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Research Article

A CASE STUDY OF CLASH DETECTION FOR EARLY DESIGN PHASES IN BUILDING INFORMATION MODELLING

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Keywords

3D Coordination; Design Errors; Soft Clash; Hard Clash; Co-occurrence Analysis

Abstract The utilization of digital modeling, monitoring, and simulation techniques in architectural and engineering projects at a real-world scale, following a predetermined workflow schedule, presents numerous advantages to key players and users involved in the construction process. Building information modeling and one of its associated advantages, clash/overlap detection, can play an important role during the initial stages of design development. The analysis of clash detection, which is a method that effectively identifies the overlap between spatial and three-dimensional geometric entities, facilitates a feedback-based design approach. The process of identifying and analyzing clashes can be conducted prior to the implementation phase, so guaranteeing long-term viability in relation to both temporal and financial aspects. In the context of this work, an examination of the available literature was conducted utilizing bibliometric approaches to get insight into the theoretical underpinnings of clash detection. In the present situation, significant clusters were acquired. In the methodology section, the modeling of the architectural design and structural project design for a two-storey architecture student center (ASC) project, spanning roughly 1200 square meters, was undertaken. The architectural and structural concepts of this project were designed using Autodesk Revit 2020 software, which is one of the building information modeling tools. Subsequently, clash detection analysis was employed. The analysis of clash detection was carried by using Autodesk Navisworks Manage 2020 software. The clashes, both soft and hard, were categorized and examined based on the achieved outcomes.

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Introduction

The successful implementation of digitalization processes holds significant value within the architecture, engineering, construction, and operations (AECO) industries. Computer-aided design (CAD) technologies and the adoption of building information modelling (BIM) practices have exerted a significant influence on both national and worldwide contexts within the facility construction management and building industry. Numerous benefits of employing BIM approaches are used by stakeholders within the construction sector. BIM has altered building design, construction, and operation, helping enhance profitability, decrease costs, improve time management, and improve client-customer interactions (Azhar, Khalfan & Maqsood, 2012). Various users in the organization, including design teams, 3d modelers, project managers, developers, investors, and field engineers, can derive advantages from the potential offered by building information modelling. Architectural design and planning processes encompass multiple dimensions and layers, necessitating collaboration with various disciplines, including civil/structural engineering, mechanical engineering, geotechnical engineering, landscape design, and electrical engineering. Accordingly, the management of these disciplines and sub-components from a singular source is a considerable challenge. The development of industry-specific digital technologies and the establishment of effective team collaboration are highly advantageous for the construction operations. The utilization of computer-aided design tools such as 2D or 3D geometry generating tools and visualization platforms has provided foundation for the advancement of digitalization in the field of construction, leading to the development of building information modelling methodologies. Though object-based parametric modeling is crucial to BIM, other design, analysis, control, presentation, and reporting tools can also play an integral part in BIM processes (Eastman, Eastman, Teicholz, Sacks & Liston, 2011). BIM culture has the capacity to coordinate the cohesion between all building components, such as architectural, mechanical, structural, and landscape and stakeholders through virtual platforms. Furthermore, the impact of BIM models is crucial in conducting 4D, 5D, and 6D simulations. By analyzing specific characteristics of construction actions, one can acquire visualizations and reports using these simulations. Besides, the utilization of BIM tools facilitates the generation and supervision of virtual digital twins of infrastructure projects, as well as superstructure projects including public housing, hotels, cultural and sports venues, and industrial facilities. BIM methodologies are useful for spatial processing and visualization, therefore using 3D models to identify possible clashes/conflicts/collisions has gained popularity (Hu & Castro-Lacouture, 2019). The verification of integrated complex digital models across all construction disciplines for a given building is an essential step that should be undertaken prior to the commencement of manufacturing or implementation. The design's effectiveness and efficiency are significantly improved through the implementation of automated clash detection, which relies on BIM techniques (Koo & O'Connor, 2022).

There are potential benefits for the architecture, engineering, and construction industries to use sophisticated BIM digital tools for a variety of purposes throughout project development phases. These benefits can be composed of the 3D spatial analysis, clash avoidance methods, and clash/collision/overlap detection for monitoring and reporting design error occurrences. The primary advantage of BIM in the initial design phase lies in its ability to facilitate design coordination, ensuring the seamless integration and coordination of all design systems to prevent clashes (Wong, Zhou & Chan, 2018). Additionally, monitoring and visualization of design coordination in a three-dimensional setting is of utmost importance, particularly for complex projects. Since collision detection is performed in a 3D environment, it is also important to develop domain-oriented algorithms. Chidambaram (2020) asserts that clash-detection procedures utilize either “rule-based or geometry-based algorithms” to analyze the model and recognize probable conflicts. Transferring digital models of the same building from different disciplines to a common environment and computing their spatial and geometric relationships in terms of intersections and three-dimensional proximity constitutes clash detection (Figure 1). Clash detection, a parametric modeling technique that evaluates the proximity of 3d constituents in a model, can be performed by stand-alone BIM tools (Bockstael & Issa, 2016). By doing clash/overlap detection, it becomes feasible to effectively handle the tasks of visualizing, reporting, and monitoring design errors, hence facilitating the formulation of revision procedures as and when required. Specifically, the ability to visually represent design errors in 3D is crucial not just for effectively managing construction in large-scale projects, but also for supporting effective communication and collaboration between the design and implementation teams. Once the design faults have been rectified through revision, the conflict detection analysis can be conducted anew, allowing for a comparison between the initial and revised versions of potential design issues. These benchmarking processes enhance the project management process by making it analytical and programmatic, hence minimizing design development efforts such as shop drawings or on-site drawings. By doing so, it enables the development of a sustainable strategy in the domains of financial management and human resources management. Clash/overlap detection can provide a significant and tangible contribution to the project stakeholders and help reduce the project timeline. Nevertheless, prior preparation is necessary for this analysis.

Clash detection necessitates the inclusion of 3D project development task packages. Initially, it is important to develop 3D project models such as exterior walls, curtain walls, slabs, suspended ceilings, foundations, doors, windows, façade elements, staircases, elevators, ramps, interior walls, structural elements, roof systems, lighting fixtures, HVAC (heating, ventilation, and air conditioning) elements, plumbing systems, car or bicycle parking elements, and landscape parts and establish a comprehensive project timeline. The initial phase encompasses several elements, including the collection of project input data such as textual data and specifications, the development of 3D semantic models that incorporate both geometric objects and qualitative data, drafting of a preliminary project schedule outlining the sequence of work packages, and the determination of the desired level of detail for the models (Figure 1).

