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Sustainable Heritage Transformation: Bridging BIM and Simulation Processes

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Abstract

Integrating Heritage Building Information Management (HBIM) into historic building preservation presents challenges despite its potential for structured information management and collaborative, data-driven processes. This research proposes a framework for integrating energy performance and lifecycle simulations with HBIM in the case study UNESCO site Speicherstadt in Hamburg.

Structuring BIM models into information containers enhances information availability. A user-oriented workflow enables non-BIM experts to make modifications. An innovative interface is proposed to simplify access, query, and manipulation of BIM data. While no single standard can ensure complete interoperability, the promotion of open standards such as Industry Foundation Classes (IFC) and Open-Source Software (OSS), contributes to the improvement of interoperability and the democratization of built heritage information. The interface allows stakeholders to directly add and modify discipline-specific data, improving accessibility.

The research acknowledges workflow challenges in the BIM ecosystem, such as data compatibility, user experience, and collaboration. It contributes to the ongoing data quality and consistency debate, focusing on leveraging HBIM for sustainable historic building preservation. The developed concept emphasizes HBIM models, user-oriented workflows, open standards, and accessible data structures to address heritage building conservation needs while enabling efficiency simulations and assessments.

Introduction

Germany targets achieving zero net emission buildings by 2045 (*BMUV: Bundes-Klimaschutzgesetz* 2021), prioritizing increased use of renewable energy and sustainable renovation of the building stock. A particular challenge in this context is adapting historical and heritage buildings to these needs while retaining their authenticity. One exemplar case is the Speicherstadt in Hamburg, the world's largest cluster of port warehouses, protected since 1991 together with the Kontorhausviertel, Europe's first pure office district. Both of them were designated UNESCO World Heritage sites in 2015.

The 'CO2 Neutrales Weltwerbe Speicherstadt' project (0-CO2-WSHH) aims to transform the Speicherstadt into a climate-neutral complex through heritage-oriented retrofitting and energy integration (Teichmann et al. 2024). This involves the development of a workflow coupling Building Information Management (BIM) and Building Energy Model (BEM), LifeCycle Assessment (LCA), Computational Fluid Dynamics (CFD), and Thermal-Hygric (THS) simulations. The main goals are to document retrofit measures, energetically assess the neighborhood, implement a redevelopment concept, explore innovative energy retrofitting techniques, and analyze the potential of roofing inner courtyards for energy efficiency.

Within this framework, the BIMLab at HafenCity University Hamburg (HCU) develops a Heritage BIM (HBIM) model and workflow for a specific building block of the Speicherstadt to facilitate and centralize data exchange. This serves as a basis for building performance and lifecycle balance simulations carried out by the Institute of Construction Materials (IWB) at University Stuttgart.

Assessment Methods

The 0-CO2-WSHH project employs a multi-faceted approach, integrating simulation methods to assess sustainability initiatives. It evaluates energetic, ecological, and flow dynamics, guiding decisions for energy efficiency, ecological sustainability, and occupant comfort. This aligns with the long-term vision of a CO2-neutral and heritage-compatible Speicherstadt.

- **Building Energy Model (BEM) Simulation** analyses energy consumption and assesses efficiency and potential for improvement. BEM simulations optimize energy use by exploring scenarios with various energy-efficient components and systems. IDA ICE software accurately maps and models the building, its systems, and its controls. This enables detailed analysis and improvement of building performance and occupant comfort. It allows the import of some building elements, spaces, and properties of simplified Industry Foundation Classes (IFC) 2x3 files as a starting point for the simulation.

- **LifeCycle Assessment (LCA)** provides a comprehensive ecological evaluation of projects, considering environmental impacts from material extraction to decommissioning. This ensures alignment with Speicherstadt's environmental goals. The LCA software MultiVaLCA, developed by IWB, facilitates interval-based evaluation of product environmental impacts through features such as complex system modeling, impact assessment calculations, and sensitivity analysis. The MultiSim software (currently in development) can calculate the annual energy consumption for buildings. These two software programs can jointly conduct an ecological assessment for the renovation of the target building and do not import IFC files or any 3D model.

