



INVESTIGATION AND ANALYSIS OF THE REQUIRED BIM DATA FOR AUTOMATED SHELL CONSTRUCTION USING A CABLE-DRIVEN PARALLEL ROBOT

Martin Piechullik¹, Rabee Taha¹, Christoph Jeziorek², Tobias Bruckmann², Alexander Malkwitz¹ and Aileen Pfeil¹

¹University of Duisburg-Essen, Institute of Construction Operations and -Management, Essen, Germany

²University of Duisburg-Essen, Chair of Mechatronics, Duisburg, Germany

Abstract

The increasing demand for automation in the construction industry requires seamless integration of Building Information Modeling (BIM) and robotic systems. This study investigates the extent to which BIM-based planning provides necessary information for automating shell construction with a cable-driven parallel robot. A six-phase methodology was developed and evaluated through a use case. The approach ensures that all relevant geometric, material, and structural properties are embedded within the BIM model and transferred to the robotic system via the Industry Foundation Classes (IFC) standard. Results demonstrate that BIM-based automation enables precise and reliable robotic task execution, increasing productivity and addressing labor shortages.

Introduction

As the construction industry continues to digitize and increasingly automate, new opportunities are emerging to make complex construction processes more efficient, accurate and cost-effective. At the same time, integrating automation solutions poses significant challenges for the industry, as construction processes are traditionally human-centric and customized.

Research projects at the University of Duisburg-Essen have demonstrated the practical feasibility of automated shell construction using a cable-driven parallel robot (CDPR). Earlier studies demonstrated that the execution of building sand-lime brick walls can be automated (Heidel et al., 2022; Roske et al., 2021). A follow up project also demonstrated the possibility to automate ceiling construction and investigated how Building Information Modelling can provide the data needed for the automated execution (Jeziorek et al., 2023).

The focus of the present study is the specific use case of automated installation of wooden ceilings on sand-lime brick walls, which requires many work steps. These include creating a ring beam with reinforced concrete, applying waterproofing, and placing and connecting the wooden ceiling elements. Each of these steps relies on specific data and information that must be read from a detailed 3D BIM model. This data is then converted into a machine-readable format before being transferred to the

robot control system, using standardized formats such as the Industry Foundation Classes (IFC) standard as an intermediate data format. While the process was demonstrated to be feasible, ensuring seamless data integration between BIM and the robotic system remains to be a key challenge.

This study addresses this gap by systematically analyzing information loss when exporting BIM models to the IFC format, focusing on data accuracy for automated structural shell construction. Key aspects of the analysis include evaluating BIM-defined attributes, comparing export options, and quantifying data loss. The methodology involves data investigation, export scenario testing, and integrity validation across different IFC versions, with the goal being to provide practical solutions for a more seamless data integration.

Background

The construction industry is undergoing profound transformation, driven by digitalization and automation of traditional processes. While many industries, such as manufacturing, have been automated for decades, construction projects face unique challenges. These include the wide variety of requirements, the fact that construction projects must meet unstructured working environments and a high degree of dependence on manual labor (Brehm, 2019).

Early steps in construction automation include robotic bricklaying, autonomous excavators and drones for surveying. Projects such as the 'SAM100' (Semi-Automated Mason) and 'Hadrian X' demonstrate the potential to automate repetitive tasks such as bricklaying (Bo et al., 2022). At the same time, efforts are being made worldwide to fully automate more complex construction processes, such as shell construction and component assembly. CDPRs are increasingly being used as a flexible and scalable solution to address that.

CDPR for automated ceiling construction

CDPRs represent an innovative solution for automating construction processes, as they can execute precise movements over large workspaces and can move large payloads (Wu et al., 2018; Xu et al., 2021). Their flexibility allows them to perform a wide range of tasks,

including the placement of bricks and ceiling elements, and other structural components. CDPRs consist of a platform that is maneuvered using actuated cables. The platform can serve as a tool carrier or transport payloads that can be precisely positioned within the workspace.

The use of cables, which are driven by winches and guided via pulleys, enables the creation of expansive workspaces. Since cables are lightweight force-transmitting elements arranged in a parallel topology, the system's moving mass is significantly reduced. This design allows for high payload capacities and a more dynamic performance. A fully tensioned platform with redundant cables enhances the system's robustness against external disturbances, such as wind (Bruckmann et al., 2021). This mechanically simple yet flexible design ensures scalability in terms of workspace size and payload capacity (Pott, 2018).