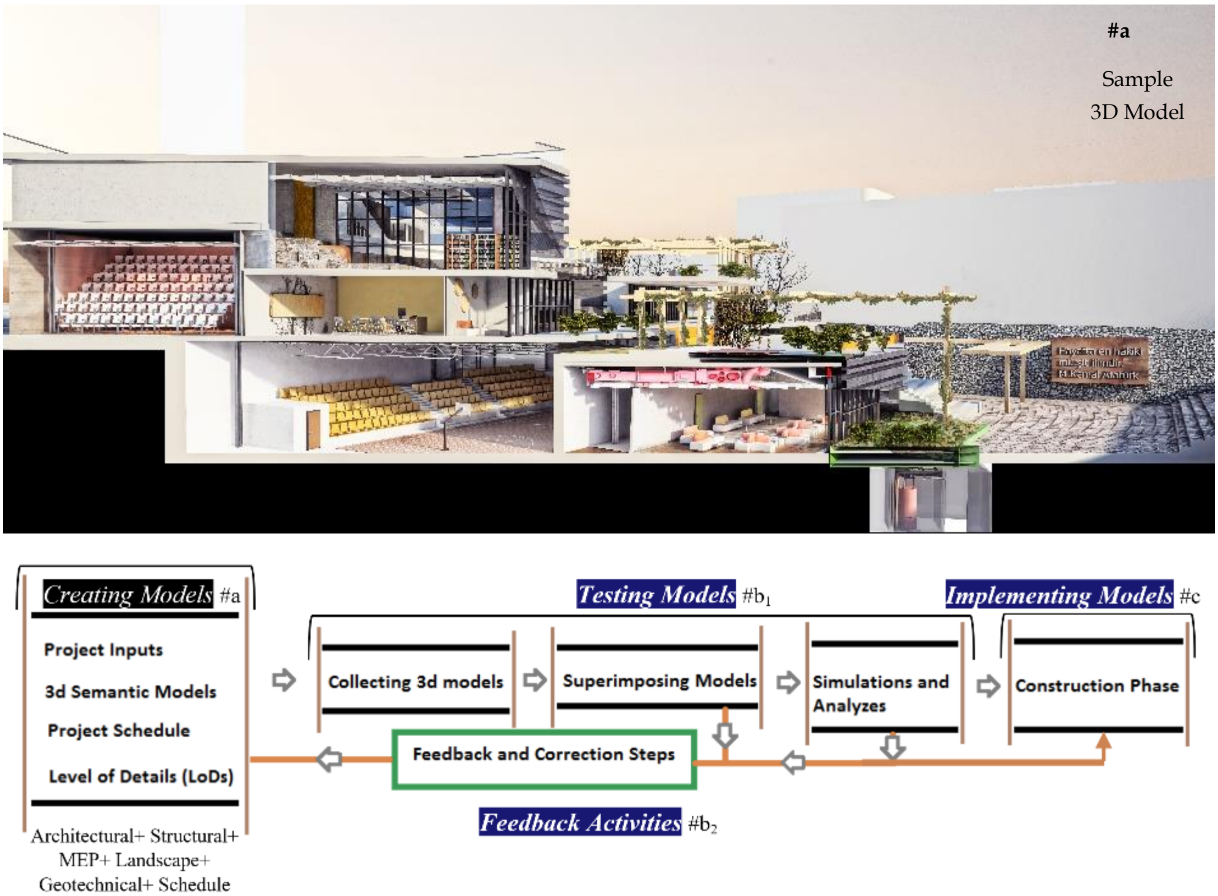


Figure 1. BIM-based clash detection sample workflow (lower) and integrated model (upper) (Drawn by Authors, 2023).

The initial clash detection stage is conducted by all project teams, including architectural, mechanical, electrical, and other relevant disciplines, with the purpose of generating models specific to each respective field. The subsequent phase involves the gathering of models from many disciplines of study. The subsequent phase involves the superimposition of the models. Subsequently, the amalgamated models are transported to alternative contexts to facilitate simulation and analysis. Given that the stages are all part of the pre-production process, it is feasible to conduct tests and simulations in virtual environments, hence allowing for the identification and rectification of design mistakes. The practical detection of clashes is encompassed within the technique employed in this study, as depicted in Figure 1. The present study involves an examination of a specific scenario, wherein a clash detection is conducted utilizing contemporary digital tools. The workflow employed in this analysis is thereafter presented in a diagram schematically. The objective of this study is to assess the clash detection methodology, which holds a significant position in the BIM culture, by conducting a case study and analyzing the procedure. This study is a practical investigation that aims to comprehend the inputs and progression of the process by conducting a case study. This study additionally investigates the various aspects related to the architectural and structural systems of a two-story social and cultural center, spanning approximately 1,200 square meters. These aspects include conceptual design, 3D modeling (such as architectural, structural, artificial lighting, and landscape), clash detection, labeling, reporting, and comparative analysis.

Progress was achieved in accordance with the architectural program, design choices, and the suggested structural system during the concept design and 3D modeling stages. Subsequently, preparations were undertaken for the analysis of clash detection. The analysis procedure was executed, and outcomes were acquired. Based on the acquired outcomes, remarks were resulted regarding the locations and types of clashes. Besides, a systematic literature review has been carried out to interpret the integration between BIM and clash detection through the studies and to understand what may be the missing aspects.

