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KNOWLEDGE PROCESS MANAGEMENT AND BIM PLATFORM-BASED SOLUTION FOR THE RECONSTRUCTION OF THE GERMAN OPERA HOUSE BUILDING

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Abstract

This article addresses the challenge of reconstructing demolished historical buildings in digital humanities, focusing on the German Opera House Building by Louis Sullivan and Dankmar Adler and emphasizing effective information acquisition and management. Despite the benefits of digitization, knowledge management remains a persistent obstacle. The proposed multidisciplinary approach utilizes Building Information Modeling (BIM) and Common Data Environment (CDE) to seamlessly integrate data from diverse sources, supporting collaboration and ensuring result consistency. This contextualized BIM-based system transforms the reconstruction of non-existent historical buildings, overcoming challenges such as non-uniqueness of historical documents and fragmented knowledge. Results highlight the methodology's effectiveness in digitally reconstructing historical buildings and improving knowledge sharing for the examined property.

Keywords

Knowledge management, Platform, CDE, BIM, Sullivan, Adler

1. *Introduction and study objective*

The contemporary landscape, influenced by the pervasive impact of digitalization, has seen the integration of digital methods within various disciplines, thereby expanding the horizons of research possibilities. This trend has been prevalent since the emergence of personal computers (Turkle, 2009). In the context of cultural heritage, two key terms are often employed: "Digital Heritage" and "Digital Humanities." The former emphasizes the object itself, primarily focusing on aspects such as preservation, education, and research. The latter term adopts a more methodological stance, emphasizing the application of digital technologies to support research within the humanities (Münster et al., 2019).

When referring to "digital technologies," we encompass a range of methodologies and tools that facilitate historical analysis, including databases, ontologies, data dictionaries, three-dimensional digital models, and geographical information systems (GIS). In the industrial sphere, the preferred terminology is "Knowledge Management", as a discipline that promotes an integrated approach to identifying, capturing, evaluating, retrieving and sharing all of an enterprise's information assets which may include document, database, policies, expertise and experiences in the individuals (Boochs et al., 2014; Duhon, 1998).

Regarding historical assets, digitization is important, but few studies are strongly focused on the knowledge management associated with them (Abergel et al., 2023; Catalano et al., 2017; Galeazzo, 2022; Vogel et al., 2023). A historical artifact results from a design process that generates ideas, information, and knowledge, manifesting them as forms and materials. Integrating this information with three-dimensional geometries is complex but still represents the dispute in this field, often well-solved by applying to specific historical objectives (Frommel et al., 2020; Garagnani et al., 2019). Within the study of historical transformations of the built environment, the reconstruction of no longer existing or unbuilt buildings poses a particular challenge (Apollonio et al., 2021; Kuroczyński et al., 2023), as it is often not possible to apply some established methodologies, such as the initial state survey (Roussel & De Luca, 2023), except partially from historical images. Moreover, typical reconstructions involve hundreds of documents, which need, as stated above, specific ability, such as database management, and tools.

On the other hand, the availability of methods and software for 3D modeling of built environment is steadily increasing (Davis, 2021), offering more increasingly effective tools in the construction industry. Among these, Building Information Modeling (BIM) is one of the most efficient examples of using digital tools to manage project information. Hence, there is an opportunity to use BIM processes to support historical research of buildings that already have graphical documentation supported by metric surveys and descriptive geometry for their definition. Considering the availability of appropriate project documentation, the reconstruction of an architectural structure follows a methodology analogous to the creation of a Building Information Modeling (BIM) model derived from two-dimensional Computer-Aided Design (CAD) files (Kouider et al., 2007). This process has been extensively examined and holds the potential for automation.

Within the above discussed framework, the primary aim of this study is to employ the BIM model as the foundational framework for formulating historical hypotheses and their subsequent empirical validation. Furthermore, it serves as the cornerstone for conveying historical findings generated during the reconstruction phase. This presentation is facilitated through digital platforms and multimedia presentations, which are adept at illustrating the precision and fidelity of the reconstruction process. This topic has been already extensively discussed for archeological reconstruction (Demetrescu et al., 2023). The paper addresses the challenges associated with historical reconstruction within a collaborative, multidisciplinary, and technologically driven context, highlighting and cataloguing the main issues usually associated to collaboration and communication among scholars. Secondly, it outlines the adopted methodology, specifically designed to partially surmount these challenges. Lastly, the verification process is delineated, showing the reconstruction of the intricate architectural structure known as the German Opera House Building, alternatively recognized as the Schiller Theatre Building or Garrick Theatre, designed by the renowned architects Louis Sullivan (1856-1924) and Dankmar Adler (1844-1900).

2. *Problem statement*

The digital reconstruction of historical buildings using 3D models has gained increasing importance. However, despite its advantages, the existing workflow still presents numerous issues (Giordano et al., 2018; Huffman & Giordano, 2021). These problems are found in both the analysis of the applied methodology and the usage patterns of the existing computational tools. These issues can be categorized into four main themes:

1. Complexity of historical document: historical documents contain a varied range of heterogeneous data and interconnected information.

2. Heterogeneous data and information: It is difficult to integrate various types of data, ranging from 2D graphical documents to non-graphical textual information, into 3D models.

3. Knowledge fragmentation: Knowledge is often scattered and fragmented, leading to the creation of isolated and disjointed pieces of information.

4. Poor knowledge sharing: Knowledge is not adequately shared, leading to its nonuniform distribution and impeding collaboration.

2.1 Complexity of historical document

The first main theme involves one of the fundamental elements through which historical knowledge is conveyed: historical documents. They are inherently complex, containing heterogeneous data and information. These documents can be classified into two main types: non-graphical and graphical documents. Graphical documents can contain numerous annotations and one or more graphical representations of different parts of a building, as well as different versions and design hypotheses. For example, a document may include an architectural floor plan and a construction detail view. Another example is photographs that can illustrate individual rooms, sets of spaces or multi-story areas. Historical documents can, therefore, illustrate a substantial number of elements, effectively linking the document itself, both graphical and non-graphical, to numerous references within the model. Consequently, due to the non-uniqueness of information in these documents, a model-based contextualized cataloging system must be adopted. In addition, it is common to find repetitive representations belonging to multiple spatial entities, such as levels in a multi-story building. This critical aspect leads to increased storage space usage without adding significant information. Monitoring this process becomes essential to optimize data management and counteract the exponential growth of data.

2.2 Heterogeneous data and information

Data, information, and knowledge prevalent in the historical and architectural context are structured either textually or graphically, following traditional representation techniques such as plans and sections. These two forms of communication, "image" and "word" (Antinucci, 2011), reflect the dual nature of historical building, both material and immaterial (Brandi, 2000). To achieve a holistic digitization of historical artifacts, it is necessary to explore not only the capabilities of software in terms of modeling but also in terms of information management (Saygi et al., 2013). The established practice of representing information graphically in two dimensions or textually clearly differs from what is required by the new methodology of semantic modeling, which demands a re-coding of the information and its structuring no longer in a two-dimensional manner using graphical codes and languages, but rather in a three-dimensional and parametric perspective. Both graphic and text documents are organized for human understanding but are not easily understood by machines. So, the challenge is to structure digitally the content, especially textual documents, and integrate them into the 3D space of historical reconstruction. However, this can be difficult because knowledge can be highly subjective and it covers various levels of abstraction, ranging from practical details to wider questions such as the reasons behind specific design choices. These are the same issues that persist in the management of knowledge for a new building (Argiolas et al., 2015). Without integration, the current trend of creating separate documents will continue, rather than consolidating them into a single Single Source of Truth (Daniska & Vrban, 2023), moving away from the possibility of synthesis.