Due to these characteristics, cable robots are particularly well-suited for large-scale applications, such as building construction. Several research projects have already explored the potential of CDPRs for automating the construction of building structures. For example, Wu et al. (2018) demonstrates the automated masonry construction of complex structures at a reduced scale, while Iturralde et al. (2022) describes the automated installation of curtain wall modules on a realistic demonstration building. Similarly, Roske et al. (2021) showcases the automated mortaring and masonry construction of sand-lime bricks.

The CDPR developed by the University of Duisburg-Essen, named *CaRLO* (Cable Robot for Large-Scale Operations), as presented in Bruckmann et al. (2021) and Roske et al. (2021) has also been employed to demonstrate the automated construction of ceiling elements (e.g. Figure 1) (Jeziorek et al., 2023).

In previous publications, intermediate results from various research projects were presented, showcasing how a CDPR can be employed to automate the construction of structural shells by laying sand-lime bricks and installing ceilings. Having demonstrated the practical feasibility of using a Cable-Driven Parallel Robot (CDPR) for constructing the structural shell of a building, the research project titled “On the Way to Digital Construction: Automation of Shell Construction with Cable Robot Technology” — funded by the Ministry of Regional Identity, Local Government, Building and Digitalization of the State of North Rhine-Westphalia — investigated the extent to which the Building Information Modeling (BIM) method can provide the data required for automated task execution by robots. In this project, a detailed 3D model served as the basis for planning, controlling and executing the robot’s tasks.

The study thoroughly described the automated installation of wooden ceilings onto walls made of sand-lime bricks (Jeziorek et al., 2023), a process which involves several steps. These included the placement of U-shaped sand-lime blocks to form a ring beam, the installation of

reinforcement, the pouring of concrete and the application of a sealing layer for the ring beam to protect the wooden ceiling from moisture ingress. As a final step, the wooden ceiling elements were installed and connected with interlocking boards to ensure the structural membrane effect. In addition, waterproofing layers are applied to the edges and parts of the top surface of the ceiling elements to allow further construction on top.

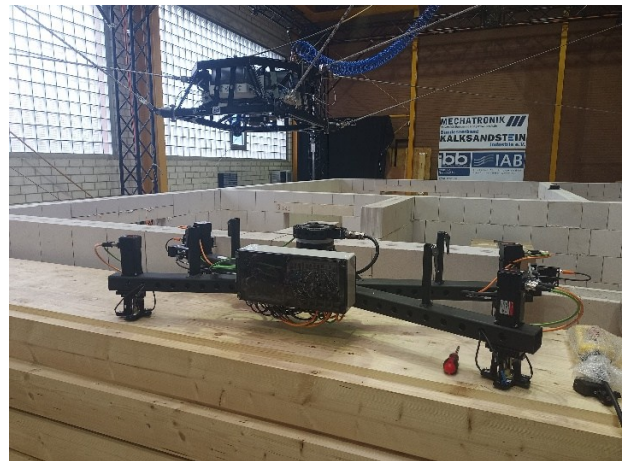


Figure 1: CDPR for automated construction of ceiling elements

Methodology and Implementation

The methodology of this research presents a structured framework for investigating and analyzing the integration of BIM data into automated construction processes, particularly focusing on ceiling installation using a CDPR. First a general overview is provided before employing a structured approach, that divides the concept into six clearly defined phases across three main categories, which are explained in detail. Figure 2 illustrates the six-phase framework applied in this research.

The approach emphasizes a systematic integration of BIM and automation by combining targeted data extraction, structured classification, standardized IFC mapping, and quality checks. It ensures that data exported from a BIM model is both explicitly described and technically suitable for machine interpretation and implementation. In particular, the framework aims to achieve seamless translation of design data into machine-readable information required for robotic control systems.

