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Rule-Based Design and Semantic Modeling: BIM and Procedural Modeling Integration for Digital Twin Architecture

* [1,2] **Tuba Kaya**
[1,] Department of Architecture, Faculty of Architecture and Design, İstanbul Aydın University, İstanbul, Turkiye
[2,] Architectural Design Computing Program, Department of Informatics, İstanbul Technical University, İstanbul, Turkiye
[1] E-mail: tubakaya7@aydin.edu.tr , [2] E-mail: kayat23@itu.edu.tr
[1,2] ORCID: https://orcid.org/0009-0005-5746-8514

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Abstract

Increasing architectural complexity necessitates the adoption of integrated methods. Convergence of Building Information Modeling (BIM) and Procedural Modeling (PM), within contemporary architecture is analyzed in this study. The limitations and potentials encountered during this convergence are discussed within an integrated framework. Digital Twin concept, as a data-driven cyber–physical simulation and optimization system, is examined as key point of the integration between BIM's rich semantic data environment and the rule-based, dynamic operational logic of PM. Therefore, contributions of integrating PM and BIM to efficiency and automation in Digital Twin production are investigated. The requirements for aligning architectural design and construction workflows with contemporary demands and for integrating them with Industry 4.0 concepts and tools are discussed through conceptual analysis, cases, and relevant literature. Open data environments, user-friendly interfaces, standardization, training and legal frameworks are proposed to facilitate the integration and widespread adoption of BIM and PM in contemporary architecture.
Keywords: BIM; Procedural Modelling; Digital Twin; Industry 4.0, Interoperability.

1. Introduction

1.1 Background and Context

Since the 1950s, when the concept of automation began to emerge alongside the development of computer technologies, the digitalization process has continuously evolved through new concepts and technological tools with increasing momentum. The integration of advanced digitalization with internet technologies has led to the transition toward a new industrial era defined as Industry 4.0, within the framework of smart manufacturing, cyber-physical systems, automation, and adaptation concepts (Lasi et al., 2014; Gilchrist, 2016; Zheng et al., 2018; McHugh et al., 2021; Parashar et al., 2023; Folgado et al., 2024). Within this transformation, architectural design practices and the digital tools utilized in these practices have also been affected, leading to the development of data-driven and adaptive solutions for design, production, and operational processes.

The integration of automation, sensor technologies, the Internet of Things (IoT), augmented and virtual reality tools (AR/VR), big data applications, and BIM processes with emerging technologies has played a significant role in the development of the Digital Twin (DT) concept. A DT can be defined as a data-driven cyber-physical simulation and optimization system that establishes a real-time data flow between a physical system and its digital representation (Ünal, 2023). Accordingly, DT systems are generally structured as multi-layered architectures consisting of perception, data, analysis, application, artificial intelligence (AI), and connectivity layers (Liu et al., 2025; Autodesk Developer, 2026). This multi-layered system structure necessitates the collaborative operation of multiple approaches and disciplines while simultaneously increasing the need for interoperable systems and effective design process management. From this perspective, it is of great importance to examine and maximize the potential of existing tools, as well as to analyze the current conditions and limitations of interoperable systems in order to reduce these limitations to a minimum.

1.2 Research Gap and Aim

BIM tools provide significant capabilities in complex project processes such as process control, project management, interoperability, clash detection, and multidimensional semantic modeling. However, they remain limited in certain aspects offered by other computational design methods such as PM. The family-based and semantic modeling logic of BIM creates constraints regarding design flexibility, generation of geometric alternatives, software expertise requirements, and time management during the modeling process. Although parametric design can be achieved through Python scripting and visual programming using Dynamo on BIM interface, the system still presents various limitations related to design interfaces and data formats (Rocha & Mateus, 2024; McClymonds et al., 2023; Anwar, 2022). The integration of buildings with the built environment is of critical importance in complex design and construction processes involving multiple systems and parameters, such as urban infrastructure and superstructure projects. Although BIM environments provide extensive interfaces and tools for building modeling, BIM libraries remain insufficient in representing the environmental context of buildings during the modeling phase. In contrast, procedural modeling enables the rapid and accurate generation of three-dimensional built environment models with minimal polygon usage through the support of Geographic Information Systems (GIS) tools.

This study aims to analyze the convergence of BIM and PM within contemporary architecture by examining their limitations and potentials in an integrated framework. The research gap lies in the limited integration between BIM's semantic data environment and the rule-based, dynamic logic of PM. Digital Twin concept is explored as a potential bridge and meeting point between these two systems.

2. Materials and Methods

2.1 Conceptual Framework

Procedural Modeling (PM)

Procedural modeling, as a discipline of parametric design, refers to holistic design systems in which design parameters are constructed through step-by-step algorithmic processes, the relationships between geometric concepts are analyzed, and the relationships between objects are defined through rules. The form-generation stages within this system represent a process in which geometric production is automated through predefined rules. Through PM, repetitive and variation-based geometry sets such as plan units, façade systems, modular elements, or urban masses can be automatically generated using specific rules and parameters. By developing shape grammar methods, procedural modeling enables the generation of highly detailed geometric models for large urban scales through the modeling of buildings together with façade elements. The procedural generation of building mass model variations using volumetric forms, followed by the creation of façade details consistent with the mass model through shape grammars, allows automated production in large-scale modeling environments such as urban-scale applications. By defining context-sensitive rules within the model, conditions such as preventing components like windows or doors from intersecting with other walls, ensuring that doors open onto terraces or street levels, and restricting terraces with railings can be integrated into the system (Müller et al., 2006; AlFadalat & Al-Azhari, 2022). In this way, building elements, urban components, roads, and façade and building details are procedurally generated instead of being manually modeled, while the entire model is defined through understandable rules (Figure 1). These rule-based systems provide more flexible and scalable environments for large-scale models. Through the definition of shape grammars, procedural modeling plays a productive role in areas such as game design, digital twin tourism, and urban visualization due to its strong visual data generation capacity, although it does not provide one-to-one accuracy in the analysis and modeling of the built environment.