2.3 Knowledge fragmentation

Knowledge fragmentation is the result of information dispersion across various storage locations and individual human factors. The knowledge we gain isn't gathered or synthesized in one place, making it hard to fully understand or develop. This is inherently linked to the continuous development of knowledge, which cyclically moves between individual and collective levels. According to the theory of two Japanese business experts, in companies producing innovative products and services, "tacit" and "explicit" knowledge alternates in a continuous cycle (Ikujiro & Hirotakquia, 1995). This has been schematized into a spiral model known as the SECI (Socialization, Externalization, Combination, and Internalization) model (Fig. 1).

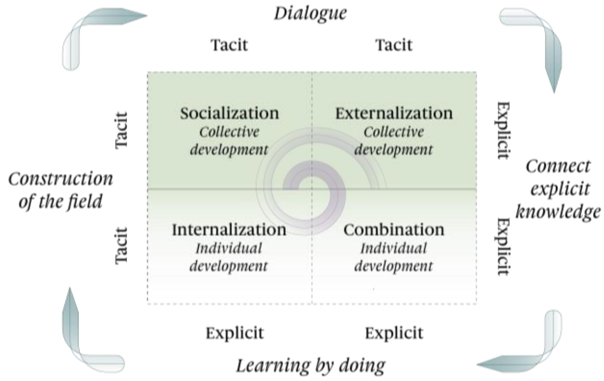

Fig. 1: SECI Model Diagram (Ikujiro & Hirotaka, 1995)

Inside an organization, knowledge is fragmented into two components: "individual knowledge" and "collective knowledge." While this cycle is fundamental, the coexistence of individual and collective dimensions, combined with poor workflow management, leads to numerous issues that exacerbate fragmentation, such as the use of a multitude of tools and software in the process, often in an uncoordinated manner, along with an imperfect understanding of these tools. The adoption of intuitive and personalized approaches to these tools causes a spontaneous workflow evolution. Focusing on communication tools, there is a trend of both expanding and diversifying the tools themselves and the communication channels within them. Within the context of collective processing, in a traditional workflow, annotations and information generated during communications regarding one or more documents, an element, or a specific part of the building, are not integrated into these resources. The document analysis process often appears unsystematic, slowing down the workflow. From the perspective of individual processing, it becomes difficult to track which documents or parts of them have already been examined. The lack of content synthesis and sharing with the workgroup hinders coordination and, consequently, progress in the project. Lastly, another significant issue is document duplication. This situation can happen when a cataloging system is not efficient and requires creating multiple copies of the same document.

2.4 Lack of knowledge sharing

The fourth main theme concerns the deficiency in sharing knowledge, both voluntarily and involuntarily, leading to an uneven distribution. On one hand, a user or organization may choose not to share data, which can hinder work progress. On the other hand, involuntary non-sharing can occur when knowledge isn't adequately structured (Polanyi, 1966). In addition, knowledge may not be shared due to misuse of communication methods, like excluding specific users or using different tools and channels. The creation of individual knowledge bases is essential in the process of transforming knowledge from "tacit" to "explicit" and vice versa, as stated above. Nevertheless, the lack of sharing can lead to inefficiencies, hinder collaboration, and result in the absence of a common vision and coordination among users, ultimately culminating in workflow interruption (Fig. 2).

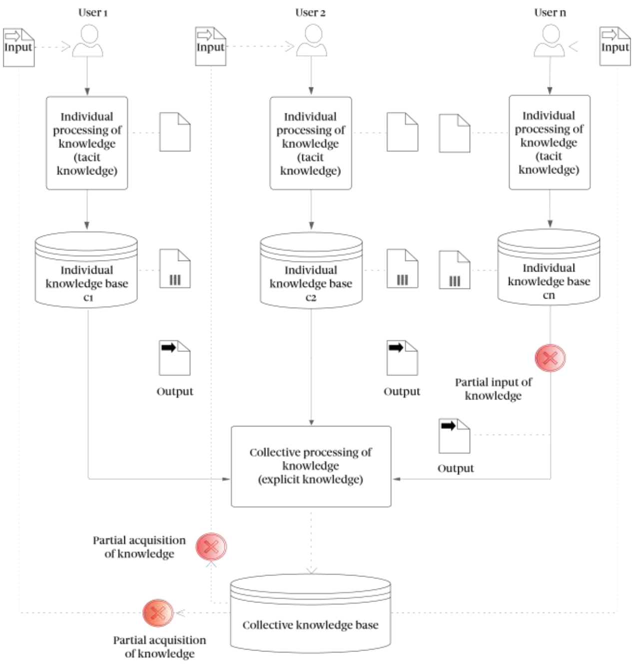

Fig. 2: Knowledge dispersion in the process of knowledge construction

The necessary individual process initially results in the creation of individual knowledge bases, which serve as storage points for the information of single users (upper part of Fig. 2). In contemporary practice, multiple technological devices are utilized even for the most basic daily tasks, leading to the potential for information to be stored in disparate locations. Therefore, a fundamental requirement is ensuring that all users within the process have access to the same data, thereby establishing a Single Source of Truth (SSOT). Information dispersion can occur in either a voluntary or involuntary manner. Involuntary dispersion arises from the absence of a systematic method for organizing information, whereas voluntary dispersion results from users not sharing data in a structured way. For instance, it is possible for the curatorial team to share only a portion of the archival documentation with other teams. Furthermore, the development of collective knowledge must be effectively interpreted by individual users. If this is not achieved, the value of subsequent cycles of work diminishes following the initial cycle of individual effort, particularly within a multidisciplinary team striving towards a common objective (lower part of Fig. 2).

3. Methodology

The approach to studying and reconstructing a no longer existing building is highly multidisciplinary and progressively evolves based on ongoing research and intermediate results, the methodology developed and validated is outlined on four foundational pillars.

The first theme involves the implementation of process and model management logic. Specifically, referencing the standardization of the ISO 19650 series, specific project objectives and model uses have been identified and described (ISO, 2018). Model uses identify and collate the Information Requirements that need to be delivered or embedded within 3D digital model (Succar, 2019). The identification of BIM uses from the early stages of organizing digital modeling allows to:

i. define the number of models to be created and assign them to the most suitable people to carry them out;

ii. define the software to be used and, if necessary, the training plan for internal collaborators;

iii. clearly express the achievable results, in terms of graphic detail and level of development, with art and architecture historians.

ISO 19650 series give access to full methodology to insert specific tool/collaborative concept such as authorization pathways, areas of expertise, and timelines.

In this way, methods for sharing information containers have been codified, as usual in well-defined BIM processes. Starting from the analysis of the traditional research and architectural and urban reconstruction process, the dynamics of data and information exchange have been emphasized to interconnect and integrate typical reasoning process to BIM model coherently.

The second area focuses on creating coordinated BIM models. These models are developed specifically for the virtualization of a no longer existing building, created upon standards and best practices consolidated in the field of existing buildings and their transformations (Borin et al., 2019).

