REVIEW ARTICLE

The Intersection of Facade Engineering and Building Information Modeling: Opportunities and Challenges

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Abstract
Building Information Modeling (BIM) represents a transformative advancement in the architecture, engineering, and construction (AEC) sector, especially in the specialized field of facade engineering. Utilizing a secondary data analysis approach focused on existing case studies, this paper offers a comprehensive examination of the synergistic interaction between BIM and emerging technologies such as generative design, machine learning, performance analysis tools, digital twins, and augmented reality. These technologies are analyzed to understand their impact on the optimization of facade design, detailing, fabrication, as well as long-term maintenance and performance. The study aims to provide a nuanced understanding of the current trends, challenges, and solutions associated with this technological amalgamation. The insights gleaned are invaluable for professionals in the AEC industry, pointing toward an increasingly digitized future where enhanced efficiency, sustainability, and functional efficacy are achievable in building facade engineering.

Keywords: Facade Engineering; Building Information Modeling (BIM); Facade Design; Facade Detailing; Facade Fabrication

Introduction

Facade engineering is a cornerstone of the architecture, engineering, and construction (AEC) industry, profoundly influencing both the aesthetic appeal and functional efficacy of structures (Azcarate et al., 2020). This discipline extends beyond mere aesthetics; its alignment with sustainable practices offers avenues for innovation, as evident in the rise of green facades in smart building designs. Such innovations promise a path towards more sustainable urban development (Aung et al., 2023). Moreover, the intertwining of green facades with renewable energy technologies proffers a robust solution to the environmental quandaries exacerbated by urbanization (Htet et al., 2023).

Amidst these advances, Building Information Modeling (BIM) stands out as a revolutionary force. Termed "disruptive," BIM isn't just another tool; it encapsulates an exhaustive digital representation of buildings, encompassing both their physical structure and functionality (Eastman et al., 2018). This disruption stems from BIM's potential to reshape traditional AEC workflows. By facilitating advanced collaboration, enriched visualization, and superior analytics, BIM is redefining how buildings are ideated, erected, and preserved, underscoring a transformative shift in the AEC landscape (Xiaozhi et al., 2018).

This paper aims to explore the convergence between BIM and facade engineering. It focuses on how this integration refines various aspects of facade design, detailing, and fabrication. A secondary data analysis approach is employed, centering on existing case studies to scrutinize the transformative effects of BIM on facade engineering. The objective is to illuminate the myriad benefits that arise from this integration, including optimized performance, improved stakeholder coordination, and enhanced efficiency and sustainability in building projects (Sacks et al., 2020)

The paper further discusses how BIM's incorporation of advanced tools like parametric design and computational algorithms amplifies the capabilities of facade engineering. These advancements are becoming increasingly crucial in a dynamic AEC environment that demands adaptability, resilience, and innovation (Seong-In, 2021).

Through detailed analysis, the paper seeks to catalyze broader adoption of BIM in facade engineering, thereby promoting the development of buildings that are not only more efficient and sustainable but also aesthetically compelling and functionally robust.

Facade Engineering: An Overview

In order to create modern, energy-efficient, and visually beautiful buildings, architects and engineers started concentrating on the design and construction of building envelopes around the beginning of the 20th century (Knaack et al., 2007). Over the years, facade engineering has evolved into a specialized discipline that combines architectural design, engineering principles, material science, and construction technology to create high-performance building envelopes (Levy, M., & Salvadori, M, 2020).

Key components and considerations in facade design include energy efficiency, sustainability, and aesthetics. Energy efficiency is crucial because the building envelope reduces energy usage for heating, cooling, and lighting (Zhang et al., 2018). Sustainable facade design entails using environmentally friendly materials, employing passive design principles, and incorporating renewable energy systems like as photovoltaic panels or sun shading devices (Faragalla, A.M.A., & Asadi, S., 2022). Aesthetics, on the other hand, contribute to the building's visual identity, urban context, and cultural significance, making it an essential consideration in facade engineering (Belarbi et al., 2023).