Theoretical Framework

BIM can be used in both infrastructure (Bradley, Li, Lark & Dunn, 2016) and superstructure (Yamazaki, Tabuchi, Kataoka & Shimazaki, 2014) projects. Furthermore, BIM has the capacity to be applied in the field of lean management (Eldeep, Farag & Abd El-hafez, 2022) and sustainable projects, also known as "green BIM" (Krygiel & Nies, 2008). The approaches of BIM techniques provide the potential to significantly transform the design culture and, consequently, the virtual design and construction phases. BIM digitally generates an exact virtual model of a building by simulating the construction process in a virtual environment (Azhar, Nadeem, Mok & Leung, 2008). A significant benefit is the provision of a shared virtual environment for users and stakeholders, which remains accessible across various design phases. Therefore, using design feedback mechanisms helps expedite the revision processes. In contrary to computer-aided design methodologies, the utilization of BIM technology and its various components, including inter-systems coordination and tangible contributions to early design phases (such as clash prevention, mass modeling, conceptual design development, creating project time schedule, cost analysis, developing fabrication strategies for prototypes, building energy analysis, and generative design), holds promising benefits for several designers and decision makers (such as BIM managers, architects, lead designers, and BIM engineers). Identification of 3D clashes is essential to solve errors or significant conflicts before implementation to prevent delays and costs, and also resolving serious conflicts is the most time-consuming and difficult task (Lin & Huang, 2019). Clash detection a crucial component of the BIM culture and is important for designers and engineers to conduct 3D analyses in virtual environments. In this context, this study uses bibliometric tool to explore the terms of “clash detection” and “building information modeling” terms as discussed in the existing literature. Bibliometric analyses are key for comprehending the overall structure of studies and assessing their distribution throughout time. Besides, bibliometric or scientometric analyses related to BIM are also available in literature (Jin, Zou, Gidado, Ashton & Painting, 2019; He et al., 2017; Zhao, 2017; Liu, Lu & Peh, 2019; Olawumi, Chan & Wong, 2017; Li, Wu, Shen, Wang & Teng, 2017). By conducting these analyses, we can observe the role of conflict/clash/overlap detection analysis in the BIM culture and its connection with other disciplines. Furthermore, we can visualize the impact of BIM through the obtained results. Therefore, during the development of the theoretical framework for this study, we applied the aforementioned analyses and visualized the outcomes as patterns.

Clash management plays a crucial role in ensuring the consistent quality of design and mitigating the need for adjustments or rework at the construction site (Hu, Castro-Lacouture, Eastman & Navathe, 2021). The field of clash detection in 3D building information modeling has undergone significant advancements since its initial development in the disciplines of computer graphics and robotics (Akponeware & Adamu, 2017). The results of the clash/collision detection analysis can be categorized into different categories. Tommelein and Gholami (2012) suggest that clashes can be categorized into three distinct types: soft clash, hard clash, and time clash. Soft clash or clearance clash is a failure caused by insufficient space between components (for reasons such as "access, insulation, and safety") (Seo, Lee, Kim & Kim, 2012, p.306). In a hard clash, two building components occupy the same space completely or partially (Trebbi, Cianciulli, Matarazzo, Mirarchi, Cianciulli & Pavan, 2020). Time clash, in contrast to the definitions of soft and hard clash, "includes spatial challenges to constructability or operability" (Tommelein & Gholami 2012, p.3). Besides, according to Wang & Leite (2016), the speed of the clash detection technique has been increased, and the visualization capabilities have been improved by utilizing programs, such as Autodesk Navisworks Manage and Solibri Model Checker. According to Elyano (2021), building information modeling-based clash analysis is a potential task for productivity on construction projects.

To comprehend and interpret the concept of "clash detection", which is a subcomponent of building information modelling technology, using bibliometric analysis on academic big data, the first step is defining the scope of this research's theoretical framework section. One of the points of this study`s theoretical framework is to understand the relationship between building information modeling and clash detection, using academic big data (Figure 2).

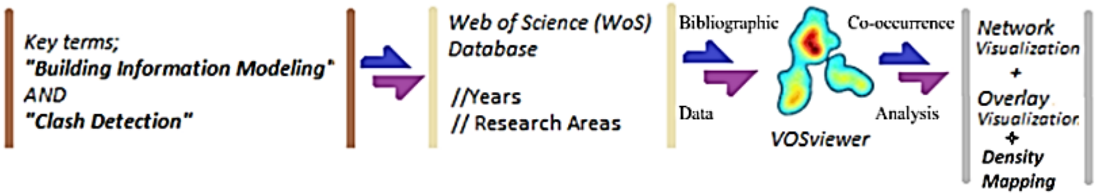


Figure 2. Bibliometric analysis path for this study (Drawn by Authors, 2023).

Using VOSviewer (Van Eck and Waltman, 2010; Van Eck and Waltman, 2014) tool, a visual representation was generated to illustrate the interconnections of scholarly publications pertaining to clash detection, which were sourced from the SCI-E and SSCI databases. Initially, the phrase "building information modeling" and "clash detection" were inputted (together and separately) as search keywords within the Web of Science (WoS) database, and the resulting metadata was subsequently transferred to the VOSviewer digital tool. Based on the findings of the co-occurrence analysis, it is evident that the word "Clash detection" term has emerged as a prominent focus in recent scholarly investigations (Figure 3).

Subsequently, a bibliometric analysis centered on the term "clash detection" was conducted by establishing rules, fine-tuning parameters, and implementing filters (e.g., cleaning repeating terms) within the VOSviewer platform. According to the co-occurrence analysis performed on the term "clash detection," seven clusters were established, and the number of items inside each group was distributed in a non-normalized technique (Figure 4a and 4b). An examination of the group components reveals that their applications are most prevalent in the sectors of construction management, information system, 4-D simulation, and design coordination. Other groupings include data visualization, perception, simulators, simulations, enjoyment, game play, and experiences.