In this area of expertise, the first BIM use is represented by the harmonization of the existing two-dimensional technical documentation, in the form of plans, elevations, sections, and construction details. The model is used to position the coordinated two-dimensional views in their actual three-dimensional position within the virtual space. This step of harmonizing information often becomes critical for digital reconstruction, as the BIM model creator identifies a series of graphical inconsistencies that need to be appropriately discussed within the project team. This BIM use becomes increasingly important as the corpus of available drawings grows, given that many BIM modelling software tools allow for hypertextual referencing of views to one another during the creation of the sheets.

The specific construction typology requires the creation of different models, each characterized by a differentiated geometric detail level. These models are essential for accurately representing and completely reconstructing the building, considering all its parts and the multiple configurative values that characterize it. Moreover the historical reconstruction of a historic building necessitates collaboration across multiple disciplines, each assigned at least one BIM model (i.e. architectural, structural, urban landscape model, etc.).

The first and second themes are intertwined with the use of a BIM-based process in its most authentic form, allowing what has been experienced to be comprehensible and diversely applicable. Considering that the proposed research relates to the post-demolition phase, commonly not integral to the building's life cycle where BIM practices are implemented, necessary modifications must be made.

The third crucial theme of the proposed methodology is about configuring a Common Data Environment (CDE), a shared data environment that plays a fundamental role in the preservation and sharing of information and documents related to the reconstruction of historic buildings, also facilitating collaboration (Cornelius et al., 2018). The CDE allows the preservation and sharing not only of the structure of federated models but also two-dimensional graphic documents and other historical documents. The CDE is configured as the preferred means for locating and referencing documents to specific objects of the model or related spatial structure, enabling users to simultaneously view the document and the model in 3D space.

Since the ongoing process requires the coordination and description of communication flows, a form of diagrammatic representation has been identified, serving both as an analysis tool and a form of communication to the process stakeholders. This fourth theme, although the last to be described, is cross-cutting to the previous applications. Business Process Management and Notation (BPMN) diagrams illustrate the workflow for analysing communication and knowledge-sharing processes among users (Fig. 3). They also help understand the logic of creating federated BIM models as collectors of graphical and non-graphical information of the reconstructed building (Fig. 12 and Fig. 13). In this sense, the use of a diagram is a fundamental step for understanding the relationships that this work involves. Moreover, the issues related to the case study and the use of digital tools were identified, defining the requirements and necessary solutions for selecting the most suitable tools to achieve the objectives.

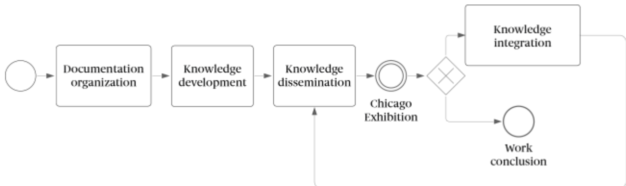

Fig. 3: Historical and critical reconstruction process, standard BPMN diagram

4. Case study: the German Opera House Building

The case study conducted to validate the suggested methodology entails a significant attempt to digitally reconstruct the German Opera House Building. The building was designed by Louis Sullivan and Dankmar Adler, built in Chicago between 1891 and 1893, and demolished in 1961 (Vinci et al., 2021) (Fig. 4). Since the physical structure no longer exists, historical documentation plays a fundamental role in legitimizing the accuracy of the work performed.

The complexity of the original drawings alongside the large amount of historical information contained in the original shop drawings necessitated a detailed documentation organization effort, centered around the logic of digital reconstruction through a BIM model. An early challenge was compiling an orderly catalog of the building's structural elements enabling their breakdown and the analysis of the building's structural intricacies and construction methods.

Fig. 4: German Opera House Building, external view (Richard Nickel, Burnham & Ryerson Library, The Art Institute of Chicago)

Following the macro-activities outlined in the BPMN diagram (Fig. 3), the initial step involved the systematic cleaning and organization of the large number of documents. This phase was crucial for the understanding, traceability, and facilitation of digital reconstruction. The digitization initiative was carried out through collaborative work remotely, resulting in exclusively digital documentation that includes both text and graphics. The bibliography is related to critical studies on the building and to manuals on the construction techniques of the era. The graphic documents include project drawings, old photographs, and critical re-drawings post-demolition.

The project drawings have been organized into theme-based folders within a shared storage. To define the levels of the BIM model, the vertical structure of the tower was taken as a reference, systematizing the documentation in specific subfolders that reflect its configuration. Each subfolder contains detailed drawings at various scales related to the architectural elements of each level. The historical photographs have been categorized into thematic folders, named after the places or details depicted in them, while the written documents have been sorted by genre and author.

The photographs of the building's demolition (Fig. 5) were archived based on locations such as "03_Inside_Stage Theatre" or "02_Inside_The Vestibule" or specific themes like "08_Phoenix Columns". These photographs were essential as they captured not only specific elements or environments such as the Phoenix Columns or the theater space but also the surrounding context, contributing to the resolution of undocumented or missing portions of the structure in the original construction drawings. It's crucial to note that this cataloging system, when viewed as an independent practice separate from the BIM model, posed challenges in locating critical details essential for addressing various issues. This is because the system's reliance on thematic folder titles led to a narrowed focus, necessitating multiple reviews of each photograph to address different aspects of the structure.

The case study analysis, addressing the common issue of knowledge fragmentation among scholars, has illuminated that communication within the group is stratified across both formal and informal levels. This stratification is generally influenced by the functionality of the tools used and the hierarchical distribution of roles within the workgroup (Fig. 12).

Fig. 5: Tower demolition, historical photograph (Richard Nickel, Burnham & Ryerson Library, The Art Institute of Chicago)

This leads to information dispersion not only across different communication tools but also among the multiple communication channels within them. As described previously, other problems can include duplicating documents, which led to increased storage space usage, as well as the modification of some documents on microfilm to improve readability while preserving the original files. These challenges were surmounted in subsequent phases through the adoption of BIM model and the CDE platform. This tool allows documents to be organized using a faceted system based on metadata, along with a direct link to the BIM model objects, thus serving as a singular source of project information.

The advancement of knowledge evolves from the goals set to be accomplished by leveraging the BIM model to strengthen the graphical aspect. Within the specialized vocabulary of the BIM field, these objectives are referred to as 'Model Uses'. The selected model uses include both specific and broader objectives. The specific aim was the digital reconstruction of the structural BIM model ("1400 Steel Frame Modeling") to verify the accuracy of the shop drawings (Succar, 2019). The work also included the creation of an architectural model ("1010 Architectural Modeling"). Another model use was the capture and representation of the building ("2010 2D Documentation"), producing new 2D representations and 3D details. Moreover, it was fundamental as purpose of the project to link the specific 2D textual documentation with the BIM model ("8010 BIM/Spec Linking"). Once the Model uses were established the actual BIM modeling phase started. As specified in the methodological section, it is necessary to declare the first use of the BIM model in this area—which is often undervalued in research—which is the harmonization of two-dimensional project views into a single three-dimensional and virtual space.

Focusing on interesting aspects of this project, specifically regarding the model use ("1400 Steel Frame Modeling"), the BIM methodology facilitated the incorporation of data, information, and knowledge into the BIM model of the opera house. This integration allowed for an in-depth understanding of the project and a clearer depiction of the construction technology involved (Fig. 6).