Facade engineering is crucial to the overall building design process, as it influences not only the building's appearance but also its performance and functionality. In addition to increasing occupant comfort and indoor air quality, a well-designed facade can also lessen the impact of the building on the environment (Shady, 2016). Furthermore, by promoting energy-efficient, low-carbon, and resilient building design, facade engineering plays an important role in tackling climate change, urbanization, and resource scarcity concerns (Webb, 2022).

Traditional facade engineering processes often face several challenges, including fragmented communication between stakeholders, inadequate performance analysis, and the reliance on manual, time-consuming design and construction methods (Sacks et al., 2018). These challenges can result in suboptimal facade performance, increased construction costs, and delays in project delivery (Hady et al., 2018). Utilizing contemporary technology, like as Building Information Modeling (BIM), can help overcome these challenges by speeding up the design, construction, and maintenance of building envelopes (Karam, K. & Jungho, Y. , 2016).

By streamlining the design, construction, and maintenance of building envelopes, new technologies such as BIM can assist address these difficulties. BIM facilitates enhanced collaboration among architects, engineers, contractors, and fabricators, enabling them to share information more efficiently and coordinate their efforts throughout the project lifecycle (Noor et al., 2019). This collaborative approach can lead to better-performing facades, optimized for energy efficiency, sustainability, and aesthetics.

Additionally, BIM offers advanced performance analysis, which enables experts to evaluate various façade design options and find the best solutions in terms of energy consumption, thermal comfort, and aesthetic appeal (Seong-In, 2021). By utilizing the power of digital tools, designers may make more informed decisions and produce building envelopes that serve the needs of building occupants, owners, and the environment.

In sum, facade engineering is a vital aspect of the building design process that has evolved significantly over the years. It encompasses critical considerations such as energy efficiency, sustainability, and aesthetics, which directly impact the building's performance, functionality, and appearance. While traditional facade engineering processes face several challenges, the adoption of advanced technologies like BIM can help professionals overcome these obstacles and pave the way for more efficient, sustainable, and innovative building design.

Building Information Modeling (BIM): An Overview

BIM (Building Information Modeling) is a digital representation of a building's structural and functional details that enables collaboration, visualization, and analysis throughout the building's lifecycle, from design to construction to maintenance (Eastman et al., 2018). BIM has evolved significantly since its inception in the early 2000s, driven by advances in computer technology, software capabilities, and the growing demand for more efficient and sustainable building practices (Succar, 2019).