Figure 1. Procedural Modelling Process Example (Source: AlFadalat & Al-Azhari, 2022).

Building Information Modeling (BIM)

BIM is the multi-dimensional and digital representation of the building construction process in order to facilitate information exchange and collaboration (Eastman, 2011). It is a process that begins with the creation of an intelligent 3D design model and subsequently utilizes this model to facilitate coordination, simulation, and visualization, while also assisting owners and service providers in improving the planning, design, construction, and management of buildings and infrastructure (Autodesk). In other words, BIM is a digital representation of the physical and functional characteristics of a building throughout its entire life cycle (Işıkdağ et al., 2013). BIM adopts a component-based approach and provides significant advantages in terms of clash detection, information richness, and integrity in visual representation during the design phase. The coordination of non-graphical data within the model and the visual integration of this data are effectively utilized throughout the process. These models produce accurate and consistent datasets capable of being automatically integrated into operational units by associating field data with the master model. Such datasets include cost estimation, production information, resources, quality assurance, and 4D planning data, thereby improving information sharing and process management during both pre-construction and construction phases (Bradley et al., 2016). A 4D construction sequence on BIM interface is given in Figure 2 below.

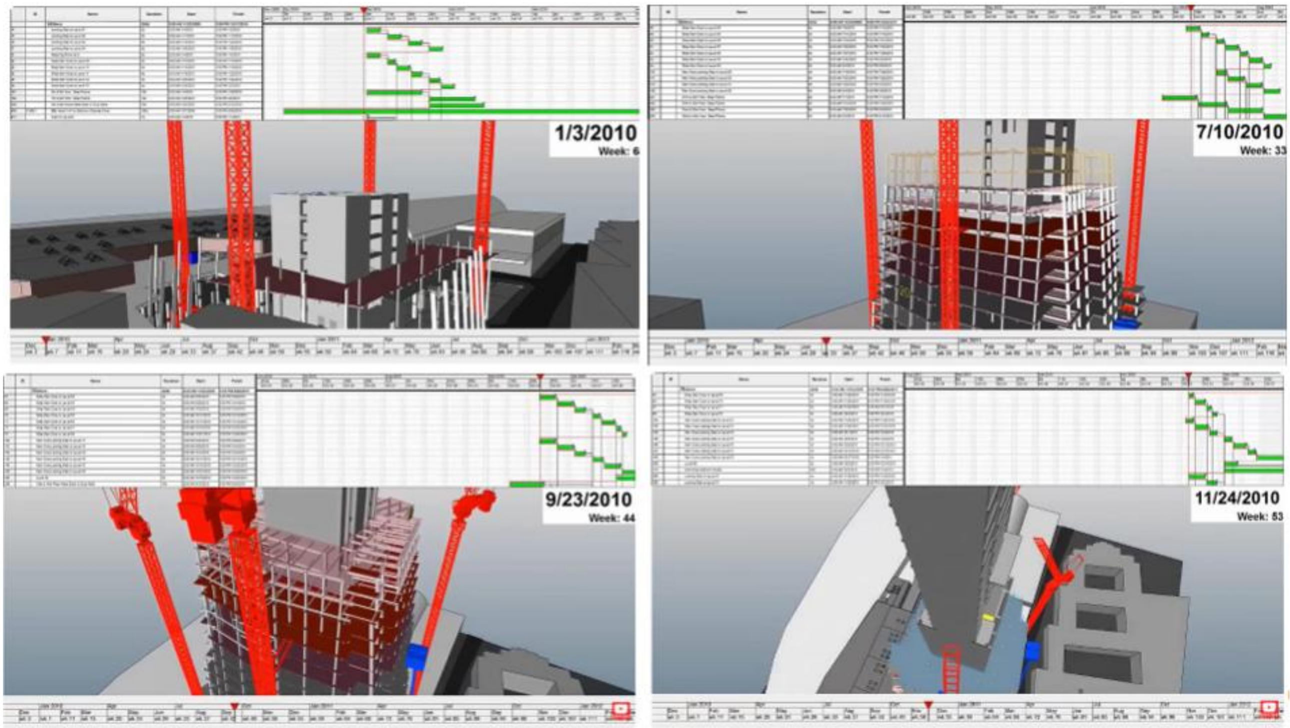

Figure 2. 4D Construction Sequence of London's Shard (Source: SYNCHRO Construction, 2010).

Digital Twin (DT)

A digital twin (DT) refers to a system that collects real-time data to monitor physical assets, enhancing operational efficiency while supporting predictive maintenance and informed decision-making (Khajavi et al., 2019). Within the scope of developing sensor technologies and the Internet of Things (IoT), processes such as on-site monitoring during production and the control of design–production accuracy have also become digitalized and capable of operating in integration with BIM. Similarly, through these technologies, post-construction facility management and maintenance processes have become integrated with BIM models, transforming rule-based design processes into simultaneous data-driven systems. This transformation enables design to be considered as a continuous process extending beyond the construction phase of the building. Building elements encoded with geometric and semantic information within BIM models can exhibit adaptive behaviors according to real-time data, environmental conditions, and contextual parameters, thereby enabling the development of more sustainable and ecological designs compared to conventional methods. Although DT and BIM are often considered integrated approaches, it would not be entirely accurate to assume that all DT systems inherently incorporate BIM. There are different identifications as BIM as a subset of DT, DT as a subset of BIM, BIM equivalent to DT, and the absence of a direct relationship between the two concepts (Radzi et. Al., 2024). This can be explained by the fact that digital twin systems operate as data-driven models with varying contexts, scales, and levels of information integration. While a building-scale DT can be readily associated with a BIM model, it may not be entirely accurate to classify urban-scale DT systems strictly as BIM systems. For instance, Figure 3 below presents a digital twin application developed through the integration of sensors into a BIM model generated from point cloud data acquired from an existing building.