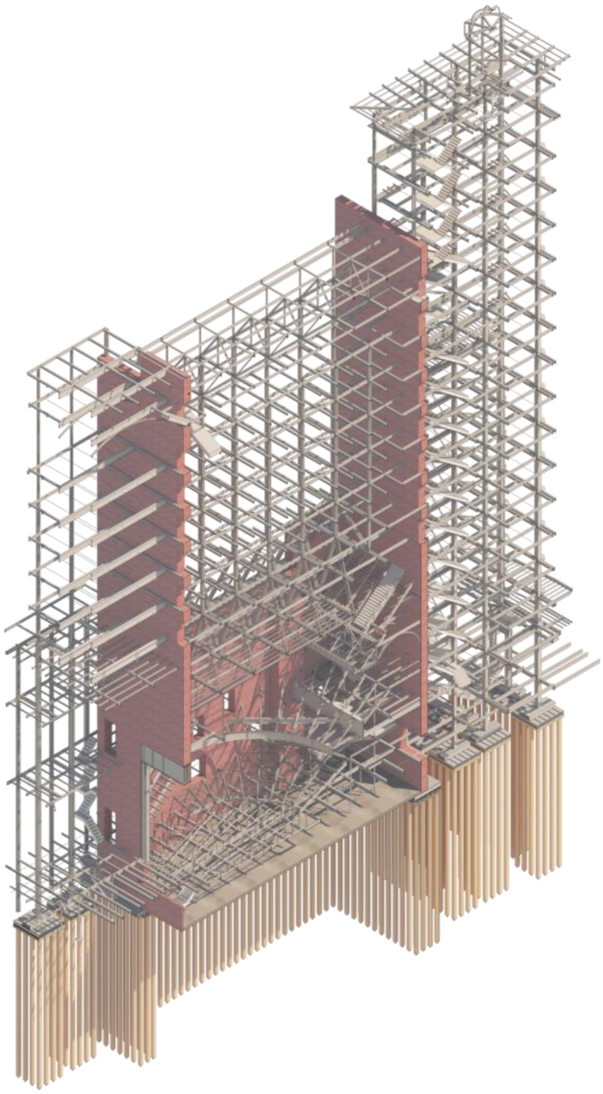

Fig. 6: The German Opera House BIM model, axonometric view of the longitudinal sectioned structured.

For example, it enabled the conversion of the traditional management system actors utilized for organizing the documentation on the structural connections of the steel frame. The management system was formalized as a Cartesian diagram where the x-axis indicates the location of a series of overlapping columns (i.e. a grid intersection), while the y-axis indicates the level at which each column was located (Fig. 15). The Cartesian plane indicates the number of the sheet with the specific executive detail. The diagram shows how the old spatial organization of the building could be replicated into typical spatial organization by grid and levels of a BIM model. Regarding the structural BIM model, specific objects were created for each type of column and beams, according with the classification of the technical manuals of the time (Fig. 9). The original project names of the different column types are maintained within each object, which varied in the dimensions of the elements of the composite section (built-up column).

Information such as their location or the associated mark was translated as the properties "location mark" and "mark," respectively. The same translation system was applied to other structural elements of the building.

The coordination of BIM models was achieved through a federation process utilizing Autodesk Revit software. This method facilitated the examination of various levels of geometric detail within the model. It included a foundational tier that outlined the geometries of macro elements such as beams, columns, and slabs, alongside a more nuanced stage focusing on the intricacies of structural connections. To further define nineteenth-century steel connection, Autodesk Advanced Steel was employed for the modeling of typical nodes, based on proprietary information exchange (Fig. 7). These nodes were then automatically positioned within the model. This approach guaranteed that the model could uphold various performance levels without sacrificing its semantic integrity (Fig. 8).

Regarding the assimilation of graphical documentation into the BIM model, the project took an innovative approach by incorporating segments of graphical documents that detail plans and sections of representative structural connections, not only during modelling phase (Fig. 10), but also within a CDE, fed by Industry Foundation Classes (IFC) models.

This was achieved through the utilization of an alignment tool, enabling the concurrent display of both 2D plans and sections alongside their BIM counterparts (Fig. 14). This dual-view capability facilitates a comprehensive understanding and analysis of the structural connections within the opera house, bridging the gap between traditional 2D documentation and modern BIM modeling.

The final stages, which involve knowledge dissemination and integration, while not the central emphasis of this document, play a critical role in the overall process.

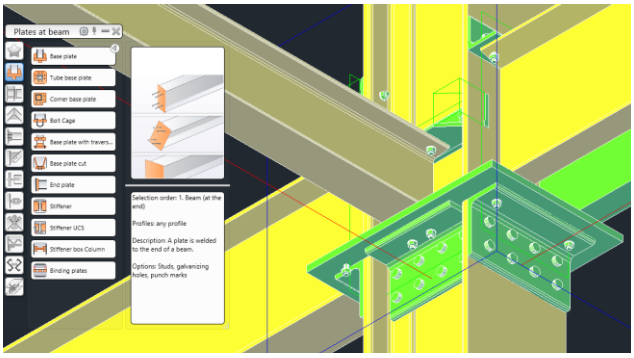

Fig. 7 Steel detailing BIM model, typical structural connection

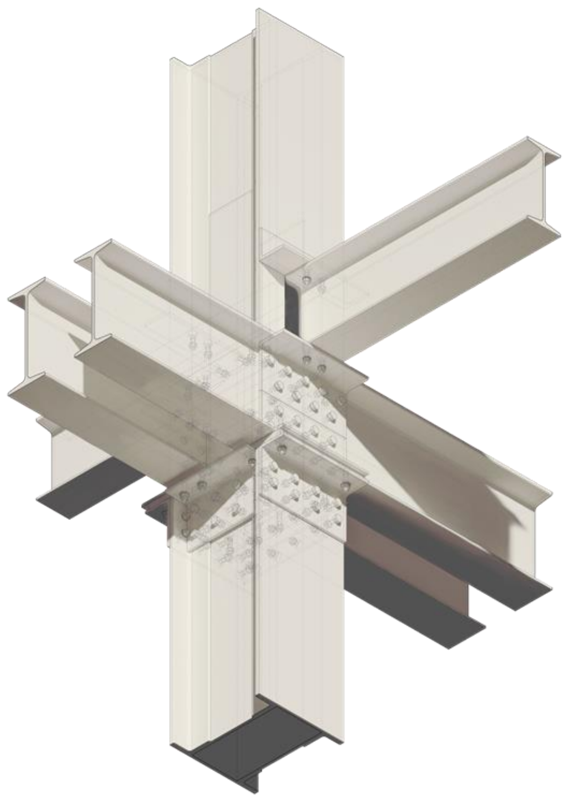

Fig. 8: Axonometric view of a type of structural node with 6 elements, as imported from specific steel design BIM model