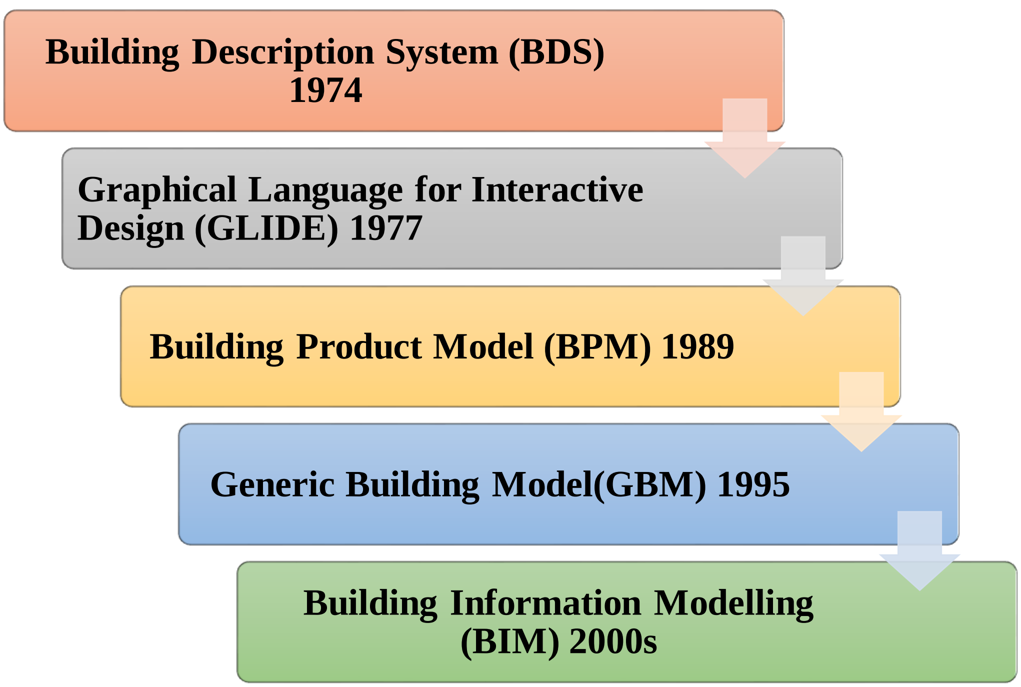

Figure 1: Evolution of BIM

The advantages of BIM in building design and construction are numerous. One of the primary benefits is improved cooperation, as BIM allows architects, engineers, contractors, and other stakeholders to collaborate on a shared digital platform, speeding communication and minimizing the chance of errors and conflicts (Chen et al., 2023). Enhanced visualization is another benefit, as BIM allows for the creation of comprehensive and interactive 3D models, enabling stakeholders to better understand and evaluate different design options (Sampaio et al., 2023). Furthermore, BIM makes it possible to do sophisticated analyses including energy modeling, structural analysis, and cost estimation, supporting professionals in improving building efficiency and reaching more well-informed decisions (Azhar, 2019).

The maturity of BIM adoption and implementation can be categorized into different levels, ranging from Level 0 (unmanaged 2D CAD) to Level 3 (fully integrated and collaborative processes). Level 1 represents the use of managed 2D CAD with some 3D capabilities, while Level 2 involves the use of managed 3D models with information exchange through common file formats (British Standards Institution, 2013). Level 3, often referred to as "Open BIM," encompasses a fully integrated and interoperable approach, with all project data stored in a single, shared model (Elbeltagi, 2021).