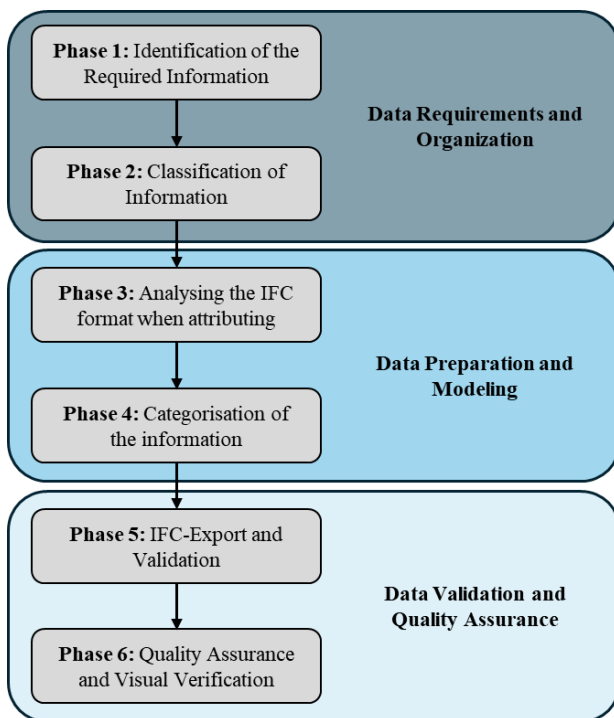


Figure 2: Overview of the six-phase framework

Data Requirements and Organization: Phase 1-2

The first category - Data Requirements and Organization - focuses on identifying, extracting, and classifying the necessary information needed to achieve automation.

In Phase 1, relevant building components were identified based on their significance in the automated execution process. These included ring beams, U-blocks, ceiling elements, and sealing layers. The selection was guided by parameters relevant to CDPR operations, such as positioning, dimensions, material properties, and structural details. The first step of the investigation involved systematically identifying the critical components used during ceiling construction. Following the identification of relevant components, the second step determined the essential component-properties required to achieve automation. These properties must remain unchanged during export to preserve accuracy and machine-readability.

Phase 2 categorized the properties identified in phase 1 into design-dependent and component-dependent properties. Design-dependent properties vary based on the specific construction project and must be handled flexibly to allow for adaptable and optimized designs. They often require explicit planning and can either be manually defined by designers or automatically generated using algorithmic design methods. In contrast, component-dependent properties remain constant across projects as they are derived from material or component specifications. These properties are intrinsic to the respective building elements and can be predefined in the BIM component itself, ensuring that fundamental characteristics are consistently available without

requiring additional planning efforts during the design phase.

A clear classification of these categories enables more efficient data processing and helps optimize the IFC export process without losing essential information. This, in turn, enhances the accuracy and reliability of automated construction workflows. The distinction is particularly relevant in automated construction processes, as component-dependent properties are fixed and define key constraints for automation, enabling feasibility checks and precise control, while design-dependent properties remain flexible and must be resolved individually prior to execution.

Data Preparation and Modeling: Phase 3-4

The second category - Data Preparation and Modeling - deals with the translation of information from a native file format into a standardized file format that is compatible with the control of the CDPR.

Phase 3 focused on mapping the content to the IFC structure, enabling a specific connection between IFC classes with the respective Revit categories, which improves the consistency and accuracy of the exported data. This also ensures that all relevant data could be accurately represented to enable seamless interoperability between the BIM model and the information transfer to the control of the CDPR. For that, the IFC structure in Revit was mapped as the following:

The 'Building storey' checkbox has been activated for all relevant levels in the properties window. This serves as an indication during export that these levels are created as BuildingStorey in the IFC model. All elements assigned to these levels, such as ceilings, walls, columns and other components, are also assigned to the corresponding Building floor.

A model element is represented in the model as a specific system, object or component. This representation includes size, shape, position, quantity and orientation as well as detailed information on design, manufacture, assembly and installation. Non-graphical information can also be assigned to the model element.

This level of detail (LOD) is essential to enable the automation of the construction process with CDPRs and to ensure that the entire construction process can be carried out precisely and efficiently. In LOD 400, geometric, material-related and structural properties are fully represented in the model.

- Geometry: All components, such as the ring beam, slab and sealing layer, are precisely modelled in size, shape and position, including relevant details such as recesses and connections.
- Material properties: Detailed information such as concrete class, reinforcement properties and material additions ensure the exact manufacturability of the components.

- Connections: Specifications of connections, e.g. between ring anchors and neighboring components, include anchorage points, reinforcement overlaps and concrete covers.

Phase 4 analyzed how the required attributes are generated during the BIM modeling process, whether these attributes are automatically stored during the modeling process or must be re-attributed manually. Predefined libraries and classification schemas were evaluated to streamline the modeling process, ensuring that the data was both accurate and efficiently embedded in the BIM model.