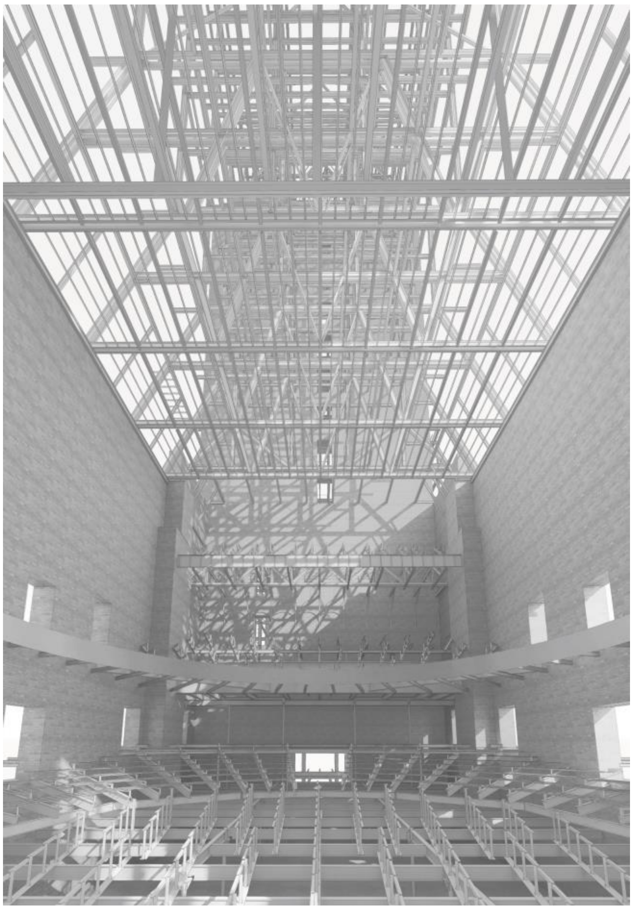

Fig. 9 Structural BIM model, perspective view of the balconies of the theatre

The exhibitions "Romanticism to Ruin" and "The Construction of Skyscrapers" facilitated the dissemination of knowledge by employing various visualizations derived from BIM models and the insights gained from them as tools to enhance the understanding of a broader audience.

This approach enhanced the comprehensibility of construction technologies, the architect's design rationale, and enabled the project to be viewed from various perspectives, not limited to those offered by historical records.

Moreover, the aspect of knowledge integration is emphasized by the opportunity to augment this knowledge base, developed via the BIM model, for subsequent research endeavors. This accessibility extends even to those lacking in-depth technical knowledge in the domain of modeling, thereby democratizing the information further.

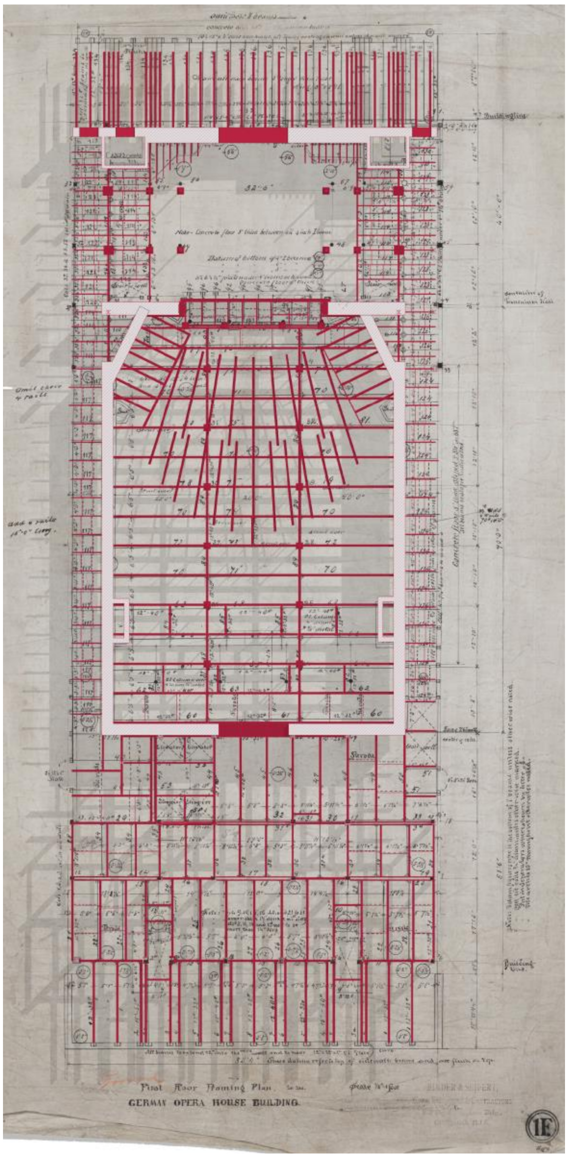

Fig.10: Structural BIM model, overlap between the BIM objects in red and original documentation of the first-floor framing plan (The Chicago Historical Society)

5. Result and discussion

The paper is closely related to how knowledge evolves and the issues of collaboration and coordination within an organization. The knowledge development process follows a sequence, moving from data to information and lastly to knowledge (Fig. 11).

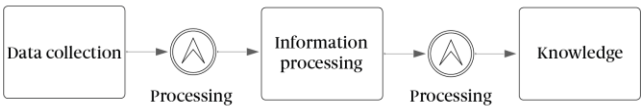

Fig. 11: Knowledge Development Process (Kendal & Creen, 2007)

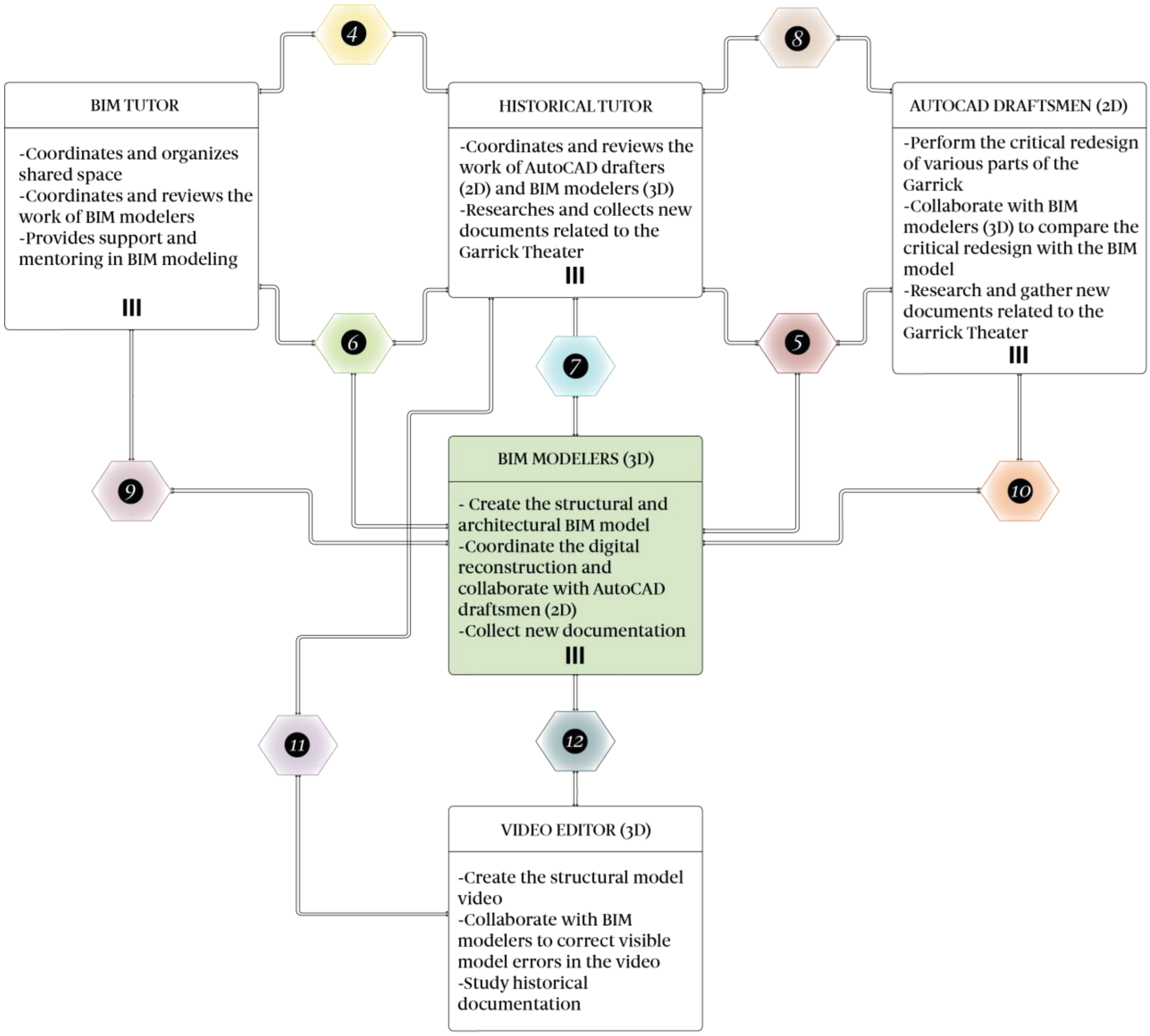

Fig. 12: Users and relationships in the historical digital reconstruction process of the German Opera House Building Workgroup, Conversation BPMN diagram