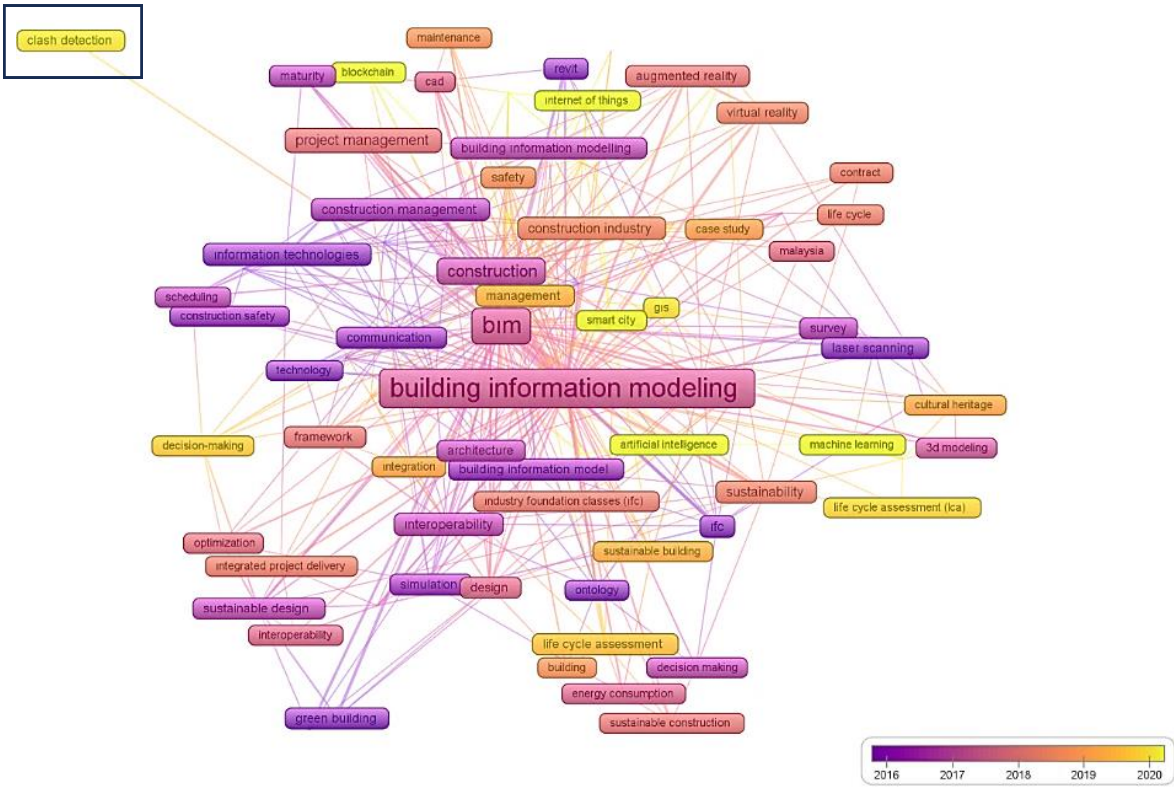
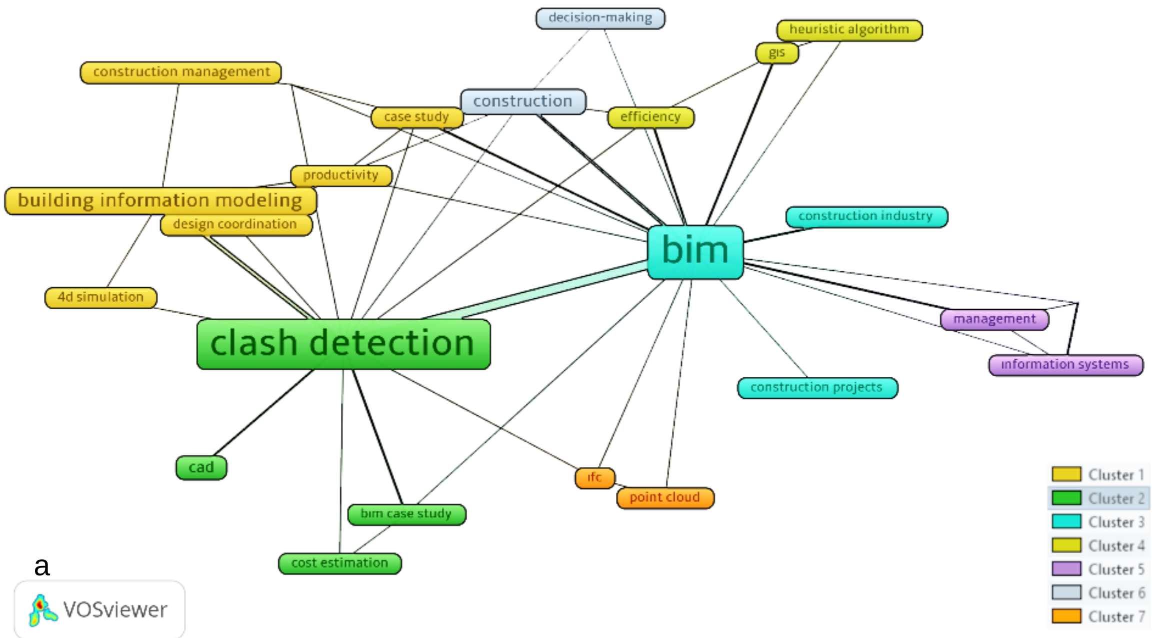


Figure 3. Results of co-occurrence analysis via network mapping (Drawn by Authors via VOSviewer, 2023).



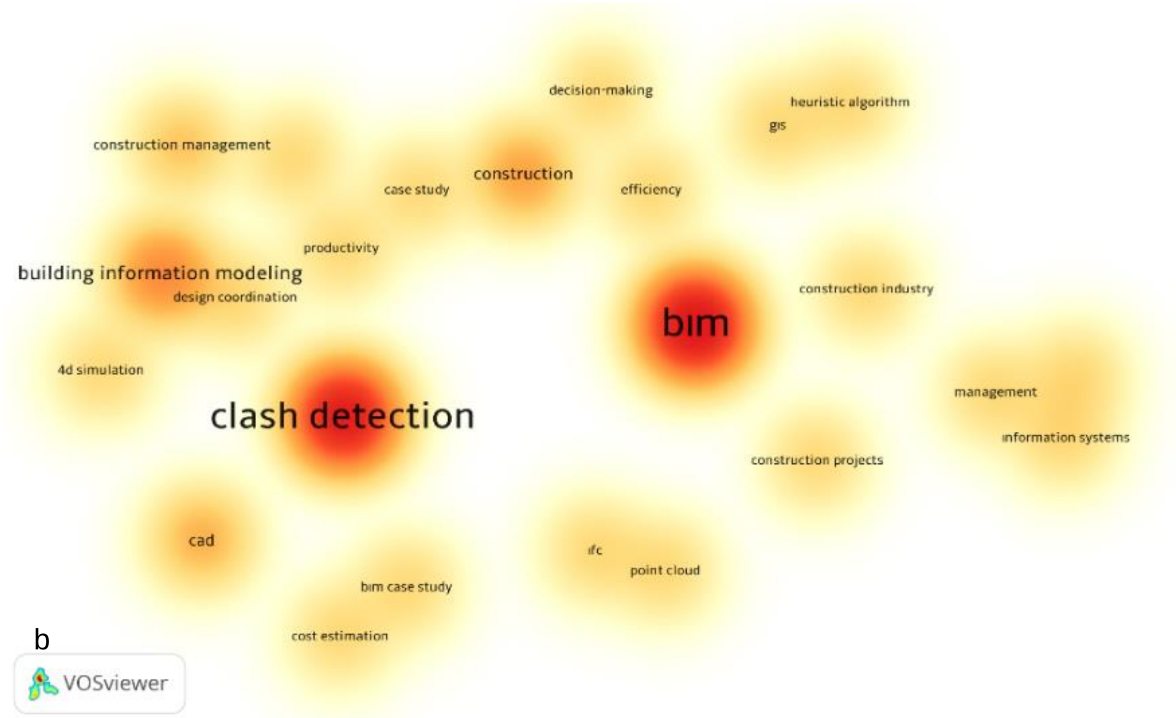


Figure 4. a) Results of co-occurrence analysis via network, b) Results of co-occurrence analysis via density mapping (Drawn by Authors via VOSviewer, 2023).