- **Computational Fluid Dynamics (CFD) Simulation** optimizes ventilation systems in buildings, ensuring compliance with efficiency and comfort standards while minimizing energy consumption. The software STAR-CCM+ enables exploring the possibilities of products operating under real-world conditions. It can import IFC files with solid elements like walls and beams but does not support spaces, openings, and some properties, ignoring them in the import.

- **Thermal-Hygric Simulation (THS)** evaluates moisture performance in various climates, optimizing insulation, preventing moisture issues, and enhancing comfort and durability. The DELPHIN simulation software, specialized in coupled heat, air, moisture, pollutant, and salt transport in building materials, assesses thermal calculations and insulation design. It does not import IFC or any kind of 3D models and is not designed for simulating entire buildings but for individual components or component design.

Heritage Building Information Management

HBIM, a specialized BIM approach, focuses on the specific needs of historic structures (Murphy et al. 2009). Based on BIM, HBIM enables the integration of all aspects of a building's lifecycle, like geometry, data, and process flow, into a unified model or repository (Andrich et al. 2022), enabling efficient simulations, testing, and information management, such as construction documents, and material quantities (Barlish & Sullivan 2012). HBIM enriches models with non-geometric data, covering historical-constructive sequences, cultural documentation, maintenance details, and environmental data (Barontini et al. 2022). This approach addresses preservation and management challenges unique to the singularity of historic buildings.

Simulations-HBIM Integration Challenges

Integrating BIM into heritage project simulations presents a challenge due to varied software requirements. Specialized approaches can ensure accurate, efficient, and successful simulations. Major challenges encountered during the project include:

- **Software Interoperability.** Importing BIM models into software, where possible, may demand significant computing resources, especially for detailed BIM models. Underdeveloped integration tools complicate power and time management, while the diversity of simulation software landscape and data formats pose interoperability problems, including inconsistent compatibility with IFC files (Gerbino et al. 2021).

- **Information Management.** Historic buildings present complicated and case-specific information that is difficult to standardize (Mansuri et al. 2022). The data updating process magnifies these problems by requiring the integration of changes and new requirements throughout the building's lifecycle. The dynamic nature of buildings should be addressed, as it demands the seamless integration of new data as it is gathered to ensure that it remains updated and available.

- **Data Challenges.** Historical building information may be dispersed over time, leading to potential loss of access. Therefore, data uncertainty in models and processes needs to be addressed. Misinterpretation or transcription errors by BIM modelers, who may lack deep domain knowledge, can also result in incomplete or inaccurate data.
- **Stakeholder Collaboration.** Varying BIM knowledge levels among stakeholders can hinder information extraction from complicated BIM data structures (Liu et al. 2023). The absence of standardized collaboration processes across disciplines with different methodologies and software further complicates teamwork. Successful collaboration requires engaging all stakeholders, aligning concerns and preferences, clarifying BIM goals, promoting effective communication, and encouraging information exchange (Daniotti et al. 2022). User-oriented tools for integrating data can boost interest in the BIM framework.

BIM Models as Data Repositories

BIM is a methodology that centralizes data for efficient management of construction and operation processes, facilitating retrieval, modification, and analysis. This enhances project management and operational efficiency.

Despite increased use in design and construction, BIM's application in post-construction phases remains limited (Saricaoglu & Saygi 2022), especially for facility and occupancy management, maintenance, and refurbishment (Daniotti et al. 2022). This limitation becomes more pronounced in the context of heritage buildings with complicated histories of alterations and changes of use. Challenges include data acquisition and modeling processes, while costly proprietary software with compatibility issues impedes data exchange and collaboration.

Aging buildings lose valuable construction details and material information over time, requiring costly and invasive tests to determine material's attributes (Lasarte et al. 2021). Limited resources often make testing impractical, increasing uncertainty. This underscores the need for innovative solutions to capture and preserve this fading wealth of knowledge.