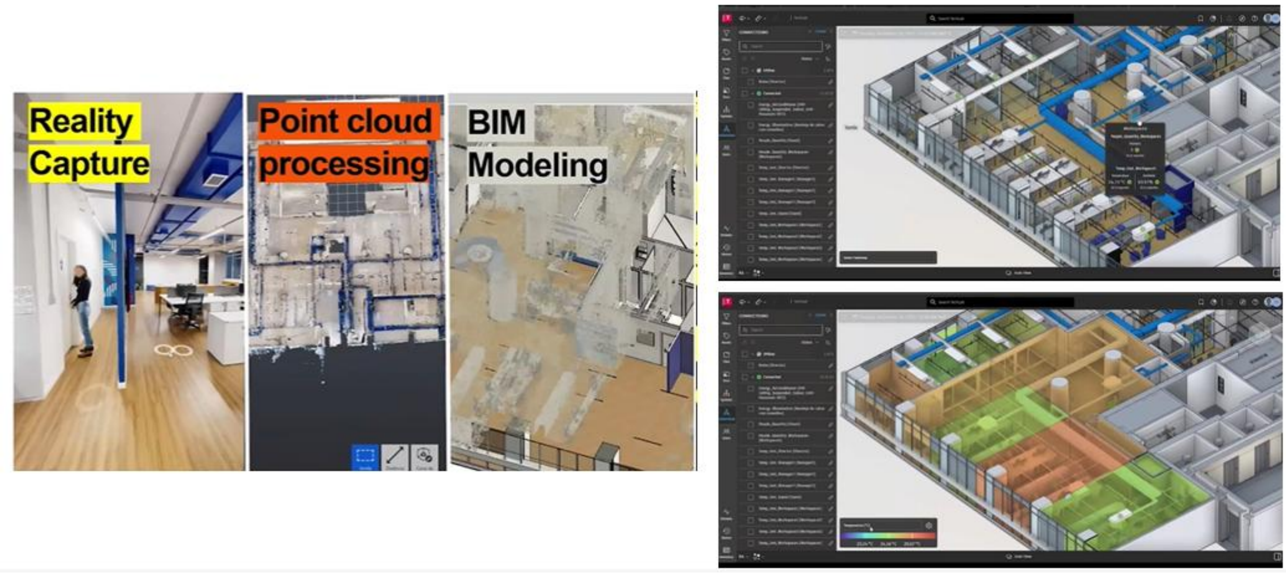

Figure 3. Digital Twin with Autodesk Tandem (Source: Autodesk Developer, 2026).

2.2 Methodological Approach

This study adopts a qualitative and exploratory methodological approach combining literature review, bibliometric analysis, and formal conceptual evaluation. First, an extensive literature review was conducted on PM, BIM and DT. Subsequently, keyword co-occurrence analyses were performed using VOSviewer software with the data set of literature review conducted in Scopus in order to identify research trends, conceptual clusters, and relational networks within the literature. In addition, selected studies and application examples were comparatively examined to evaluate the limitations, potentials, and integration possibilities between BIM, PM, and DT systems. Based on these findings, a conceptual framework for interoperable and data-driven design processes is discussed.

3. Results

For a comprehensive comparison and situational analysis, the relationships between “BIM” and “Procedural Modeling” and secondly between “BIM” and “Digital Twin” were systematically reviewed within the relevant literature. Concept maps illustrating the associated keywords were generated using VOSviewer software. The analyses presented in this section will be discussed separately based on the results of these pairwise literature reviews.

3.1 Bibliometric Findings

3.1.1 BIM and PM Integration

In order to better understand the relationship between BIM and Procedural Modeling, as well as their areas of integration, the relevant literature was reviewed through Scopus using the following search query:

"TITLE-ABS-KEY(("building information model" OR BIM OR HBIM OR "semantic model*" OR "semantic modeling" OR "semantic modelling") AND ("procedural model*" OR "procedural generation" OR "rule-based design" OR "rule based design" OR "rule-based system*" OR "rule based system*" OR "parametric design" OR "parametric model*" OR "generative design" OR "algorithmic design" OR "computational design" OR "shape grammar*" OR "design grammar*" OR "design automation" OR "ontology-based" OR "ontology-based modeling" OR "knowledge-based system*")) AND (LIMIT-TO (SUBJAREA,"ENGI") OR LIMIT-TO (SUBJAREA,"ENER")) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT-TO (DOCTYPE,"cp")) AND (LIMIT-TO (LANGUAGE,"English"))"*

As a result of this search, a dataset consisting of 1221 papers was retrieved from the Scopus database and imported into VOSviewer software in order to generate a concept map. Keywords such as rule-based design, algorithmic design, parametric design, and shape grammars were manually grouped under the title of "Procedural Modeling" through the preparation of a thesaurus file. In this way, the relationship between rule-based design and semantic modeling concepts became more clearly identifiable. The co-occurrence map obtained after processing the dataset with the thesaurus file is presented below (Figure 4).

