values for the early planning phases.

To integrate simulation-specific properties into the BIM model, a (Revit specific) so-called shared parameter file must be imported into Revit. While a default import file is available, any required or desired changes must be made manually. The adapted file is then usable only within the same Revit project. During import, a mapping text file is generated to configure the IFC export through Revit2DALEC, allowing the BIM model to be exported as an IFC file compatible with DALEC. This IFC file is subsequently used by the DALEC simulation kernel, which operates independently of the Revit2DALEC plugin.

While the approach presented offers benefits, it has notable limitations. It is specific to DALEC, limiting compatibility with other simulation tools. Additionally, data management and property mapping are confined to Revit, restricting the approach to this BIM authoring tool and assigning tasks to architects beyond their core expertise and responsibilities.

8.2. BIM2BEM using the proposed Model Augmentation System

We have realized the same scenario presented in [20] to evaluate the viability of our proposed model augmentation approach. Closely following the conceptual workflow introduced in Section 6, we present the steps necessary to enable BIM2SIM in the described scenario:

1) Relevant properties, property sets, their association to model elements as well as mapping data relevant for the SIM tool DALEC are defined on the YAPS (see screenshot in Figure 4).

2) The BIM model is created / edited in Revit.

    2.1) and 2.2) Since the AA is implemented as a plugin in Revit (called RWM), no export of the non-augmented BIM model nor its import into the RWM is necessary.

3) Model augmentation is started.

    3.1) A workflow is created in the RWM, defining that the BIM model created in Revit should be augmented for the SIM tool DALEC and the simulation type day- and artificial light simulation and energy calculation.

    3.2) The relevant properties and property sets are requested from the YAPS, based on the workflow meta data defined in the previous step, and created automatically in Revit. Based on the information defined in the YAPS, automatically associating them with the correct model elements is done.

    3.3) The user defines values for the created properties. Default values defined on the YAPS may be used. A screenshot of the implemented property editor as part of the RWM can be found in Figure 5.

    3.4) No synchronization of changes in the BIM model with the augmented model is necessary, since all changes are directly done in the BIM model. Augmentation of changes takes place automatically.

    3.5) A basic first version of a model checker is used to ensure the augmented model contains all relevant properties and for all of them a value is assigned.

4) and 5) Export the augmented model using the RWM and import into DALEC. Mapping information defined on the YAPS is used to automatically configure the export and ensure compatibility with DALEC.

6) The exported model has then been used successfuly for simulation in DALEC.

[8]https://www.uibk.ac.at/bauphysik/forschung/projects/dalec/index.html.en

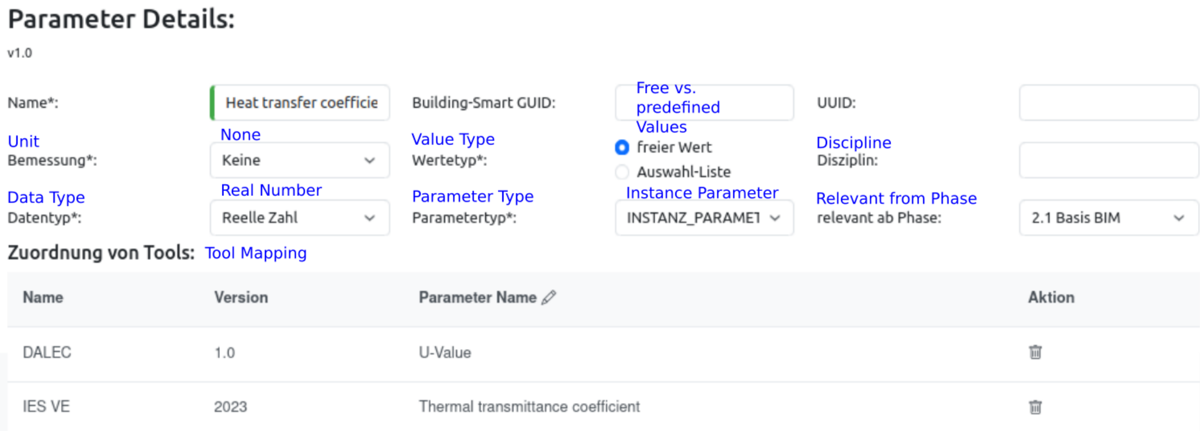

Figure 4: Screenshot of the property detail view in the SSoT. The defined property contains mapping information for two SIM tools, DALEC and IES VE.