Methodology

Within the context of the building information modelling culture, the generation of three-dimensional models and the identification of conflicts through clash detection analyses play a crucial role in the design process. A process referred to as clash detection, collision detection, or coordination must be performed on multiple BIM models to achieve harmonious coordination (Chidambaram, 2020). An essential and fundamental component of BIM, conflict detection occurs during the design phase to rectify issues or errors discovered prior to construction beginning (Rakib, Howlader, Rahman & Bhuiyan, 2019). This study encompasses various components related to a two-story social-cultural institution with an enclosed space of approximately 1200 square meters, including design development, digital modeling, transferring 3D models, clash detection analysis (e.g., architectural model and draft structural model), manual inspection and labeling, reporting, 4D simulation such as micro and macro 4D simulations for time clash, and comparative analysis (Figure 5).

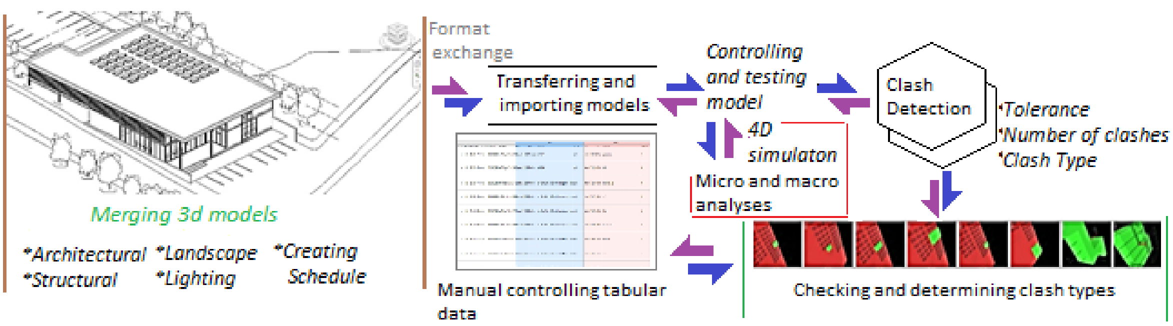
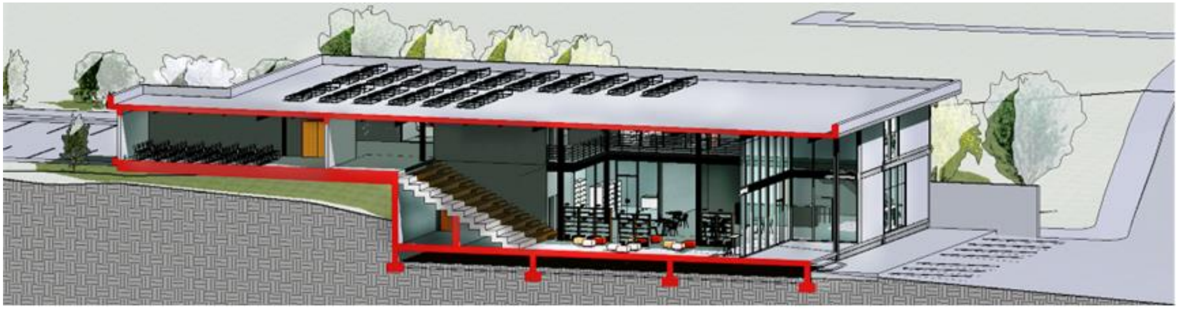


Figure 5. Workflow of this study's clash detection process (Drawn by Authors, 2023).

Initially, the requirements program was delineated, and subsequent design selections were formulated through a collaborative manner, incorporating ergonomic and sustainable considerations pertaining to the facility. The project aims to create a novel environment that facilitates student interaction, as the current lack of designated spaces for socializing, collaborating, studying, and knowledge exchange among students is evident. The objective of this project was to include principles of sustainability into the curriculum of architecture students as well as extend its impact to the entire campus community. The proposed project is intended to be constructed on the northeastern side of the E block, which is situated at the Urla campus of Izmir Institute of Technology (IZTECH), specifically within the premises of the Faculty of Architecture. The determination of the spatial arrangement of semi-open, open, and closed areas, as well as the selection of landscape features and architectural spaces, was undertaken at the initial phase of concept design. Concurrently, an architectural model was generated using building information modeling tools (i.e., Autodesk® Revit® 2020) to facilitate the conceptual mass design and visual depiction of preliminary concepts (Figure 6). The level of detail (LoD) was established as 100 during the concept phase and increased to 300 for the final model. The proposed project's structural system, characterized by a composite form in structural terms, has been meticulously planned and modeled with a comparable level of detail. Lighting components were designed and integrated into the interior space. Simultaneously, the draft 3D model incorporated both semi-open and open space configurations, as well as landscape design decisions. An integrated model was generated by incorporating architectural, structural, lighting, and landscape design selections into the modeling process. The model's components, which incorporate both architectural and structural features, may require verification in accordance with the conceptual design rules. Hence, verifying the integrated 3D model is another crucial step. Adjusting the geometry of the components in the model is another factor that aids the process. The attribute tables that have been generated should also undergo verification during the control phase. The final stage of the process was conducting a clash detection analysis (Figure 7).

The three-dimensional geometric system was subsequently loaded into Autodesk® Navisworks® Manage 2020, utilizing the specific (.NWC) file format (Figure 7). Several research have demonstrated the contribution of this digital tool to the process of clash identification and reporting (Porwal & Hewage, 2013; Valunjkar, 2017; Kermanshahi, Tahir, Lim, Balasbaneh & Roshanghalb, 2020). After being transferred to a Navisworks environment, it is important to quickly verify the geometry. Prior to conducting an analysis, it is necessary to establish clear and well-defined clash rules.