Databases play a fundamental role in information management, providing structured data organization and retrieval. BIM models serve as specialized repositories for the construction industry (Coli et al. 2022), which, when combined with specialized tools, can offer database-like features. These include data structure, integrity rules, querying, concurrency control, security, and scalability. BIM models interconnect geometry, spatial relationships, building properties, material specifications, cost data, and construction schedules for efficient queries, manipulations, and analyses (Sagarna et al. 2022).

Enhancing data accessibility for all stakeholders requires innovative approaches (Mansuri et al. 2022), like establishing instruments that enable the use of BIM models as 'databases' accessible to all stakeholders, streamlining information management, allowing the interlinking of diverse datasets, improving operational efficiency, and providing insights for informed decision-making and strategic planning. This approach allows stakeholders to input data, prevent interpretation errors, extract valuable information, conduct simulations, and contribute to optimal building performance across lifecycles.

Information Management

Standardizing information requirements enhances collaboration and streamlines processes throughout the project lifecycle. This applies across disciplines, like design, construction, and facility management, promoting interoperability for efficient information interpretation, exchange, and utilization (*Zukunft Bau* 2021).

The IFC schema, regulated by DIN EN ISO 16739-1 (*DIN EN ISO 16739-1* 2021) and developed by buildingSMART International (bSI), is a vendor-neutral standardized format (Borrmann et al. 2018) that enables the exchange of BIM models. IFC files organize building data, covering aspects like geometry, spatial relationships, and component properties. By adopting an object-oriented modeling approach, the schema ensures interoperability among software tools (Khan et al. 2022), overcoming the barriers proprietary formats pose in construction projects.

The Level of Information Need (LOIN) (*DIN EN 17412-1* 2020) manages information complexity in BIM collaboration, specifying required information depth at different project phases (Daniotti et al. 2022). LOIN aligns stakeholder expectations (*buildingSMART International* 2022), enhancing collaboration and decision-making throughout the project lifecycle. A BIM model, using the IFC schema, serves as a data repository (Khan et al. 2022) organized based on project-specific LOIN. In the Speicherstadt context, developing a comprehensive LOIN proved challenging, as multiple aspects, like energy efficiency, turbulence behavior, and ecological footprint had to be considered simultaneously before the LOIN could be used for accurate inventory and data collection. Technical objectives of the project include seamless data transfer to the IFC schema and establishing a control system for data integrity and consistency, improving communication and understanding among stakeholders.

Existing buildings have diverse, sometimes inaccessible, or unreadable information formats, such as old plans or documents in various digital and physical file structures. These documents often contradict or do not match, requiring user interpretation or costly surveys. The use of a central data repository provides a unified source for stakeholders, accessible even to those unfamiliar with BIM. Abstracting semantic information from 3D visualization allows simulators to access data by semantic searches, facilitating BIM data usage for a wider range of stakeholders.

Before explaining the workflow for mapping the LOIN to the IFC schema, a few concepts central to IFC need to be described. As the IFC schema is based on an object-oriented modeling paradigm, each element related to a building is considered an entity, such as IfcSite, IfcSpace, and IfcWall. An entity can store geometric and alphanumeric data, documenting both its spatial features and semantic properties. These entities are hierarchically organized, with parent entities defining common properties inherited by their children (Figure 1).

Any relation between entities is itself an entity too, which ensures machine-readability of not only objects but also their relations with each other. Furthermore, it allows for templating common properties for multiple entities, promoting consistency and reducing redundancy. The same applies to properties, quantities, their sets, materials, and element types (groups of similar elements), each of which is also an entity. Entities act as a data container with a Global Unique Identifier (GUID), allowing changes to be tracked by comparing different versions of the same project.