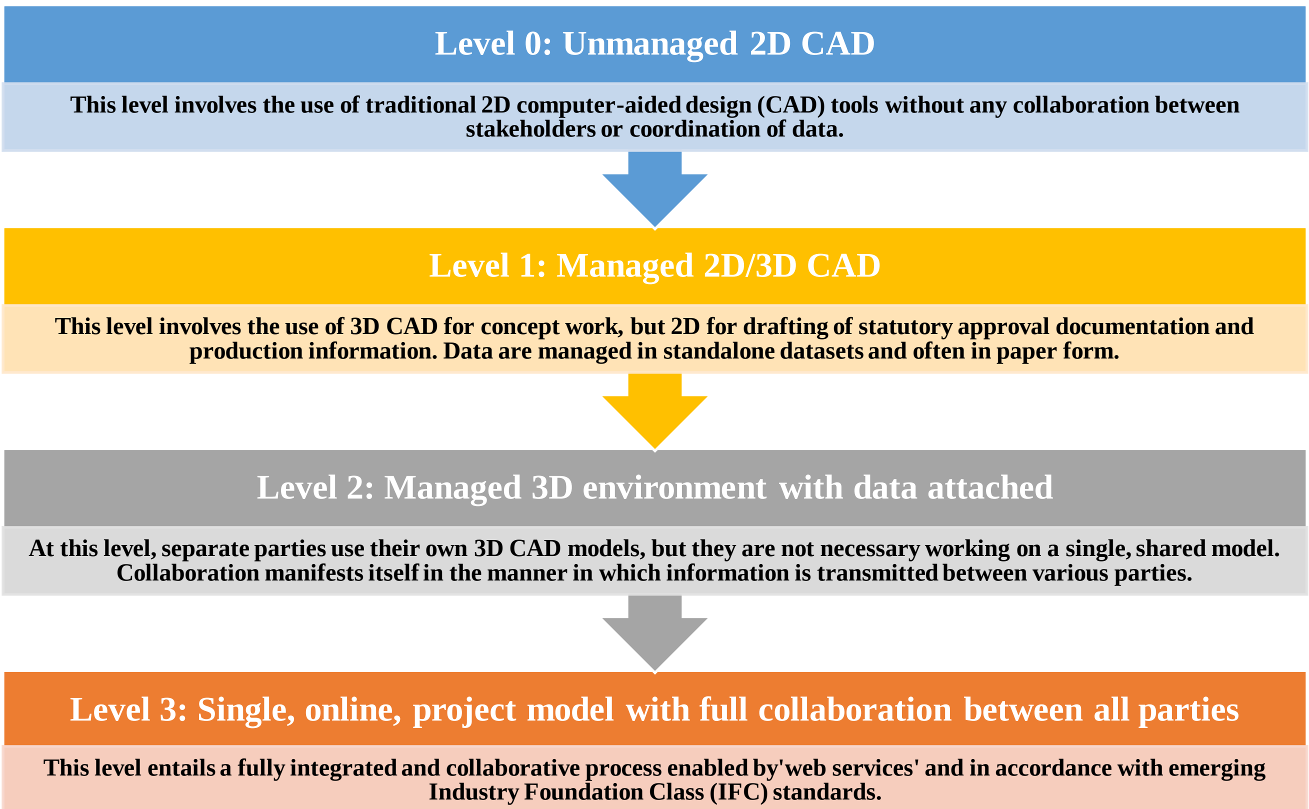

Figure 2: Levels of BIM Maturity

The implications of these different levels of BIM maturity for the industry include varying degrees of efficiency, collaboration, and technological integration, with higher levels offering greater potential for improving building design and construction processes (Gledson et al., 2020).

BIM adoption and implementation rates in the building industry vary by location and sector. According to a recent poll performed by Dodge Data & Analytics (2021), the global BIM adoption rate among architects, engineers, and contractors has reached roughly 67%, with greater rates recorded in nations such as the United States, the United Kingdom, and Singapore.

Factors contributing to the varying adoption rates include government policies, industry awareness, and the availability of skilled professionals (Jung et al., 2020). Despite increasing BIM acceptance, it is crucial to remember that many businesses are still in the early stages of BIM maturity, emphasizing the need for additional investment in training, technology, and research to fully fulfill BIM's potential (Eadie et al., 2018).

The Intersection of Facade Engineering and BIM

Facade Design

BIM is critical in the conceptualization and design of building facades, providing a platform for visualizing, assessing, and optimizing façade system performance (Lee et al., 2020). By incorporating 3D modeling and data management capabilities, BIM enables architects and engineers to explore various facade configurations and materials, assess their impact on building performance, and make informed design decisions (Sung-Chi et al., 2019).

The role of BIM in optimizing facade performance is significant, as it facilitates the analysis of factors such as energy efficiency, solar control, and acoustic insulation. BIM-based energy modeling tools enable professionals to assess the thermal performance of various facade systems, thereby reducing energy consumption and improving occupant comfort (Lin et al., 2019). Similarly, BIM can be used to evaluate the efficacy of sun management measures such as shading devices and glazing qualities in terms of decreasing glare and overheating (Wang et al., 2018).

To visualize the steps involved in facade design using BIM, refer to Figure 3 below. The flowchart outlines the typical process from initial conceptualization to final design decision, illustrating how BIM tools support each step.

Figure 3:The process of facade design using BIM

In addition, the integration of parametric design and computational tools in BIM-enabled facade design opens new possibilities for innovative and high-performance facade systems. Designers can use parametric design to specify connections between design characteristics, allowing them to explore a large range of design choices and automatically generate facade variations based on performance criteria (Hendro, T. P., & Luhur, S. P., 2019). This approach supports the development of optimized and responsive facade designs that can adapt to specific site conditions and performance requirements.

Facade Detailing

BIM can significantly streamline the facade detailing process, including the development of fabrication drawings and schedules. By providing a collaborative platform for architects, engineers, and contractors, BIM enables efficient communication and coordination during the detailing phase, reducing errors and inconsistencies that can lead to costly delays and rework (Jung et al., 2020). Furthermore, BIM allows for the automatic generation of detailed 2D drawings and schedules from the 3D model, ensuring accuracy and consistency throughout the project documentation (Sacks et al., 2018).