Level	Room Name	Area (m²)
ENTRANCE LEVEL (-3.00 m)	Entrance Hall	38.00 m²
	Cafe & Bar	151.40 m²
	Hall	49.28 m²
	Multifunctional Area	101.01 m²
	Stores	71.52 m²
	Service Room	23.50 m²
	Storage	32.26 m²
	WCs	6.68 m²

Level	Room Name	Area (m²)
SECOND LEVEL (+1.00 m)	Administration Office	30.43 m²
	Conference Room	92.63 m²
	Entrance Hall	75.39 m²
	Hall	73.46 m²
	Lecture Room	56.19m²
	Medical Room	12.74 m²
	Meeting Room & Group Study	30.87m²
	Office	38.04 m²
	Rest Room	4.54 m²
	Service Room	23.50 m²
	Storage	7.40 m²
	WCs	18.06 m²

Figure 6. Architectural conceptual program (lower) and proposed conceptual 3D model (upper) (Drawn by Authors, 2023).

During clash detection protocols, it is necessary to define the types of clashes, so it is important to accurately determine the rules and metric limits. These rules are entered into the system prior to analysis. The determination of tolerance value ranges is conducted during this stage. Besides, the precision of clash detection can be enhanced by eliminating conflicts that are no longer pertinent (Hu, Castro-Lacouture & Eastman, 2019). Hasannejad, Sardrud & Shirzadi Javid (2022, p.2431) posit that the present approaches to enhance clash detection precision can be classified into three key sections: "avoiding clashes, improving clash detection algorithms, and filtering irrelevant clashes." After filtering and extracting the analysis results in XML format, a thorough examination was conducted to identify and classify both soft and hard overlaps. To determine if there is a collision in workflow or a time overlap, a conceptual work plan was designed. This schedule tries to depict the chronological link between work packages. During the final phase of the project, 4-D simulation models were generated at a macro level of detail, taking into consideration schematic construction durations. Besides, 4-D simulations are highly efficient for visualizing the construction process and project schedule simultaneously.

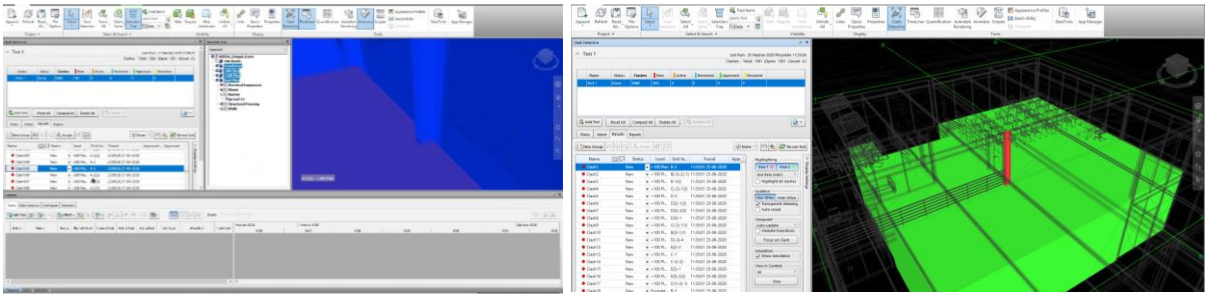


Figure 7. Transferring 3D model to Navisworks environment and defining clash tolerance rules (Drawn by Authors, 2023).

Results

The present study aimed to evaluate the efficacy of clash detection approaches in the context of architectural and structural projects pertaining to a small-scale socio-cultural facility (Figure 8).

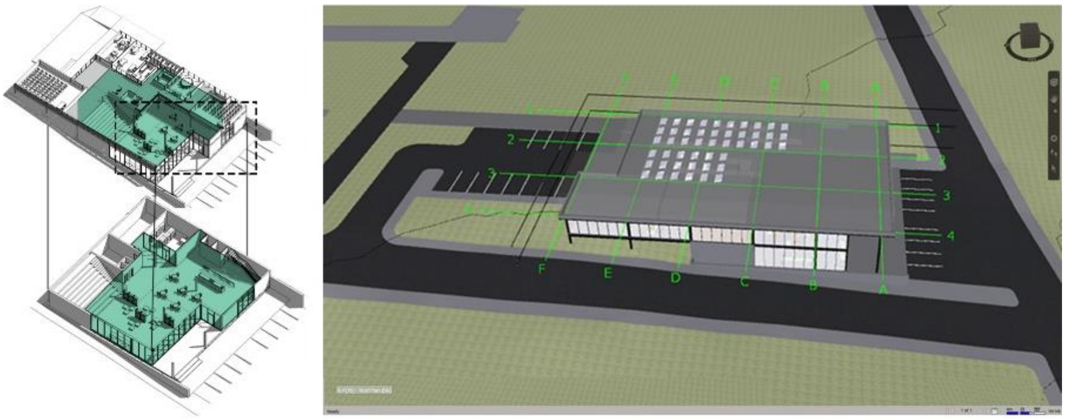


Figure 8. Integrated 3D model for clash detection tests and BIM-based 4-D simulations (micro and macro levels) (Drawn by Authors, 2023).

Within the scope of the study, the clash detection tests were examined in two distinct areas, namely the bottom floor and the first story (Figure 9). Overlap locations and items can be categorized into two main groups: architectural components, such as interior walls, span elements, objects, structural elements (including columns, beams, and slabs). Each section's soft and hard overlaps were painstakingly fine-tuned and manually regulated to ensure consistency. Based on the findings, the first floor exhibited the highest level of inaccuracy, while the bottom floor demonstrated the lowest level of error. The primary factor contributing to the higher rate of overlap on the ground floor can be attributed to the points of connection between the partition walls and the steel beams. The presence of soft overlaps has been attributed to modeling flaws, particularly those related to the inaccurate positioning of components and their interconnections with other objects. While analyzing the geometric relationships between intersecting and closely positioned pieces, it was observed that there were a greater number of architectural-static groups compared to architectural-architectural and static (structural)-static (structural) groups. When analyzing time overlap at the macro detail level for the BIM model, the schedule generated with schematic durations does not contain nesting.