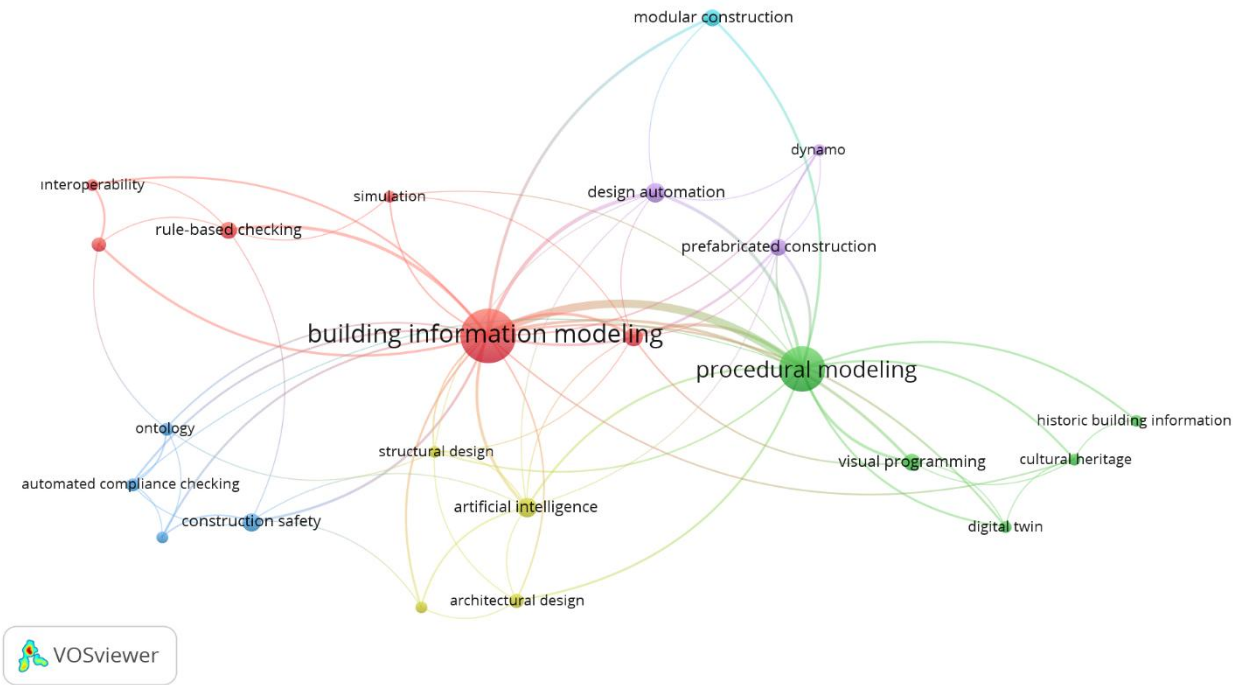

Figure 4. BIM and PM Co-occurrence Map (Source: Author's own work).

According to the generated co-occurrence network, BIM and PM appear as dominant central nodes interconnected with various related keywords. When the overall network structure is examined, the concepts of "rule-based checking," "interoperability," and "simulation," located within the red cluster closer to the BIM node, indicate the use of BIM tools in supervision, control, standardization, simulation, and analytical processes. From the BIM perspective of the BIM+PM integration, BIM can be interpreted not only as a geometric modeling tool but also as an information system through which regulation and control processes are managed.

The network containing the concepts of "ontology," "automated compliance checking," and "construction safety" is associated with the use of BIM as a semantic data structure and decision-support system. Furthermore, the branch of this network connected with artificial intelligence demonstrates the integration of AI-supported control systems. In addition, the Procedural Modeling concept is linked toward application areas such as digital twins, automation, modular and prefabricated construction, and HBIM, thereby relating BIM and PM integration to productive and dynamic operational layers. The average year of publication on both "building information modeling" and "procedural modeling" keywords analyzed as 2021 in the publication data set that has no date restrictions.

3.1.2 BIM and DT Integration

In the second literature review conducted for conceptual analysis, the combined use of BIM and Digital Twin concepts was examined through the Scopus database using the following search query:

“TITLE-ABS-KEY (("building information modeling" OR BIM) W/5 ("digital twin" OR "digital twins") AND (integration OR framework OR workflow OR interoperability OR "data exchange")) AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English"))”

Following the processing of a comprehensive thesaurus file prepared to enable a clearer interpretation of the dataset, the concept map generated from the keywords, titles, and abstracts of 239 scientific publications is presented below (Figure 5).

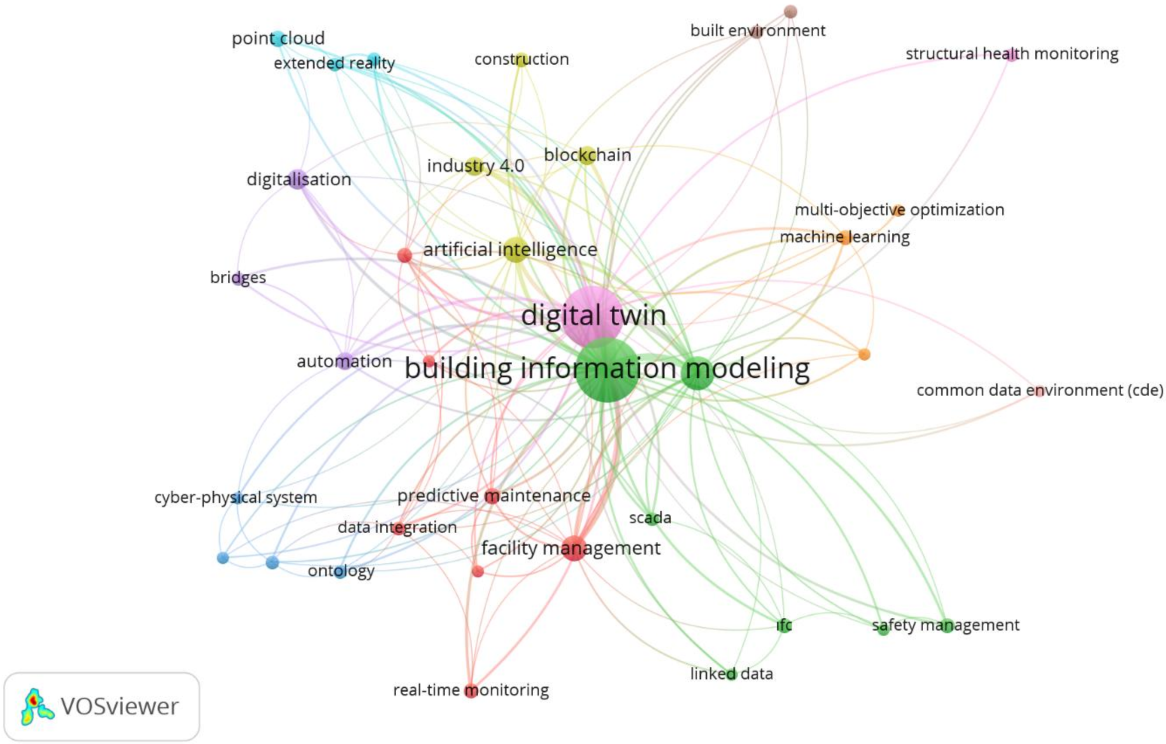

Figure 5. BIM and DT Co-occurrence Map (Source: Author’s own work).