By connecting facade elements with other building systems including structural and MEP systems, BIM plays a significant role in enabling interdisciplinary collaboration and information exchange. This coordination helps prevent conflicts and design errors, improving the overall efficiency of the building design and construction process (Lin et al., 2019). For example, BIM can be used to ensure that facade elements, such as curtain walls and cladding systems, are accurately aligned with structural components and do not interfere with the installation of MEP systems (Khanzode et al., 2018).

The benefits of using BIM for clash detection and resolution in facade detailing are significant. By creating a comprehensive 3D model of the building, BIM enables stakeholders to identify and resolve potential conflicts between facade elements and other building systems before they become costly problems on site (Ahmed, A., & Kassem, M., 2020). This proactive approach to clash detection and resolution contributes to improved project outcomes, including reduced costs, shorter schedules, and better overall building performance (Chien et al., 2019).

Facade Fabrication

BIM can be effectively utilized for digital fabrication of facade components, including the use of CNC machines and 3D printing technologies. By directly exporting geometry and data from the BIM model to fabrication equipment, designers and manufacturers can achieve greater precision, efficiency, and customization in the production of facade components (Gallaher., 2021). This digital fabrication process reduces material waste, increases production speed, and enables the fabrication of complex and intricate facade designs that would be difficult or impossible to achieve through traditional methods (Rahmani et al., 2018).

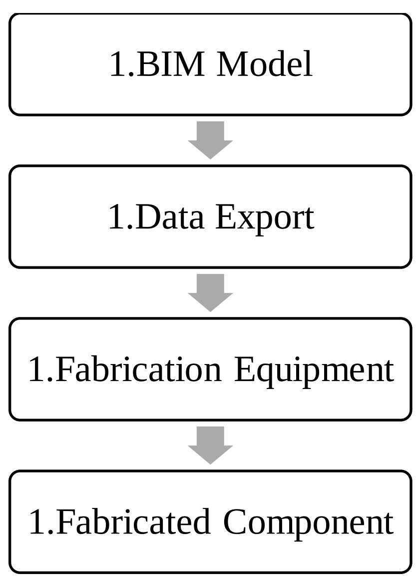

Figure 4: The process of digital fabrication of facade components using BIM

The potential for BIM to improve collaboration between facade engineers, fabricators, and installers is substantial. By providing a shared digital platform for communication and data exchange, BIM facilitates the seamless integration of design, fabrication, and installation processes, reducing the likelihood of errors and miscommunications that can lead to costly delays and rework (Zhen et al., 2015). This enhanced collaboration ultimately contributes to better facade performance, higher-quality construction, and more efficient project delivery (Li et al., 2018).

The benefits of using BIM for quality control and tracking during the fabrication process are also significant. BIM can be utilized to create digital twins of facade components, allowing for real-time monitoring and documentation of the fabrication process (Yu-Cheng et al ., 2019). This digital tracking enables manufacturers to identify and address any deviations from the design specifications, ensuring that the fabricated components meet the required quality standards (Volk et al., 2021). Additionally, BIM can facilitate the integration of fabrication data with other project information, such as schedules and procurement, enabling more efficient project management and better decision-making (Jiang et al., 2018).

The intersection of facade engineering and BIM gives various prospects for improving building facade design, detailing, and fabrication. BIM can help to build high-performance, sustainable, and aesthetically pleasing facade systems by improving collaboration, visualization, and analysis. In addition, combining BIM with new manufacturing technology and quality control methods can result in more efficient and innovative construction techniques. As BIM use grows in the building sector, its potential to alter facade engineering will become more apparent.

Case Studies: Empirical Insights into the Integration of BIM and Facade Engineering

To corroborate the theoretical underpinnings of the BIM and facade engineering integration, the following section presents a series of case studies. These empirical analyses serve to illuminate the practical implications, challenges, and efficiencies achieved through the application of BIM in facade engineering. Each case study was derived from a meticulous review of secondary data sources, encompassing published research articles, whitepapers, and industry reports. These investigations aim to offer a multidimensional view, capturing both the technical and managerial aspects of leveraging BIM for facade optimization. Furthermore, the case studies work in tandem with the preceding discussions to provide actionable insights for stakeholders in the architectural, engineering, and construction (AEC) sector. By examining real-world applications and outcomes, this section seeks to enrich the theoretical discourse with empirical evidence, thereby offering a more holistic understanding of the subject matter.