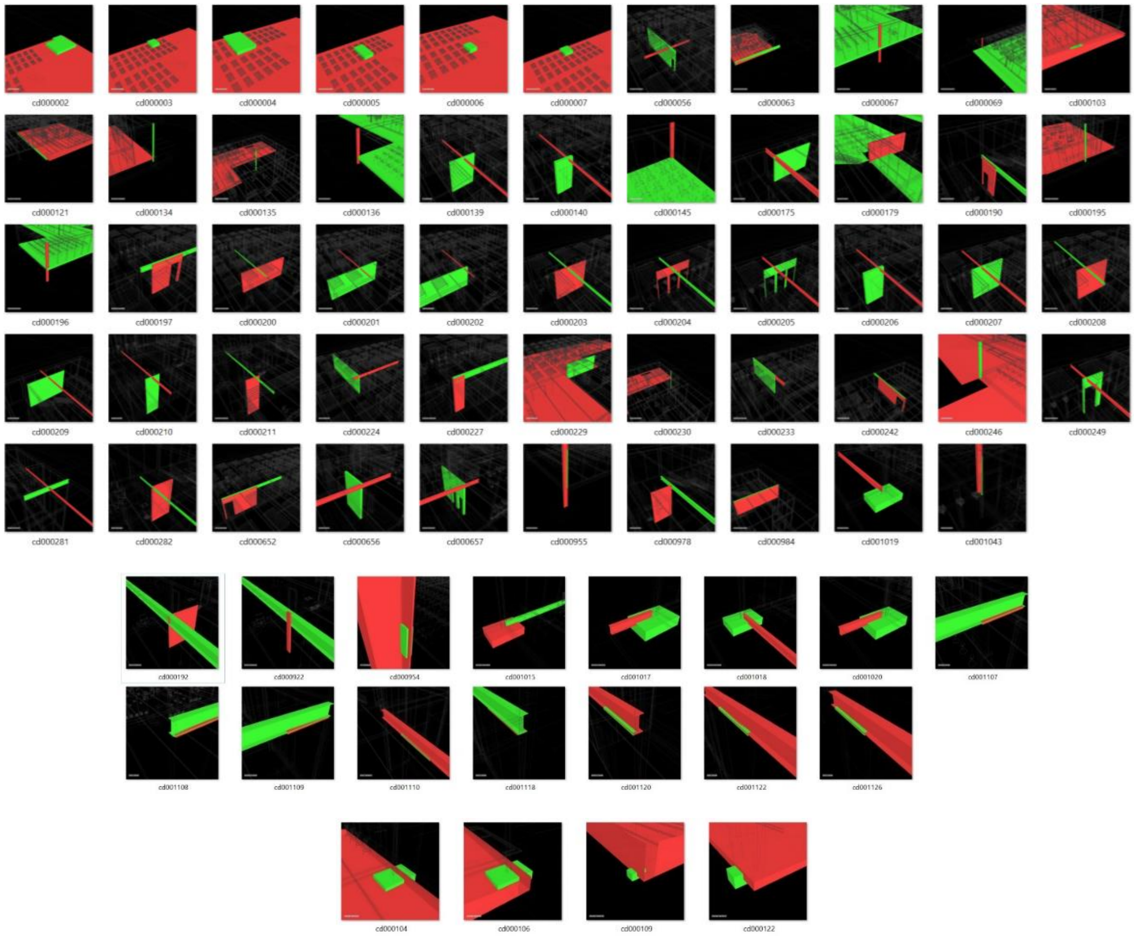


Figure 9. Preliminary Results of Soft and Hard Clashes (Drawn by Authors via Navisworks, 2023).

Conclusion

The utilization of digital environments to produce 1:1 scale replicas of architectural and engineering projects, along with their subsequent monitoring and simulation in accordance with the workflow schedule, offers numerous benefits to stakeholders and users within the construction industry. The utilization of computer-aided design and building information modeling tools has resulted in a pervasive demand for digital documentation within the construction sector. Once comprehensive three-dimensional models have been generated, a wide range of spatial analyses can be conducted. The implementation of BIM culture in construction and project processes enables the execution of 3D spatial analyses in both the design phase and construction activities, leading to more manageable responsibilities for designers. BIM tools enable the design, analysis, and visualization of the coordination and integrity of 3D models. One of the analyses conducted is conflict/clash/collision detection analysis, which examines whether the models from different disciplines intersect geometrically in the virtual environment. Virtual 3D modeling and clash/collision/overlap detection analysis provide numerous advantages to design teams, particularly throughout the design phases of extensive projects. Primarily, it enhances the ability to predict and intervene in the architectural project, hence mitigating the likelihood of comparable challenges being encountered by other teams. The technique facilitates the three-dimensional assessment of the compatibility between architectural projects and projects from other disciplines, including structural, mechanical, and electrical aspects. Hence, the presence of any potential issues related to the intersection of different geometric entities becomes apparent. Once intersection 3D models have been identified, it is crucial to analyze the detection of overlaps and devise solutions for potential issues. Reports can be labeled either manually or automatically. Developing efficient procedures, equations, or algorithms is vital due to the time-consuming nature of this operation.

Clash/collision/overlap detection analysis constitutes a fundamental component within the BIM process, enabling pre-production assessment in both design and field settings. Clash detection analysis also aids in the implementation of feedback design concept, as it allows for the identification of design errors, leading to the development of solutions and subsequent redesign. This analysis effectively unveils the junction between spatial and three-dimensional geometric entities. Besides, the improvement in the design-focused teams' cooperation and problem-solving approach. Spatial and geometric overlaps are a source of difficulty. The model's outcomes in this context are useful for identifying and assessing prospective clashes, as well as developing viable resolutions. Throughout all phases of the project, architects or engineers must employ clash avoidance tactics or conduct clash detection testing. Thus, as part of this study's scope, clash detection, analysis, and reporting were performed on a sample model, and the error causes were identified and reported. Throughout the design phases, there were also tests into the effectiveness of generally clash detection systems, which proved to be useful. This practice yields significant benefits in terms of cost reduction, time efficiency, and labor optimization. The present study exhibits a limited sample size, hence necessitating future investigations to encompass larger and more intricate endeavors. Furthermore, future studies will include testing collision/clash avoidance software that is specifically developed as an extension within the BIM software.

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References

Akponeware, A. O., & Adamu, Z. A. (2017). Clash detection or clash avoidance? An investigation into coordination problems in 3D BIM. *Buildings*, *7*(3), 75.

Azhar, S., Khalfan, M., & Maqsood, T. (2012). Building information modeling (BIM): now and beyond. *Australasian Journal of Construction Economics and Building, 12*(4), 15-28.