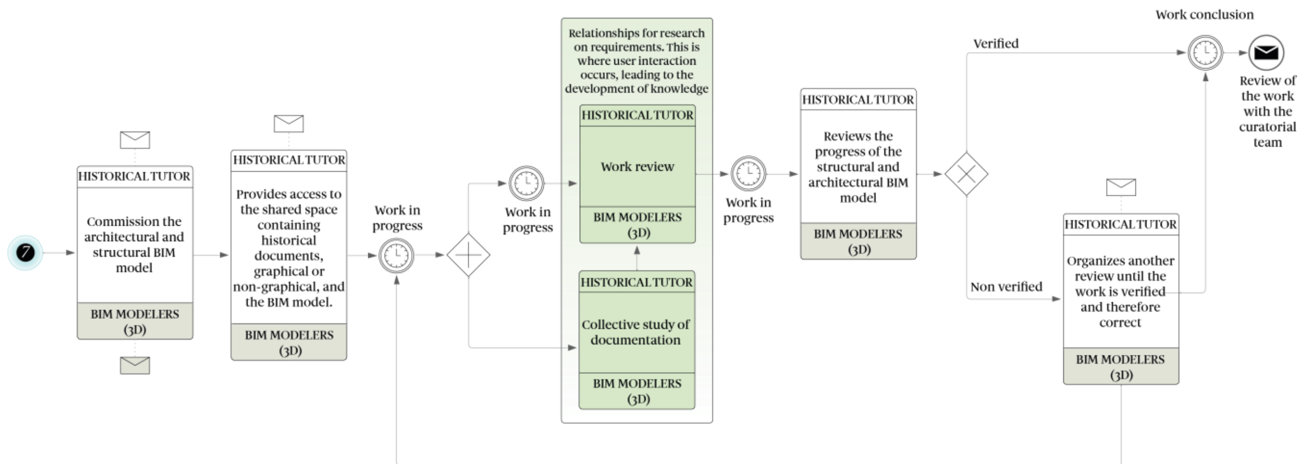

Fig. 13: Analysis of interactions between historical scholar and BIM modelers, choreography BPMN diagram

Fig. 14: Integration of historical 2D detailed documentation with IFC model in a CDE platform, to enrich and adding value to BIM model.

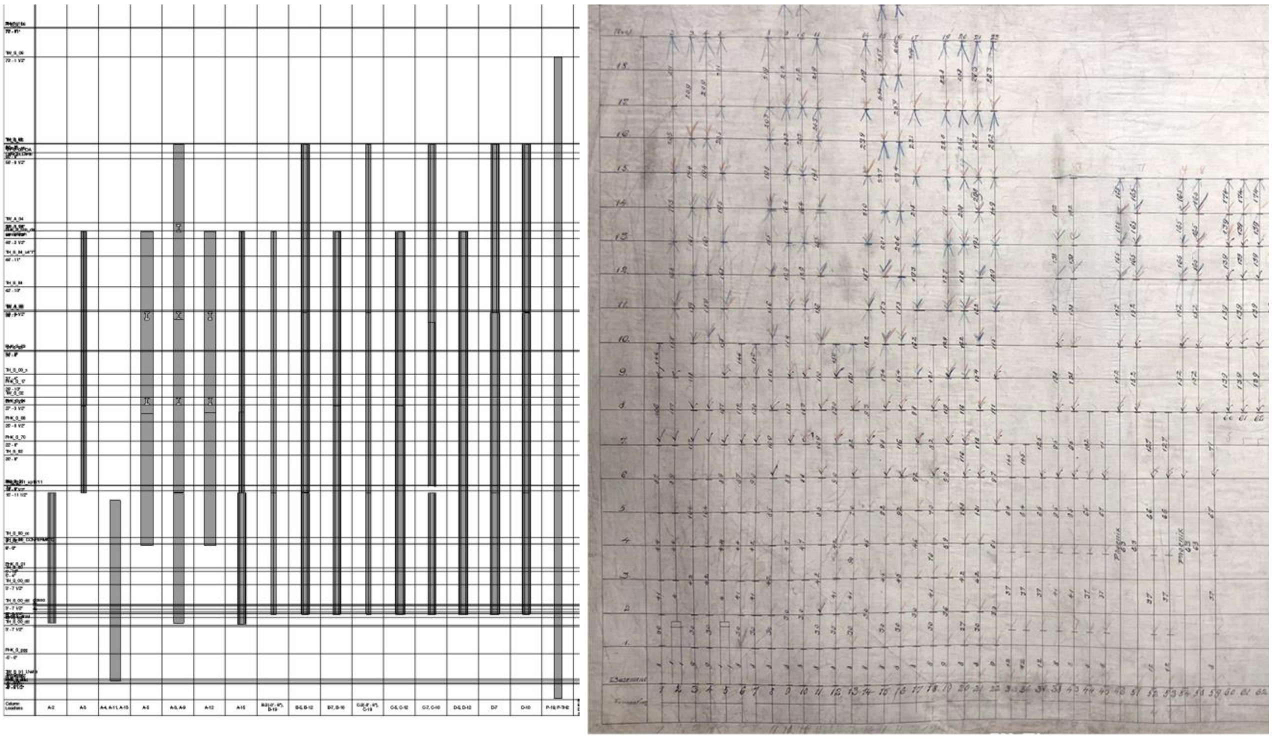

Fig. 15: Column schedules, organized by grid and levels. Derived from BIM (on the left) and original documentation (on the right, The Chicago Historical Society)