When this concept map is examined, it can be observed that studies integrating BIM and DT are strongly associated with Industry 4.0 concepts. The machine learning and artificial intelligence concepts positioned close to the central nodes indicate the use of AI-based data analysis, prediction, and optimization applications within digital twin studies. The blue cluster located in the upper-left part of the network map, containing the concepts of Extended Reality (XR) and Point Cloud, reveals the use of visualization and scanning technologies, as well as the integration of cyber-physical systems within DT–BIM integration.

As a result, the analysis of this conceptual network demonstrates the transformation of BIM from a static data system into a dynamic system capable of processing real-time data through its integration with DT technologies, artificial intelligence, IoT, and cyber-physical systems.

The conceptual analyses further reveal that the integration of BIM, PM, and DT concepts proposes an important framework for data-driven, flexible, and automation-supported intelligent architectural processes, while also enabling the continuous management of the building life cycle.

3.2. BIM and PM Integration

Procedurally generated geometries can be transferred into BIM environments as parametric families or objects; thus, not only quantitative geometric information but also semantic data associated with these geometries—such as material, performance, cost, and time information—can be integrated within the same model. This integration combines the scalability and automation capabilities of procedural modeling with the management infrastructure of BIM, resulting in a more integrated and automated design–production–construction–operation cycle.

When the rich data environment provided by BIM is integrated with the rule-based geometry generation capability of Procedural Modeling (PM), a powerful decision-support system emerges. This integration provides a common modeling framework for analysis during the detailed design, production, and construction phases of the building lifecycle, while also offering a technological infrastructure capable of responding to contemporary operational and maintenance requirements through building operation systems and smart facility management automation in post-design phases. However, processing all parameters required throughout the building lifecycle as input within BIM processes requires substantial time and computational resources. Particularly in complex structures and urban-scale models, including semantically rich BIM data in areas where geometric information alone would be sufficient causes both increased process complexity and a significant growth in required resources and storage capacity.

3.2.1 Applications and Workflow Potentials

The integration of BIM and Procedural Modeling (PM) appears in both literature and practice across a broad range of applications within contemporary architectural design and construction workflows, including Digital Twin ecosystems, Historic Building Information Modeling (HBIM), Serious Games studies, smart city design, urban infrastructure and superstructure projects, as-is modeling of the built environment, Scan-to-BIM, and Point Cloud-to-BIM transformation processes. These applications demonstrate the extensive research and practical potential of BIM–PM integration.
Modeling the entire built environment within a BIM platform when only geometric information is required leads to unnecessary time and resource consumption and creates storage-related challenges. Particularly in urban design and urban digital twin production, the integration of PM methods with BIM models makes the process more practically applicable. Through geometries generated at adjustable levels of detail depending on project scope, storage requirements and modeling duration can be controlled, while the amount of data defined within the BIM environment can be reduced. In such processes, managing the geometric and semantic information detail becomes a critical issue for overall efficiency.
For BIM models, a model development framework has been structured by the American Institute of Architects (AIA) and the Associated General Contractors of America (AGC) under six Levels of Development (LOD) (American Institute of Architects (AIA)):

LOD 100 — Conceptual Design:
At this stage, the model represents the basic shape and size of elements without detailed information. It is used to communicate the overall design intent.

LOD 200 — Schematic Design:
The model becomes more refined and includes approximate quantities, dimensions, shapes, and locations of elements. It supports the analysis of spatial relationships and early design concepts.

LOD 300 — Detailed Design:
At this level, the model contains geometric information, specific dimensions, forms, and detailed object components. It is used for producing construction documents and coordinating different disciplines.

LOD 350 — Construction Documentation:
The model includes detailed assemblies and fabrication/construction-level information. It is used for generating construction documents and shop drawings.

LOD 400 — Fabrication and Assembly:
This level involves detailed models suitable for fabrication and assembly purposes, including specific connections and assemblies.

LOD 500 — As-Built / Facility Management:
At this stage, the model reflects real-world conditions and contains information regarding installed and operational building components for maintenance and facility management purposes.

While LOD 100–300 levels cover the conceptual and detailed design phases of the building lifecycle and represent two- and three-dimensional BIM models, LOD 400 and LOD 500 are considered advanced BIM dimensions that generate data related to time (4D), cost (5D), sustainability (6D), and facility management (7D).

Similar to the AIA Level of Development framework used for BIM models, CityGML (City Geography Markup Language) employs the concept of *Level of Detail* (LoD) in urban-scale projects to describe how accurately a digital model represents its real-world counterpart. This concept is widely accepted and applied in various contexts, including the three-dimensional procedural modeling of buildings (Büyüksalih et al., 2013; Tang et al., 2018). In different contexts, similar concepts are expressed through terms such as "Design Process Staging Concepts", "Information Levels", "Object Data Levels", "BIM Content Levels", "Completion Level", "Model Maturity Index", and "Level of Geometry (LoG)" (Dever et al., 2025; Abualdenien et al., 2022). An example of the representation of building elements at different LoG levels is presented below (Figure 6).