Azhar, S., Nadeem, A., Mok, J. Y., & Leung, B. H. (2008, August). Building Information Modeling (BIM): A new paradigm for visual interactive modeling and simulation for construction projects. In *Proc., First International Conference on Construction in Developing Countries* (Vol. 1, pp. 435-46).

Bockstael, D., & Issa, M. H. (2016). A methodology for contractor clash detection using building information modelling on commercial construction projects. *Journal of information technology in construction (ITcon)*, *21*(16), 233-249.

Bradley, A., Li, H., Lark, R., & Dunn, S. (2016). BIM for infrastructure: An overall review and constructor perspective. *Automation in construction*, *71*, 139-152.

Chidambaram, S. (2020). The application of clash-detection processes in building information modelling for rebars. *Proceedings of the Institution of Civil Engineers-Smart Infrastructure and Construction*, *172*(2), 53-69.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.

Eldeep, A. M., Farag, M. A., & Abd El-hafez, L. M. (2022). Using BIM as a lean management tool in construction processes–A case study. *Ain Shams Engineering Journal*, *13*(2), 101556.

Elyano, M. R. (2021). Analysis of clash detection and quantity take-off using BIM for warehouse construction. In *IOP Conference Series: Earth and Environmental Science* (Vol. 794, No. 1, p. 012012). IOP Publishing.

Hasannejad, A., Sardrud, J. M., & Shirzadi Javid, A. A. (2022). BIM-based clash detection improvement automatically. *International Journal of Construction Management*, 1-7.

He, Q., Wang, G., Luo, L., Shi, Q., Xie, J., & Meng, X. (2017). Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis. *International journal of project management*, *35*(4), 670-685.

Hu, Y., & Castro-Lacouture, D. (2019). Clash relevance prediction based on machine learning. *Journal of computing in civil engineering*, *33*(2), 04018060.

Hu, Y., Castro-Lacouture, D., & Eastman, C. M. (2019). Holistic clash detection improvement using a component dependent network in BIM projects. *Automation in Construction*, *105*, 102832.

Hu, Y., Castro-Lacouture, D., Eastman, C. M., & Navathe, S. B. (2021). Component change list prediction for BIM-based clash resolution from a graph perspective. *Journal of Construction Engineering and Management*, *147*(8), 04021085.

Jin, R., Zou, Y., Gidado, K., Ashton, P., & Painting, N. (2019). Scientometric analysis of BIM-based research in construction engineering and management. *Engineering, Construction and Architectural Management*, *26*(8), 1750-1776.

Kermanshahi, E. K., Tahir, M. B. M., Lim, N. H. A. S., Balasbaneh, A. T., & Roshanghalb, S. (2020). Implementation of building information modeling for construction clash detection process in the design stage: a case study of Malaysian police headquarter building. In *IOP Conference Series: Earth and Environmental Science* (Vol. 476, No. 1, p. 012009). IOP Publishing.

Koo, H. J., & O'Connor, J. T. (2022). A strategy for building design quality improvement through BIM capability analysis. *Journal of Construction Engineering and Management*, *148*(8), 04022066. Utilizing building information modeling for automatic collision recognition significantly improves the design process's quality and efficiency.

Krygiel, E., & Nies, B. (2008). *Green BIM: successful sustainable design with building information modeling*. John Wiley & Sons.

Li, X., Wu, P., Shen, G. Q., Wang, X., & Teng, Y. (2017). Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach. *Automation in Construction*, *84*, 195-206.

Lin, W. Y., & Huang, Y. H. (2019). Filtering of irrelevant clashes detected by BIM software using a hybrid method of rule-based reasoning and supervised machine learning. *Applied Sciences*, *9*(24), 5324.

Liu, Z., Lu, Y., & Peh, L. C. (2019). A review and scientometric analysis of global building information modeling (BIM) research in the architecture, engineering and construction (AEC) industry. *Buildings*, *9*(10), 210.

Olawumi, T. O., Chan, D. W., & Wong, J. K. (2017). Evolution in the intellectual structure of BIM research: A bibliometric analysis. *Journal of Civil Engineering and Management*, *23*(8), 1060-1081.

Porwal, A., & Hewage, K. N. (2013). Building Information Modeling (BIM) partnering framework for public construction projects. *Automation in construction*, *31*, 204-214.

Rakib, F. H., Howlader, S., Rahman, M., & Bhuiyan, A. Y. (2019). Application of BIM based interoperability-A case study. *Journal of Logistics, Informatics and Service Science*, *6*(1), 106-114.

Seo, J. H., Lee, B. R., Kim, J. H., & Kim, J. J. (2012). Collaborative process to facilitate BIM-based clash detection tasks for enhancing constructability. *Journal of the Korea institute of building construction*, *12*(3), 299-314.

Tommelein, I. D., & Gholami, S. (2012, July). Root causes of clashes in building information models. In *Proceedings for the 20th Annual Conference of the International Group for Lean Construction* (Vol. 1, No. 510, p. 10). IGLC San Diego, LA.

Trebbi, C., Cianciulli, M., Matarazzo, F., Mirarchi, C., Cianciulli, G., & Pavan, A. (2020). Clash detection and code checking BIM platform for the Italian market. *Digital Transformation of the Design, Construction and Management Processes of the Built Environment*, 115-125.

Valunjkar, M. S. P. R. S. (2017). Improve the Productivity of Building Construction Project using Clash detection Application in Building Information Modeling.

Van Eck, N. J., & Waltman, L. (2014). Visualizing bibliometric networks. In *Measuring scholarly impact: Methods and practice*, 285-320. Cham: Springer International Publishing.

Van Eck, N., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *scientometrics*, *84*(2), 523-538.

Wang, L., & Leite, F. (2016). Formalized knowledge representation for spatial conflict coordination of mechanical, electrical and plumbing (MEP) systems in new building projects. *Automation in construction*, *64*, 20-26.

Wong, J. K., Zhou, J. X., & Chan, A. P. (2018). Exploring the linkages between the adoption of BIM and design error reduction. *Building information systems in the construction industry*, *113*.

Yamazaki, Y., Tabuchi, T., Kataoka, M., & Shimazaki, D. (2014). 3D/BIM applications to large-scale complex building projects in Japan. *International Journal of High-Rise Buildings*, *3*(4), 311-323.

Zhao, X. (2017). A scientometric review of global BIM research: Analysis and visualization. *Automation in Construction*, *80*, 37-47.