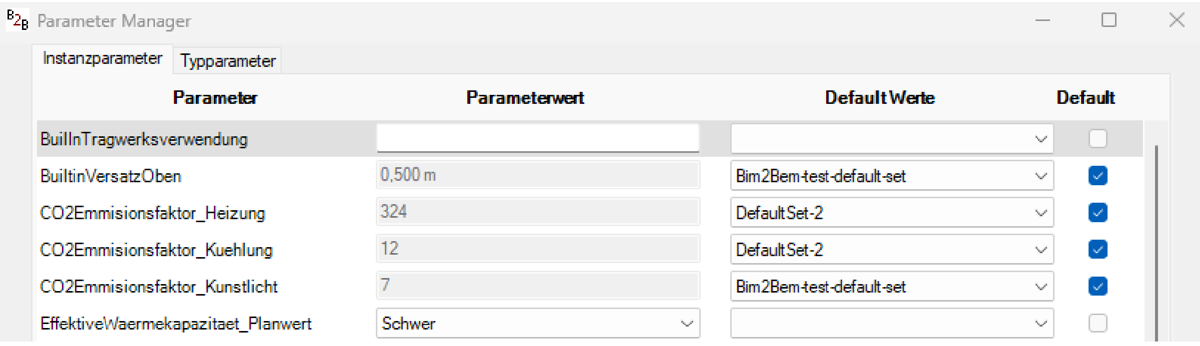

Figure 5: Screenshot of the property editor in the AA plugin in Revit. Parameters for a specific workflow (BIM tool, SIM tool and simulation type) are shown and values can be set. It is also possible to choose default values.

8.3. Comparison and Discussion

While both approaches enable BIM2BEM, our method resolves key issues identified in Miller et al. [20]. Unlike the previous method, which relies on DALEC and Revit for property management, our system is independent of specific SIM tools, allowing for alternatives like IES VE while reusing the same properties defined on the YAPS. By re-defining only the necessary mapping information, we effectively reduce redundancy. Addtionally, by moving property management outside the BIM tool, responsibilities are clarified: building physics specialists handle data management, allowing architects to focus on their core tasks, and reducing the potential for errors.

In conclusion, our approach not only successfully enables a continuous integrated BIM2SIM (specifically BIM2BEM) workflow but also offers significant improvements over previous methods. By substantially reducing the entry barriers for users with limited technical and simulation-focused expertise, our approach broadens the accessibility of BIM2SIM to a wider range of stakeholders. Furthermore, the separation of concerns incorporated into our methodology enhances time efficiency, thereby reducing the time required for users of different roles to become proficient with the system. However, a more detailed evaluation encompassing all specified functionality for the SSoT and AA as well as tests with a multitude of SIM tools is necessary for a full-fledged evaluation. This is out of scope for this paper, but is part of our future work.

9. Conclusion and Future Work

This paper has presented a novel BIM2SIM approach, utilizing model augmentation and transformation strategies to address the research questions defined in Section 1: (RQ1) How can continuous integrated open BIM BIM2SIM workflows be enabled? (RQ2) How can the properties necessary for different kinds of simulation be managed in an efficient way? (RQ3) How can the different actors (architects, simulation specialists) be supported in their work?

To address RQ1, the challenges of BIM2SIM instance model interoperability have been systematically analyzed, drawing upon both existing literature and insights from the BIM2BEM research project. These challenges primarily include data mismatches, structural mismatches, and exchange format inconsistencies. This study has concentrated specifically on addressing data mismatches, presenting the specification of a model augmentation system designed to overcome these obstacles. The system specification encompasses a detailed requirements definition, system architecture, and a conceptual workflow, addressing RQ2. RQ3 is addressed by allowing architects and simulation specialists to focus on their core expertise: architects can use inferred properties and sensible defaults without needing detailed building physics knowledge, while simulation specialists can base their work on the existing BIM model without re-creating the structure.

To substantiate our research, we developed a prototype implementation of the proposed system and conducted a preliminary evaluation. The results indicate that our approach is less error-prone, reduces redundancy, allows for broader user accessibility, and improves time efficiency compared to a previously published approach. While the preliminary results are promising, significant future work remains in advancing this BIM2SIM approach. Currently, a comprehensive implementation of the proposed system, incorporating all specified requirements, is underway. This system will serve as the foundation for necessary, more extensive evaluations, which will involve a broader range of SIM tools and simulation types. Additionally, future research will investigate the development of a (semi-)automatic model transformation system [21, 22], guided by the modelling guidelines established in the BIM2BEM-Flow research project. We also intend to apply the Technology Acceptance Model (TAM) framework, conducting a formal user survey to evaluate our approach in a standardized manner.

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