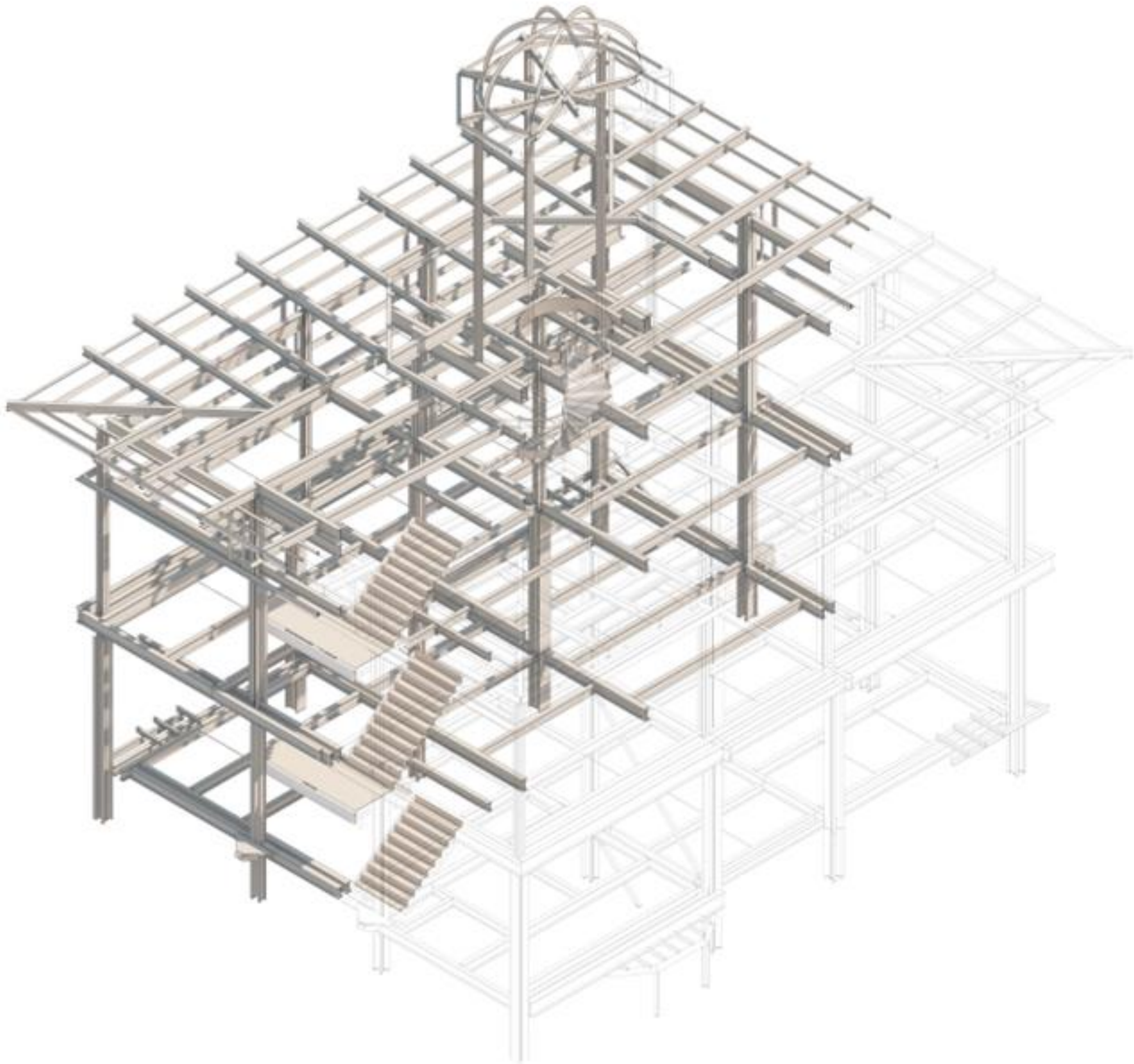

Fig. 16: Attic of the tower with micro-variations in the intrados levels of the beams

Data are considered "raw" elements, subsequently processed for a specific purpose. Once processed, they become "information," taking a form more suitable for human analysis and thus becoming "structured data." Finally, "knowledge" is what an individual develops after understanding a certain amount of information and thus represents a synthesis (Kendal & Creen, 2007). Historical documentation thus constitutes "knowledge" for its original authors and an intermediary point between "data" and "information" for those who will later analyze it. Consequently, analyzing existing data always implies the automatic generation of new information and knowledge. An organization's efficiency is closely related to its ability to collaborate and coordinate. However, as illustrated in the SECI model diagram (Fig. 1), this cycle is efficient only when knowledge is explicit and shared, which leads to considering the issues related to a fourth main theme.

In the context of the case study of the German Opera House Building authors tried to overcome the problems by applying well-evaluated BIM process for the construction industry to historical studies. The approach used requires an organized structure from the early stages. The building has been reconstructed in two BIM authoring tools. As already presented in literature and discussed in the fourth paragraph, the digital reconstruction followed the design logic as extracted by shop drawings, demonstrating that BIM can support historical studies better than generic CAD systems (Fig. 16).

The architectural and the structural models created have been coordinated thanks to a Common Data Environment which can link modelled objects to both graphical and textual documentation. Moreover, graphical documentation may be shown in the 3D environment to demonstrate accuracy and the origin of the data. The CDE provides other valuable functions for information management and solving the issues discussed in this paper. For example, it offers a metadata document organization system, which is useful for cataloging complex documents. In addition, it includes an annotation feature that integrates discussions and information sharing with specific document and/or model components. This function also allows users who may not have expertise in the BIM field to participate in the process.

The innovation of the case study lies in its integration of traditional architectural documentation with state-of-the-art BIM-based technology. This approach supports the visualization and management of non-existing buildings by combining historical data with advanced modeling techniques, in a different level of geometry. By embedding detailed graphical documentation into a CDE and aligning it with BIM models, the project set a new standard for accuracy and efficiency in architectural and construction planning. This innovative strategy bridged the gap between conventional 2D blueprints and modern 3D modeling, offering a more comprehensive and interactive understanding of structural technologies, especially in the case of lost construction and the overall architectural essence of the Opera House.

Since the physical structure no longer exists, historical documentation plays a fundamental role in legitimizing the accuracy of the work performed. Due to the complexity of the material and the structural technological setting of the building, the case study is significant, making it suitable for an investigation into knowledge management in the digital reconstruction of an historical building. The digital reconstruction was useful in identifying gaps in the original documentation.

From an historical perspective, the work revealed how the building represents a fusion of technologies from two ages, combining thick brick walls with a steel, iron, and cast-iron frame. Structural joints feature both established and innovative solutions that foreshadow future construction techniques. Consequently, the German Opera House Building is a fundamental piece for advancing historical studies related to the development of construction technologies for tall buildings between the 19th and 20th centuries.

6. *Conclusion and future works*

The article addresses the challenge of reconstructing demolished historical buildings in digital humanities.

In the area BIM modeling for existing building, it is crucial to organize and harmonize two-dimensional representations and documents to attain a clear understanding of the asset's initial conditions. Typically, document analysis is complemented by metric survey operations, which accurately capture the current state and, if necessary, compare it with project alternatives indicated by design documentation.

In cases where buildings no longer exist and surveys are not feasible, organizing existing documentation—such as images, written records, and graphic materials supporting both the project and execution phases—is essential for the quality of historical research outcomes.

Thes paper catalogs the primary challenges in creating a shared knowledge base, highlighting the intrinsic complexity of historical documents. It explores the heterogeneity, fragmentation, and interconnectedness of data and information within these documents, as well as the complexity of tools and collaborative processes for knowledge sharing within a team.

To address these challenges, it has been proposed to adapt BIM model construction methods for historical research on non-existent buildings. It specifically examines the relationship between graphic documents and model components, both within existing BIM software and Common Data Environments. The methodological principles discussed are applied to a particularly representative case: the German Opera House Building by Louis Sullivan and Dankmar Adler. The results are detailed in the fifth section of the article.

The forthcoming advancements in this study are directed towards investigating analogous case studies via a thoroughly digitized methodology. This approach entails assembling a proficient team capable of engaging with interoperable platforms, encompassing not only BIM models, as demonstrated in this present study, but primarily focusing on semantically annotated documents. These documents can facilitate the correlation between segments of textual data and corresponding model elements or their aggregations. This methodology enhances the linkage between textual data and model elements, elevating understanding and facilitating broader dissemination of knowledge to a wider audience.