A property set stores a collection of properties,

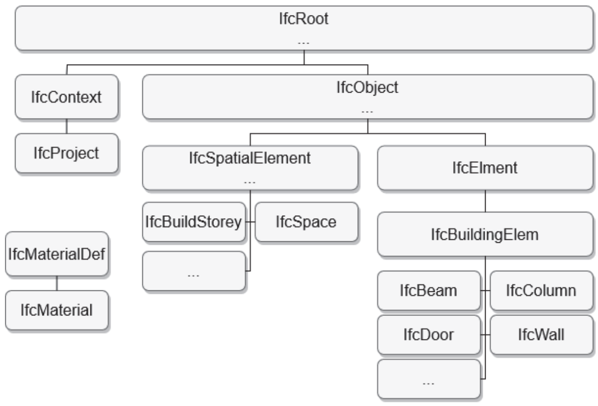

Figure 1: Extract from the hierarchy between entities according to bSI IFC schema

which can then be added to entity types or specific instances of that entity. The IFC schema predefines properties and property sets. However, depending on the specific LOIN of each project, custom properties and property sets may be necessary. Working with the IFC schema gives the possibility to integrate in a structured way properties and property sets not predefined in it. This is an important prerequisite for the approach chosen in this project.

When defining and adding properties, the IfcMeasureResource for value types and the partial concept template for data templates have to be considered. A property can store common value types like IfcInteger, IfcReal, IfcBoolean, and IfcText but the schema is also equipped to store other value types such as IfcDate, IfcTime, and IfcPositiveLengthMeasure. Apart from value types, there are data templates, of which bSI defines five: Single, Bounded, Enumerated, List, and Table Value, depending on the kind of data to be stored in each property. When defining the LOIN to add new properties to a BIM model, stakeholders need to ensure that the correct value type and data template are chosen.

To meet the needs of various stakeholders simultaneously in a project's LOIN, it is necessary to identify, summarize, and consolidate common property requirements. These are organized into property sets, some of which may not be part of standard properties listed by bSI, requiring the creation of project-specific property sets. In the 0-CO2-WSHH project, these property sets are labeled with the 'WSHH_' prefix for easy management and access by the stakeholders.

In the project, the LOIN was created as a spreadsheet, including details such as IFC Mapping, Property Set, Property Name, Data Template, Value

Ifc Mapping	Property Set	Property Name	Data Template	Value Type	Unit	Notes
IfcSpace	WSHH_ Indoor Climate	Inside Temperature	Bounded Value	Ifc Thermodynamic Temperature Measure	°C	(...)
IfcWall	WSHH_ Results BEM	HeatLoss	Single Value	IfcPower Measure	W	(...)
...	...	...	...	...	...	...

Figure 2: Extract from the stakeholders' LOIN

Type, Unit, and Notes, as shown in the example in Figure 2. The process of creating the LOIN is iterative, so it must be adapted as stakeholders' requirements change throughout the lifecycle of the building. By implementing these practices, stakeholders can efficiently manage data for various disciplines and projects within a BIM data repository.

Bridging the Gap: Interface between BIM and Simulations

Using BIM models as central repositories faces challenges in data type compatibility and IFC schema usage across different modeling and simulation programs. Widely adopted proprietary simulation and modeling software often have incomplete IFC schema implementation, prioritizing proprietary data formats and leading to unreadable data or loss during exchange with both proprietary and Open-Source Software (OSS) (Gerbino et al. 2021). Prioritizing long-term interoperability and data access suggests adopting open standards and formats that are readable without relying on specific software vendors. Achieving this requires significant efforts and resources from simulation and modeling software developers to implement the evolving IFC schema in both proprietary and OSS, with OSS currently having more complete IFC implementation.

To overcome the challenges presented previously, a web interface between the HBIM model and simulations is developed within the 0-CO2-WSHH project. This approach relies on the IFC schema for standardized, open, and consistent information exchange, ensuring the long-term readability and usability of the HBIM model. This unified interface bridges the gap between BIM and simulators and other stakeholders without BIM knowledge, allowing them to directly add and modify their discipline-specific data, without requiring the BIM modeler to interpret and enter the data as an intermediary. This enhances accessibility and ease of use, fostering a collaborative environment that meets diverse stakeholder needs.