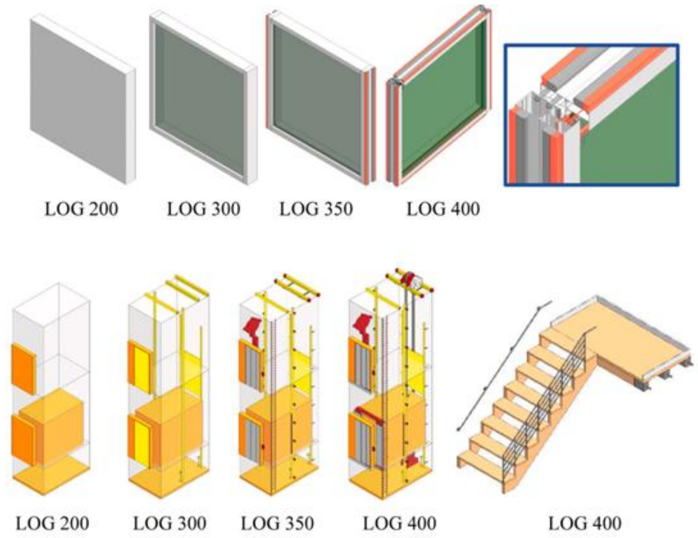

Figure 6. Different LoGs for Building Elements (Source: Abualdenien et. al., 2022).

Since BIM modeling is based on predefined building element families, the mass generation of built environment components such as site boundaries and contextual geometries through procedural modeling reduces the load on the BIM model and enables faster modeling workflows. Furthermore, rule-based floor plans, façade drawings, and structural system models can be updated instantly through the simultaneous modification of predefined parameters. In this way, the design alternative space can be evaluated rapidly and the problem-solving process can be optimized efficiently.

During the modeling of the built environment (as-is modeling), coordination can be established between modeling tools to transform geometric data obtained through photogrammetry and laser scanning into BIM models. However, issues such as data loss, data inconsistency, and obstacles surrounding the building—such as vegetation, vehicles, and neighboring structures—hindering efficient model generation create uncertainty regarding model accuracy. Göçer et al. (2016) processed data for building performance simulations by integrating a three-dimensional SketchUp model, generated through photo-matching techniques in Google SketchUp, into Autodesk Revit. The authors emphasized that inconsistencies were observed between the actual building dimensions and the resulting as-built BIM model.

Historic Building Information Modeling (HBIM) is a BIM-based approach aimed at the detailed modeling, analysis, conservation, and adaptive reuse of historical and cultural heritage structures. The retrospective modeling of historical buildings lacking original design and construction documentation is particularly difficult to perform manually in BIM environments due to limitations such as missing construction details, the measurement of irregular and unique forms, and insufficient geometric information (Bagnolo et al., 2021). In such applications, Scan-to-BIM methodologies are frequently employed, where model data are generated from point clouds. Although integrated Scan-to-BIM and Point Cloud based methodologies enable highly accurate and detailed modeling, the resulting point cloud data creates extremely large and heavy datasets, limiting flexibility within the modeling process. Within this context, PM tools provide a flexible and controllable production methodology based on rules and algorithms, enabling the generation of historical structures without requiring each element to be modeled individually. Since serious game design does not require exact physical accuracy or precise measurements, structures generated through PM tools provide sufficient visual data for experience, narrative, and geometric representation within gaming environments. The integration of HBIM and PM offers a flexible and generative design-production alternative by utilizing point cloud data obtained through laser scanning together with the semantic infrastructure of BIM, enabling adjustable levels of detail according to project requirements (Bagnolo et al., 2021).

3.2.2 Interoperability and Technical Limitations

Despite the integration advantages, interoperability and data management issues remain as critical challenges. The data content within BIM environments diversifies and expands in scope in parallel with the increasing level of model development. Industry Foundation Classes (IFC) is a standardized open data model for BIM information exchanged and shared among various participants involved in a building construction or facility management project, enabling the management of complex communication throughout the building lifecycle (Laakso et al., 2012). Despite the semantic similarities between CityGML and IFC, their geometric modeling paradigms differ due to differences in scale representation. While building models in the GIS domain are represented through observable surfaces, the BIM domain typically consists of volumetric and parametric fundamental components (Tang et al., 2018).

Achieving BIM–PM integration requires the combined use of multiple tools and software environments, as well as the establishment of a common data environment. However, this requirement also constitutes a limitation due to interoperability and data-flow issues between the IFC file structure used in BIM processes and the data structures of procedural modeling tools such as Rhino Grasshopper, Unity, and Houdini. Biancardo et al. (2021) conducted a study on railway system design using a PM-based BIM approach and investigated the integration between BIM and PM tools (Figure 7). The study emphasized that while the use of different coding languages by these tools provides flexibility in model generation, the same condition also creates a limitation in terms of interoperability.

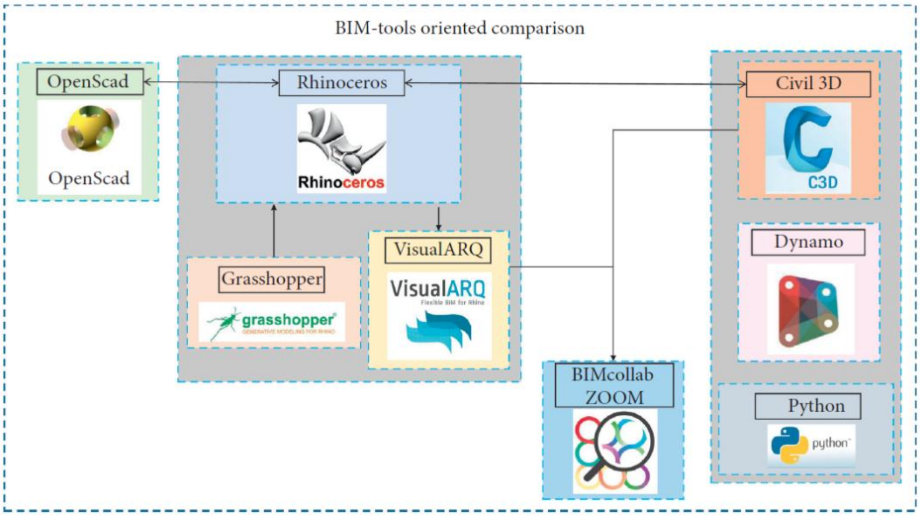

Figure 7. PM based BIM approach methodology (Source: Biancardo et. al., 2021).