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REFERENCES

Abergel, V., Manuel, A., Pamart, A., Cao, I., & De Luca, L. (2023). Aïoli: A reality-based 3D annotation cloud platform for the collaborative documentation of cultural heritage artefacts. *Digital Applications in Archaeology and Cultural Heritage*, *30*(December 2021)

Antinucci, F. (2011). Parola e immagine: storia di due tecnologie. In *Parola e immagine : storia di due tecnologie*. Laterza.

Apollonio, F. I., Fallavollita, F., & Foschi, R. (2021). The Critical Digital Model for the Study of Unbuilt Architecture. *Communications in Computer and Information Science*, *1501 CCIS*, 3–24. https://doi.org/10.1007/978-3-030-93186-5_1

Argiolas, C., Prenza, R., & Quaquero, E. (2015). BIM 3.0 dal disegno alla simulazione: nuovo paradigma per il progetto e la produzione edilizia. In *BIM 3.0 dal disegno alla simulazione nuovo paradigma per il progetto e la produzione edilizia*. Gangemi.

Boochs, F., Trémeau, A., Murphy, O., Gerke, M., Lerma, J. L., Karmacharya, A., & Karaszewski, M. (2014). Towards a knowledge model bridging technologies and applications in cultural heritage documentation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *2*(5), 81–88. https://doi.org/10.5194/isprsannals-II-5-81-2014

Borin, P., Monteleone, C., Bernardello, R., & Gazzetta, A. (2019). Hypothetical Engineering: from drawing to BIM-based simulation for the Civic Museums in Padua by Maurizio Sacripanti. In P. Belardi (Ed.), *Reflections. The art of drawing / The drawing of art* (pp. 1071–1080). Gangemi.

Brandi, C. (2000). *Teoria del restauro*. G. Einaudi.

Catalano, C. E., Repetto, A., & Spagnuolo, M. (2017). A Dashboard for the Analysis of Tangible Heritage Artefacts a Case Study in Archaeology. In T. Schreck, T. Weyrich, R. Sablatnig, & B. Stular (Eds.), *Eurographics Workshop on Graphics and Cultural Heritage*. The Eurographics Association.

Cornelius, P., and Borrmann, A., Hannah, and M., Markus, and K., & Sven-Eric, and S. (2018). Common Data Environment. In Borrmann André, M. and König, and K. Christian, & and B. Jakob (Eds.), *Building Information Modeling: Technology Foundations and Industry Practice* (pp. 279–291). Springer International Publishing. https://doi.org/10.1007/978-3-319-92862-3_15

Daniska, D., & Vrban, B. (2023). Decommissioning planning: Empowering efficiency through BIM modelling and a single-source-of-truth framework. *Nuclear Engineering and Design*, *414*.

Davis, D. (2021). *CAD's Boring Future and Why it's Exciting – Daniel Davis*. https://www.danieldavis.com/cads-boring-future/

Demetrescu, E., Fanini, B., & Cocca, E. (2023). An Online Dissemination Workflow for the Scientific Process in CH through Semantic 3D: EMtools and EMviq Open Source Tools. *Heritage*, *6*(2), 1264–1276.

Duhon, B. G. (1998). *It's all in our heads*. https://api.semanticscholar.org/CorpusID:147965152

Frommel, S., Apollonio, F. I., Gaiani, M., & Bertacchi, G. (2020). Some reconstruction hypotheses of Leonardo's project for the tiburio of the Milan cathedral by using 3D digital models. *SCIRES-IT - SCIentific RESearch and Information Technology*, *10*(1), 53–66. https://doi.org/10.2423/I22394303V10N1P53

Galeazzo, L. (2022). Analysing Urban Dynamics in Historic Settlements Using a Geo-Spatial Infrastructure. The Venice?s Nissology project. *Journal of Art Historiography*, *27s*, 1–13.

Garagnani, S., Cancilla, A., & Masina, E. (2019). Understanding the design intent through the analysis of Renaissance drawings. The digital reconstruction of an unbuilt mausoleum by Giuliano da Sangallo. *SCIRES-IT - SCIentific RESearch and Information Technology*, *9*(2), 57–68. https://doi.org/10.2423/I22394303V9N2P57

Giordano, A., Friso, I., Borin, P., Monteleone, C., & Panarotto, F. (2018). *Time and Space in the History of Cities* (pp. 47–62). https://doi.org/10.1007/978-3-319-76992-9_4

Huffman, K. L., & Giordano, A. (2021). Visualizing Venice to Visualizing Cities - Advanced Technologies for Historical Cities Visualization. *Communications in Computer and Information Science*, *1501 CCIS*, 171–187. https://doi.org/10.1007/978-3-030-93186-5_8

Ikujiro, N., & Hirotaka, T. (1995). The knowledge-creating company: how Japanese companies create the dynamics of innovation. In *The *knowledge-creating company how Japanese companies create the dynamics of innovation*. Oxford university press.

ISO. (2018). *ISO 19650-1:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) -- Information management using building information modelling -- Part 1: Concepts and principles*.

Kendal, S., & Creen, M. (2007). *An Introduction to Knowledge Engineering* (1st ed. 2007.). London :Springer.

Kouider, T., Paterson, G., & Thomson, C. (2007). Bim as a viable collaborative working tool: A case study. *CAADRIA 2007 - The Association for Computer-Aided Architectural Design Research in Asia: Digitization and Globalization*, 57–68.

Kuroczyński, P., Apollonio, F. I., Bajena, I. P., & Cazzaro, I. (2023). Scientific Reference Model - Defining Standards, Methodology and Implementation of Serious 3d Models in Archaeology, Art and Architectural History. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVIII-M–2*, 895–902. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-895-2023

Münster, S., Apollonio, F. I., Bell, P., Kuroczynski, P., Di Lenardo, I., Rinaudo, F., & Tamborrino, R. (2019). Digital Cultural Heritage meets Digital Humanities. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLII-2/W15*, 813–820. https://doi.org/10.5194/isprs-archives-XLII-2-W15-813-2019

Polanyi, M. (1966). *The tacit dimension*. Doubleday.

Roussel, R., & De Luca, L. (2023). An Approach to Build a Complete Digital Report of the notre Dame Cathedral after the Fire, Using the Aioli Platform. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVIII-M–2*, 1359–1365.

Saygi, G., Agugiaro, G., Turan, M., & Remondino, F. (2013). Evaluation of GIS and Bim Roles for the Information Management of Historical Buildings. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *II-5/W1*, 283–288.

Succar, B. (2019). 211in - Model Uses Table. In *BIMe Initiative*. https://doi.org/10.5281/zenodo.3563403

Turkle, S. (2009). *Simulation and Its Discontents*. MIT Press.

Vinci, J., Samuelson, T., Nordstrom, E., & Chris Ware. (2021). *Reconstructing the Garrick: Adler & Sullivan's Lost Masterpiece*. Alphawood Foundaton.

Vogel, Q., De Luca, L., & Borruey, R. (2023). Building AN Intrinsic Protection of 20TH Century Architectural Heritage in Marseille: a Tooled Methodology for Knowledge Enrichment. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVIII-M–2*, 1637–1644. https://doi.org/10.5194/isprs-archives-XLVIII-M-2-2023-1637-2023.