Furthermore, the use of OSS and open-source libraries promotes this centralized information management approach by overcoming compatibility issues. OSS, publicly distributed programs, allow users to run, study, and adapt them within the scope of their licenses (Wong & Sayo 2004). Depending on the license, modified programs can be redistributed. This flexibility, especially in permissively licensed software, aids in tailoring software for specific needs. Leveraging, extending, and building upon existing OSS, along with open data formats such as the IFC schema, facilitates data processing independent of software vendors or predefined functionality, enhancing adaptability in academic work.

Aiming for efficient data storage, modification, and management in the HBIM model, an innovative cloud-based interface for streamlined collaboration among stakeholders is proposed, including simulators, decision-makers, and BIM modelers. The integrated interface allows viewing and modifying data within the HBIM model, emphasizing the use of open formats, for seamless workflows across multiple software from different vendors used by the simulators.

The HBIM model must be available in the IFC data format to use the interface as a central hub. This model is used as a repository for data storage (Figure 3). The simulators not only write data into the HBIM model but also source data for new simulations directly from it.

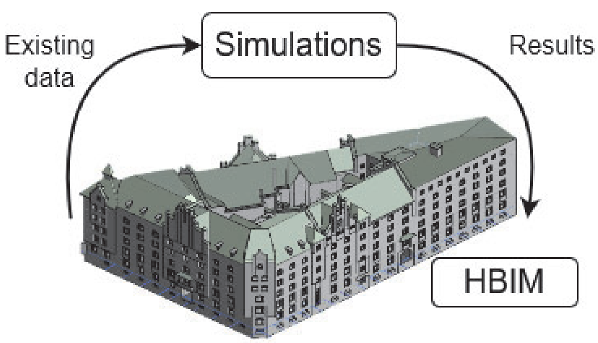

Figure 3: Circular workflow connecting HBIM model to simulations using it as a data repository

The interface allows stakeholders to query specific elements and element types, consult quantities, manage properties, and download reports in machine-readable form, such as Comma-Separated Value (CSV) files. While the interface is the front end for users, IfcOpenShell processes their requests in the background (*IfcOpenShell*

Repository 2024) and is available as a library for Python (*IfcOpenShell Documentation* 2024), serving as a high-level API for complex IFC authoring. Despite a learning curve to a new application, documenting and standardizing the interface and hiding complex data operations ensures safe user interaction regardless of their background. By controlling the data environment, consistent information management and secure modifications through peer reviews by authorized stakeholders can be encouraged.

To build an effective interface accommodating stakeholders of various knowledge levels, the development needs to be cyclical, incorporating continuous user feedback collected since the start of the 0-CO2-WSHH project. This approach aligns with project objectives and stakeholder needs. In essence, the interface utilizes the IFC schema's flexibility, offering users a standardized and intuitive means to access, query, and manipulate data within the HBIM model.

Workflow: Simulations-Interface-HBIM

The current interface status facilitates stakeholders in managing data within the HBIM model by the following workflow (Figure 4): Once the BIM modeler inputs the geometry in the HBIM model (1) and the stakeholders' requirements are organized within the data containers within the LOIN (2), the IFC is exported (3). To ensure that no unauthorized access is possible, the web interface will prompt the user to enter their username and password. Upon successful IFC file upload (4), the user gains access to the tailored subpages for data retrieval and manipulation. Here the user can choose specific entities like building elements, space types, or materials, and run a query to display their information (5). Dropdown menus with ready-made selections sourced from the HBIM model streamline the process of choosing entities and property sets, as well as consulting quantities or modifying properties (6). The app eliminates the need for external software, allowing the direct display and modification of property values. Changes made to the HBIM model are persistent within the interface and retrievable in the 'Downloads' tab by users with granted access (7). The user can download the current and all previous states of the HBIM model as an IFC file, with an option to export quantities in CSV form available.

This workflow illustrates the current functionality of the interface as a proof-of-concept, proving the capability to retrieve and modify information in BIM models seamlessly without the use of external software. It tackles data exchange challenges and offers a user-oriented solution within a central repository. The open-source nature of the interface enhances future adaptability, cost-effectiveness, and development of a collaborative environment.