The attribution of a BIM model comprises the systematic assignment of properties and standard information to components to precisely describe their geometric and functional characteristics. IFC classes (entities) define the basic structure of a BIM model. Each class represents a specific component or entity that is described by standardized attributes and dependencies. These properties are provided by the IFC data model to ensure interoperability between different software solutions.

Modern BIM software simplifies the modelling process by automatically assigning standard information based on predefined classification schemes. This automation reduces manual effort, minimizes errors and enables the efficient management of large construction projects with numerous entities. Nevertheless, it requires careful configuration to avoid inconsistencies.

Data Validation and Quality Assurance: Phase 5-6

Finally, the third category - Data Validation and Quality Assurance - ensured the integrity and usability of the exported data. In Phase 5, possible export settings for the IFC export were analyzed in terms of data consistency. This step focused on optimizing the export settings to minimize data loss and ensure that all necessary information was correctly stored in the exported file.

In order to assess the quality and completeness of the export process, various export settings were tested with the IFC 4 format in Revit, supplemented by a test with the older IFC 3x2 format. The analysis focused on the correct representation of the model structure and properties in the IFC format. This rigorous approach ensured the creation of a reliable dataset for subsequent comparative analysis of information loss during the export process. The export of Revit models to the IFC format was evaluated through a series of trials, with a focus on maintaining data integrity and compatibility for structural analysis.

The export process was evaluated through two trials using the IFC 4 Reference View (Structural) configuration and two trials using IFC 2x3 Coordination View 2.0. In the first export attempt, the default setting 'IFC4 Reference View [Structure]' was used in Revit. This setting is based on the structural reference view and provides a good basis for the export. As part of the second export test, the IFC4 Reference View (structure) was again used as the basic configuration, whereby the export

parameters were specifically modified. These modifications served to optimize the data transfer in terms of precision and project relevance. In the third export attempt, the default setting 'IFC 2x3 Coordination View 2.0' was used in Revit. This setting is based on the coordination view and provides a good basis for the export. For the fourth export, IFC 2x3 Coordination View 2.0 was used and, as in the second attempt, user-defined settings were adjusted to optimize the result of the export.

Phase 6 focused on ensuring the integrity and accuracy of the exported IFC data through a Information Consistency Analysis. The attributes of the IFC model, such as GUID, classification, material specifications, and dimensional parameters, were validated. In the first trial, the default export settings IFC4 Reference View (Structural) were applied, successfully transferring the overall structure, GUIDs, and level hierarchy. However, some components were misclassified, such as a U-Brick being incorrectly mapped as an `IfcBuildingElementProxy`, and predefined properties like material density were partially lost.

In the second trial, adjustments were made to the IFC4 Reference View [Structure] to improve the accuracy of the export. Key modifications included integrating property sets for project-specific data, applying filters to reduce the exported data volume, and grouping properties by component type. These changes improved the structure and accessibility of exported data, exemplified by the "Pset-Structural Connection" property set for the U-Brick.

In the third and fourth test, the model was exported twice in IFC 2x3 Coordination View 2.0 format, analogue to the procedure in IFC4 format in the previous tests. Once the export with the default settings and once with customized mapping. The results of the third and fourth attempt were comparable to those of the previous export attempts in IFC 4 format.

Results of the Six-Phase Framework

This chapter presents the results derived from the implementation of the six-phase framework, structured according to the previously established categories.

Results of Data Requirements and Organization

Table 1 presents the findings of the investigation implemented in phase 1 regarding relevant component-properties.

The component's position is defined by the cartesian coordinates x , y and z in relation to the center point. These coordinates are flexibly adjustable during the planning phase to meet specific requirements such as structural analyses and optimizations, collision-free arrangements, or design requirements. For CDPR systems, precise position data is essential for navigation and accurate placement.

In addition to the position, the dimensions of a component affect its compatibility with the CDPR and define the spatial requirements necessary for accurate placement. Furthermore, the direction property determines the orientation of the component, specifying the required

installation angle for correct positioning within the structure.