Case Study 1: Application of BIM in the New Primary School of Melzo (Giuseppe et al., 2020)

This case study exemplifies the effective use of Building Information Modeling (BIM) in constructing a new primary school in Melzo. Collaboratively executed by the Municipality and Politecnico di Milano, this project emphasizes the benefits of BIM in tendering, construction management, and architectural planning, particularly in the realm of facade engineering.

The New Primary School in Melzo serves as a comprehensive model illustrating the multifaceted advantages of employing BIM methodologies from conceptual design to construction and operations. The project involved extensive stakeholder collaboration and integrated various facets of engineering and management.

Architectural Overview

The school building is organized into three primary functional units:

- A central core built with reinforced concrete, housing administrative spaces like offices, a library, and an auditorium.
- Three wooden structural components comprising classrooms and laboratories.
- A double-height section in reinforced concrete that includes amenities like a canteen, gym, and technical rooms.

Information Workflow and BIM Utilization

During Tender Phases: BIM was instrumental in the Most Economically Advantageous Tender (MEAT) approach, enhancing transparency and improving data organization for effective bid evaluations.
Parameters for Bid Evaluation: The evaluation considered four key areas:

- Quantitative Parameters (e.g., energy consumption, performance, waste management)
- Qualitative Parameters Related to Quantitative Classes (e.g., technical requirements for finishing, maintenance)
- Qualitative Requirements of Subjective Matters (e.g., aesthetic and functional characteristics)
- Additional Requirements (e.g., certifications, legal compliances)

Facade Engineering

The application of BIM in the design of the facade enabled optimal use of open space and improved the building's relationship with its exterior environment. The design incorporated expansive glass surfaces as opposed to traditional windows, enhancing the perception of natural surroundings.

BIM Implementation Details

During Construction Phases: BIM played a pivotal role in quantitative and geometric control, aligning material specifications with tender offers, and thereby reducing rework.
For Advanced Project Activities: A custom script in Dynamo was linked to the BIM model for the evaluation of a specialized curved façade. A multi-criteria Design Optioneering approach informed the decision-making process.

Limitations

- **Lack of Mandate for BIM in the Tender Phase**: This necessitated maintaining a parallel traditional documentation process.
- **Absence of a Contractual Information Exchange Platform**: This led to traditional methods for material approval and acceptance.

Conclusions and Future Outlook

The Melzo school project establishes a robust blueprint for integrating BIM into various stages of construction projects, from planning to execution. While the study underscores the significant gains in quality, transparency, and efficiency, it also brings to light the limitations that need to be addressed for fuller BIM integration.

Case Study 2: Facade Engineering through BIM in Signal House, Washington DC (Tejjy Inc. , 2021)

This case study concentrates on the role of Building Information Modeling (BIM) in the facade engineering of Signal House, a mixed-use construction in Washington DC. It highlights the advantages of BIM in managing complex exterior materials and facilitating stakeholder coordination.
Signal House offers an insightful case for understanding the importance of BIM in facade engineering, especially given its unique blend of terracotta, metal, and glass exteriors that enrich the architectural landscape.

Architectural Overview

The building features:

- 11 stories with an emphasis on mixed-use space.
- An architectural facade designed with terracotta, metal, and glass, in harmony with the surrounding historical architecture.

Facade Engineering and BIM Utilization

During BIM Implementation Phases: BIM proved invaluable in modeling and visualizing the unique terracotta, metal, and glass exteriors. It assisted engineers and designers in determining the viability of these materials together, particularly concerning structural integrity and aesthetic cohesion.