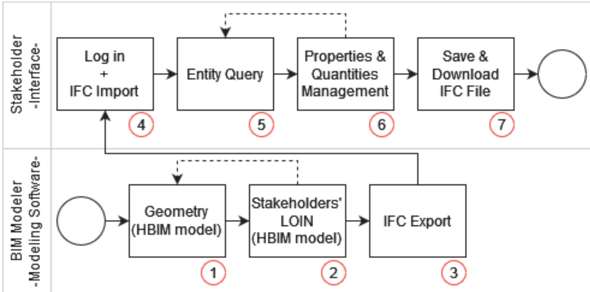

Figure 4: Simplified flowchart interface usage

Limitations and Outlook

The current workflow, serving as a proof-of-concept for integrating the HBIM model into simulation processes, has limitations. Further development is needed to enhance the web interface for improved user experience and effectiveness.

The following interface enhancements may address current workflow limitations: Integration of filters for entity selection instead of relying on GUIDs would improve the intuitiveness of entity search and querying. Eliminating continuous uploading of the updated model, enabling multi-user collaboration with diverse levels of access, and implementing an approval process can improve data quality and change control. Providing information on the relationships between a selected building element and other entities would improve contextual understanding. Expanding CSV capabilities for batch import of values and export of properties and element lists would streamline information management. Implementing an interface-integrated file system for non-alphanumeric data, like CAD drawings, images, and PDFs, linked directly to entity properties, would contribute to a more organized data structure. Allowing the creation of new properties and property sets without relying on external tools, would improve flexibility and usability.

Improvements in proprietary and OSS for modeling are necessary to overcome other limitations: A streamlined process for handling geometry changes is needed to ensure direct registration of modification in the latest IFC file version, a difficult task now due to the limitations of importing IFC files in proprietary software and modeling in OSS. It is also challenging to add properties to specific entities, such as IfcBuildingElementPart, highlighting the need for future development to align with the IFC schema definitions of bSI. Inconsistencies in the availability and functionality of data templates pose interoperability challenges with both proprietary and OSS. Stakeholders would benefit from improved clarity through the incorporation of descriptions, outlined in the IFC schema but still not fully implemented in current proprietary modeling software.

IFC schema enhancements can also overcome some limitations: Integrating uncertainty into entities can be addressed by allowing the use of nested data templates, such as tables containing bounded values.

Although the proposed short- and medium-term improvements may enhance the integration of BIM into simulation processes, the long-term goal is the native integration of full IFC files into simulation software. This eliminates the need for an intermediary interface, streamlining the workflow and ensuring consistent use of a central repository for importing and exporting simulation results.

Conclusion

The 'CO2 Neutrales Weltwerbe Speicherstadt' (0-CO2-WSHH) project evaluates energy, lifecycle, and flow dynamics for a CO2-neutral and heritage-compatible Speicherstadt. For that purpose, one of the goals is to achieve the integration of Heritage Building Information Management (HBIM) and simulation processes, overcoming challenges such as software interoperability, information management, and stakeholder collaboration with the development of an innovative interface.

The developed solution, based on the Industry Foundation Classes (IFC) schema, connects the HBIM model and simulations by providing a centralized cloud-based web interface. This solution allows standardized and collaborative information management within the HBIM model. The proof-of-concept workflow demonstrates its potential to streamline data retrieval and modification, making it an innovative solution in the construction industry.

While the proposed workflow provides a foundation for the integration of BIM in simulation processes, further enhancements are proposed aiming for a long-term goal: integrating comprehensive IFC-reading and writing capabilities into simulation software, eliminating the need for an intermediary interface.

As the project progresses, it provides valuable insights and solutions for sustainable and heritage-compatible built environments. The results and proposed improvements in interface design and modeling software contribute to growing knowledge on integrated building data collection and use. Managing information with HBIM models as central repositories can serve as a reference for future building practices. Implementing this approach aims to make the Speicherstadt district a CO2-neutral World Heritage Site, setting an example for global districts and cities.

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