Table 1: Identified components and critical properties

| Structural Element | Specific Component | Property |
|--------------------|--------------------|---|
| Ring Beam | U-brick | Position, Dimension, Density, Direction, GUID |
| | Concrete | Position, Dimension, Viscosity Density, GUID |
| | Reinforcement | Position, Dimension, Density, Direction, GUID |
| Sealing Layer | Sealing Layer | Position, Dimension, Viscosity, Direction, GUID |
| Ceiling | Ceiling element | Position, Dimension, GUID |

The density of a material, in conjunction with its geometric dimensions, enables the calculation of the component’s weight. This information is critical, as the CDPR has a limited load capacity, requiring adjustments to the selected tool and the forces applied within the model-based control approach of the CDPR accordingly. Furthermore, the density property is used to store information on fastening materials (e.g. in nails per meter for fastening connection boards in a wooden ceiling) allowing the CDPR to autonomously position and install them at predefined intervals.

Viscosity is relevant for processable materials like concrete or sealants, ensuring accurate application and avoiding processing errors. Finally, the Global unified Identification (GUID) ensures that each component is uniquely identifiable in the IFC model, which is essential for reliable automated processing. The results of the classification of the identified properties introduced in phase 2 are summarized in Table 2.

Table 2: Overview of the classification of the properties

| Property | Design-dependent | Component-dependent |
|-----------|------------------|---------------------|
| Position | x | |
| Dimension | x | |
| Density | | x |
| Direction | x | |
| Viscosity | | x |
| GUID | | x |

The results showed that the position and dimension of components, such as U-shaped bricks, are primarily design-dependent. These characteristics varied based on structural requirements, aesthetic choices, or other design constraints. In the use case, this led to customized elements that differed from standard dimensions.

In contrast, component-dependent properties like density and viscosity remained unchanged across design variations. These intrinsic properties stem directly from the materials used and are not affected by the planning process. The GUID was also identified as a component-dependent property. It consistently ensured unique identification of elements across software environments and project phases.

The exact position of a component in the model depends on the design, as it can be flexibly adjusted during the planning phase to meet specific requirements such as structural analyses, static optimizations, collision-free arrangements or design requirements. The geometric dimensions of a component are mostly also design-dependent, as they are variable during the planning phase and can be adapted to functional, aesthetic or structural requirements.

For example, a U-shaped brick in automated ceiling construction has standard dimensions defined by the manufacturer but may need to be cut to fit the specific design. This results in customized dimensions that differ from the original standard sizes. The same applies to custom-made components, which are specifically tailored for each design—otherwise, they would not be custom-made. However, this classification does not apply universally to all components. Extending this categorization to fasteners such as nails and screws and assigning them to the design-dependent category would not be accurate. These components are not altered or cut to fit a specific design. Instead, they are selected based on predefined requirements and constraints, such as material compatibility, load-bearing capacity, or environmental conditions. The correct screw, for example, is chosen from a set of standard screws, meaning that its dimensions are already known and directly assigned to the component. This approach presupposes that each screw is explicitly defined as an individual element within the 3D model. However, this level of detail in planning is not yet standard practice in the construction industry.

The orientation and setting angle of a component are design-dependent, as they can be customized during the planning stage. An example of this is the alignment of U-shaped bricks. If two adjacent walls are perpendicular to each other, the U-bricks of one wall must be rotated by 90 degrees in relation to the adjacent wall to ensure that the recess for the reinforcement and the concrete are correctly aligned.

From a data structure perspective, the distinction between standard and custom-made components is reflected in how parameters are stored and interpreted. Standard components are typically linked to predefined objects in a

component library, with fixed attributes such as dimensions, material properties, and tolerances. In contrast, custom-made or customized components are defined by parameterized templates or unique geometry entries that are generated based on the design context. This distinction is essential for the automated assembly steps, as it affects how components are identified, picked up, and positioned.

The density of a component is a different matter. Density is an intrinsic property and remains constant regardless of the design. It results directly from the physical and chemical properties of the respective building material. The same applies to the flowability or viscosity of a material, which is also a component-dependent property, as it depends on the chemical composition of the building material.

GUID is a component-dependent property, as it assigns a unique identification to each component. It remains independent of the planning and enables consistent assignment of the component across different software environments and planning steps.

Results of Data Preparation and Modeling

The results from phases three and four demonstrate how the information should be correctly stored in the native format to optimally prepare for the IFC export. It also shows from which library the information was sourced.