Among the most significant barriers to the adoption of BIM applications in the construction industry are the lack of expertise, training deficiencies, software costs, and the unequal levels of technical proficiency among project stakeholders (NBS, 2020). BIM models in construction processes are not only shared among design teams but also with numerous subcontractors and operators who may not possess the same level of expertise (McGraw Hill, 2012). These factors similarly constitute major limitations for automation systems in which multiple applications and workflows are integrated. As the amount of data embedded within the model continuously increases, storage and data-sharing processes become more difficult, while additional challenges emerge regarding the updating of models through real-time data acquisition.

Although software plug-ins and in-platform tools such as Dynamo aim to reduce workflows into a single interface, the use of these tools remains constrained by requirements related to programming knowledge and specialized training. Considering the implications for time and cost management, these limitations hinder the widespread adoption of cyber–physical systems. Yang et al. (2023), in their study on the automation of geometric generation within BIM applications, addressed the limitations affecting the dissemination of such automation processes through the communication gap between domain experts and professional designer/programmers. The authors expressed this limitation as: “domain experts do not possess programming knowledge, while professional programmers are not experts in domain-specific knowledge,” and proposed enabling knowledge transfer through a text-based representation transformation approach (Figure 8).

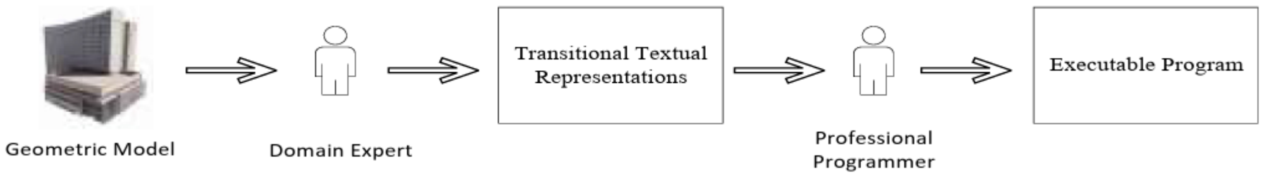

Figure 8. The role of transitional representation for collaboration between domain experts and programmers (Source: Yang et. al., 2023).

4. Discussion

4.1 Potentials of Integration

The integration of Building Information Modeling (BIM), Procedural Modeling (PM), and Digital Twin (DT) concepts discussed within the scope of this study, together with the potentials and significance of this convergence, is illustrated through the following conceptual diagram (Figure 9), based on the conducted literature reviews, case studies, and conceptual analyses. According to the synthesized findings, when the automation capabilities and design flexibility offered by PM are integrated with BIM's rich semantic data environment, high level of accuracy, interoperability infrastructure, and lifecycle-oriented management capabilities, a more optimized, intelligent, and complementary system framework emerges in which the limitations of both approaches can be reduced efficiently.

When evaluated together with the DT concept, this integrated system increases the potential for developing intelligent architectural designs and buildings capable of adapting to technological advancements and to future conditions that cannot yet be fully anticipated. In particular, decreasing resources and increasingly complex processes requiring rapid adaptation are intensifying the need for automation systems within the architecture, engineering, and construction (AEC) industry. The implementation of real-time and responsive design strategies in smart buildings, together with the management of form and performance optimization processes, necessitates integration with cyber–physical systems. Within the integration framework discussed in this study, the further development and combined utilization of existing systems, as well as the incorporation of their potentials into future-oriented scenarios, are considered to be of critical importance.