Ring beam (U-brick)

Instead of using a standard library family from Revit for the U-bricks, a custom family was manually created. The properties of this family are directly based on information provided by the manufacturer KS-ORIGINAL GMBH, sourced from their website and integrated into the model. For the modeling, the predefined type IfcBeam with the subtype IfcBeam was selected for these U-bricks.

Concrete

The concrete used to fill the U-bricks is specified based on structural calculations. The properties of the concrete are derived from these calculations and integrated into the model using the standard library family provided by Revit. The predefined type IfcBuildingElementPart was selected for the concrete.

Reinforcement Bars

For precise modeling of reinforcement bars in IFC models, appropriate classification is essential to clearly define their structural function. Reinforcement bars serving as primary reinforcement have been classified as IfcReinforcingBar.PREDEFINEDTYPE = MAIN. This classification ensures automated parameter assignment, with the key properties of the reinforcement automatically assigned in Revit. Specifically, the parameters managed under the "Dimension" and "Construction" categories are drawn from the Structural Reinforcement Library in Revit, which offers a selection of reinforcement shapes for primary load-bearing structures.

Sealing Layer

The sealing layer at transition points between wood and other building components has been classified as IfcCovering.PREDEFINEDTYPE = MEMBRANE. This classification defines the function of the sealing layer as a protective barrier that prevents moisture ingress and ensures the durability of the construction. The sealing layers were manually modeled as a custom Revit family. A specialized Wall Sweep technique was used to precisely position the sealing layers at the required locations. The newly created family was then integrated into the model to enable detailed sealing layer modeling and ensure correct incorporation into the BIM model.

Key properties such as material, thickness, and function were manually assigned to maintain consistency and accuracy in both the BIM and IFC models.

Ceiling Element

The ceiling elements have been classified as IfcRoof.PREDEFINEDTYPE = FLATROOF, as they serve the function of a flat roof. A project-specific Revit family was developed for the ceiling to meet the unique requirements of the project. The connection between the panels is achieved through an insert board, ensuring the structural integrity and stability of the entire roof surface. The relevant properties of the ceiling elements were manually assigned in the model based on the specifications provided by Holzwerk Gebr. Schneider GmbH.

The attribute of the interlocking board was classified as IfcPlate.PREDEFINEDTYPE = SHEET. The insert boards were modelled manually, based on the specifications of the manufacturer Holzwerk Gebr. Schneider GmbH. A summary of the results of the data preparation and modelling is presented in Table 3.

Table 3: Results of data preparation and modelling

| Specific Component | IFC classification | Library |
|--------------------|----------------------------------|---|
| U-brick | IfcBeam | created manually (KS-ORIGINAL GmbH) |
| Concrete | IfcBuildingElementPart | Revit standard library |
| Reinforcement | IfcReinforcingBar.PREDEFINEDTYPE | Revit Engineering - Reinforcement library |
| Sealing Layer | IfcCovering.PREDEFINEDTYPE | Position, Dimension, Viscosity Direction, GUID |
| Ceiling element | IfcRoof.PREDEFINEDTYPE | Project-specific Revit family, based on Holzwerk Gebr. Schneider GmbH |

Results of Data Validation and Quality Assurance

The results of phases five and six showed that the second and the fourth export version accurately transferred key properties from Revit to the IFC file. Notably, the Brick was correctly classified as IfcBeam (unlike in the first export attempt), and key physical parameters like length, width, height, and material were properly transferred, reducing the need for post-processing adjustments.

The results of phases 5 and 6 demonstrate a successful data validation process, ensuring the accurate transfer of attribute data. The improved export settings proved effective in supporting automation readiness.

Discussion and Conclusion

It was shown that the methodology consisting of the three categories: Data requirements and organization, data preparation and modeling, and data validation and quality assurance, is a good method for providing the necessary information for automated construction processes to the target system via the IFC standard. The methodology was tested and presented using the use case of automated ceiling placement.

This study shows that the IFC format provides a reliable basis for data exchange. However, to achieve optimum results, careful export settings and adaptation to the specific requirements for automated construction processes are necessary.

A sensible next step would be to create a standard IFC export setting for automated construction processes to ensure that all necessary information is transferred without loss during the IFC export.

There is increasing discussion as to whether IFC is the best format for transferring data using the BIM method. Alternative formats such as USD (Universal Scene Description) are increasingly being discussed. It would therefore be an interesting next step to carry out the study with a focus on the USD format and compare the two results.

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