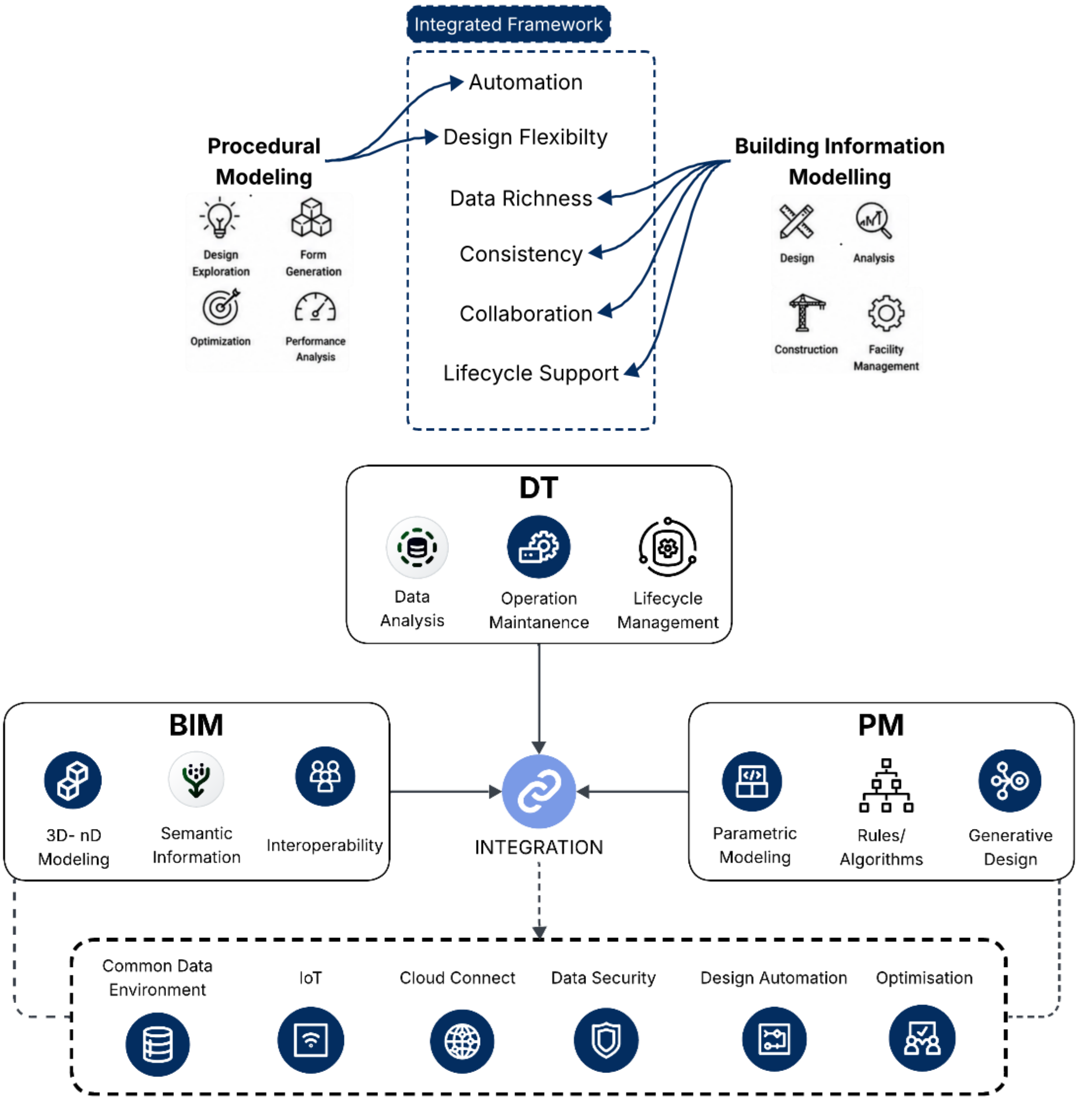

Figure 9. Integrated Framework Diagram for PM, BIM and DT (Source: Author's own work).

4.2 Future Implications and Limitations

As a conceptual use-case scenario, this integration can be evaluated through a façade design system that is responsive to sunlight and optimized according to façade performance and interior lighting requirements (Figure 10). In such a scenario, parametrically designed façade components would respond dynamically to daylight data and generate adaptive changes on the building envelope as programmed; similar applications are already achievable with existing technologies. However, when evaluated within the framework of PM, BIM, and DT integration, the façade system could evolve into a more intelligent and interconnected structure capable of receiving real-time data at desired levels, while enabling the tracking of information and material passports for each individual component through the BIM model. Such a system could also facilitate maintenance, repair, and adaptive reuse processes more efficiently. Owing to the PM infrastructure, the system would possess the potential to become more flexible and adaptive by responding to varying contextual conditions, requirements, and operational objectives.

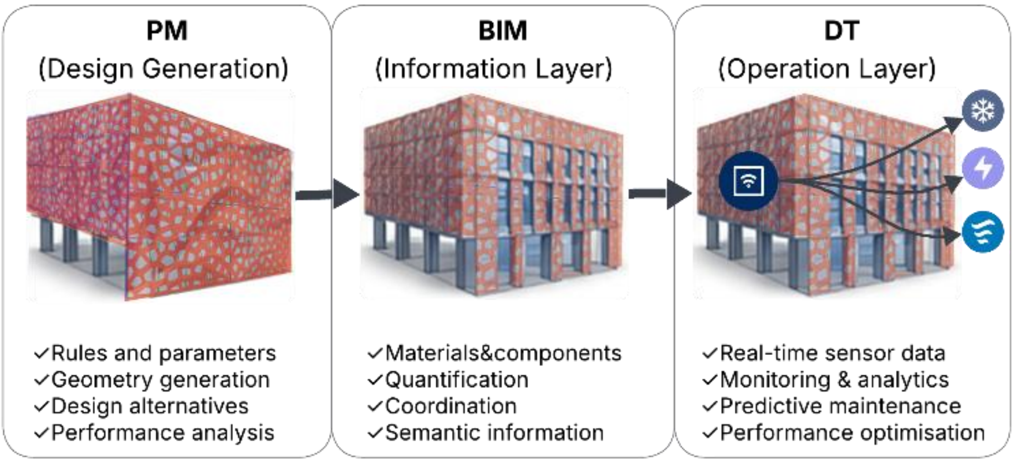

Figure 10. Conceptual use Case Scenario on Parametric Façade (Source: Author's own work, façade design : Yılmaz, & Arpacıoğlu,, 2025).

The major barriers to such application scenarios include interoperability and software transition difficulties, challenges in transforming conventional design approaches, the requirement for advanced expertise, and the costs associated with software and training processes. Depending on emerging future requirements, these integration frameworks may evolve from building-scale architectural applications to urban-scale systems and, in industrial contexts, toward a wide range of product and system scales. In this regard, the increasing development of artificial intelligence technologies and the orientation of relevant stakeholders toward such technological transformations are considered highly significant for the future evolution of integrated digital design and construction ecosystems.

5. Conclusion

In conclusion, considering the increasing complexity, information-intensive nature, and governance requirements of construction projects and Common Data Environments (CDEs) emerge as fundamental forward-looking approaches for the integration and effective utilization of the vast amounts of data generated in contemporary construction projects. The inherently growing complexity of projects necessitates continuous and adaptive innovation throughout implementation processes. In this context, the convergence of Procedural Modeling (PM) and Building Information Modeling (BIM) provides efficiency and automation in digital twin production across different application scopes.

While the integration of hybrid methods and design tools offers a solution space for managing increasing complexity, it also introduces limitations such as interoperability issues, data storage challenges, expertise requirements, software costs, and training-related expenses. To address interoperability problems, the development of project-specific object and software libraries has been proposed (Biancardo et al., 2020). In order for architectural design and construction processes to align with the requirements of the contemporary era and integrate with Industry 4.0 concepts and technologies, it is necessary to establish open data environments, user-oriented design and management tools, standardization frameworks, educational infrastructures, and legal contracts and specifications that support and encourage the use of digital technologies.

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Conflicts of Interest

The author reports no conflicts of interest.

Data Availability Statement
No new data were created or analysed in this study; all sources are cited within the article. The literature review data can be provided upon request.

Institutional Review Board Statement
Not applicable.

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