Parameters for BIM Evaluation in Facade Engineering

- Material Compatibility
- Structural Integrity of the Facade
- Aesthetic Integration with Surroundings
- Energy Efficiency

BIM Implementation Details

Software: RAM Concept from Finite Element Modeling Software was crucial for detailed facade modeling.
Scope of Work: Beyond structural and interior aspects, special emphasis was given to BIM modeling for facade engineering, involving calculations on material tolerances, stress points, and aesthetics.

Limitations

- Lack of pre-existing standards for integrating such diverse facade materials within BIM software.
- Complexity in stakeholder communication when discussing highly specialized facade engineering topics.

Conclusions and Future Outlook

The Signal House case study underscores the potential for employing BIM in facade engineering. It points out that while BIM can facilitate the integration of complex and diverse materials in building exteriors, more standard protocols for such applications need to be established for more extensive usage.

Case Study 3: Facade Engineering and Parametric Design in the Alto Tower Project (BIM Community, 2018)

This case study delves into the significant role Building Information Modeling (BIM) and parametric design play in the construction and facade engineering of the Alto Tower, a high-rise building with a complex double-skin facade. The study explores how these technologies ensure precision, manage complexity, and enhance collaboration among project stakeholders.
The Alto Tower is not just unique for its 38 levels or 51,000 m² area but also for its distinctive flared-cone shape. One of the standout features is the double-skin facade, accomplished through a complex process of parametric design. BIM serves as a cornerstone in managing this complexity.

Architectural Overview

The tower's flared-cone shape allows it to expand threefold from its base to its top floor.
A double-skin facade shifts 12 cm outwards from floor to floor, creating an angle of 1.5° towards the outside.

Facade Engineering and Parametric Design

Parametric Design Workflow: Designed by IF Architects, the Alto tower uses a parametric design process enabled by the Rhino/Grasshopper software. This allows for the intricate details of the facade, which features hundreds of windows, each with unique dimensions.
BIM Implementation: Permasteelisa, in partnership with Autodesk, adopted the initial design to produce BIM models that carried the project from design to manufacturing stages seamlessly.

Critical Facade Elements Managed Through BIM

- The 12 cm outward shift of each floor
- Angulation of the facade beams for smoke extraction

Collaboration and Stakeholder Involvement

- Construction Privée teams integrated and codified equipment parameters from the beginning, aiming for automated connections among equipment, datasheets, and plans.
- All architectural lots work on the digital model, facilitating technical and architectural syntheses.

Data Utilization for Future Operations

The BIM models of the facade are rich in data, offering potential interface points with GTB and CMMS tools for future building management.

Limitations

- The complex facade design necessitated advanced parametric tools, which may not be universally accessible.
- Data management and codification require careful planning and adherence to standards for future exploitation.

Conclusions and Future Outlook

The Alto Tower case demonstrates the capabilities of BIM and parametric design in managing highly complex architectural and engineering feats, especially in facade engineering. It also signifies a step forward in data utilization for the operation and maintenance of high-rise buildings.

Emerging Trends in BIM for Facade Engineering

Generative Design and Machine Learning

The fusion of generative design algorithms with machine learning techniques is catalyzing a paradigm shift in the facade design process. While generative design offers a myriad of design possibilities constrained by specific performance criteria, machine learning adds a layer of predictive analytics that can help in refining these designs (Joshi et al., 2021). New research is also exploring the role of deep learning algorithms for predictive maintenance, leveraging real-time data to anticipate issues and offer remedial solutions before any major system failure (Das et al., 2022).

Integration of BIM with Performance Analysis Tools

Another significant trend is the seamless integration of BIM with performance analysis tools. These integrative platforms offer a symbiotic environment, where changes to the facade design can be instantaneously evaluated for their impact on energy efficiency, comfort levels, and other key performance indicators (Jorge et al., 2022). This effectively moves the process from reactive performance evaluation to a more dynamic, proactive design approach. It is worth mentioning that cloud-based BIM platforms are making these analyses more accessible and collaborative, thereby influencing decision-making processes in real-time (Smith et al., 2022).

Digital Twins and Augmented Reality

The concept of Digital Twins and the adoption of Augmented Reality (AR) technologies represent a significant leap toward real-time asset management and interactive maintenance strategies. Digital Twins offer a data-rich, real-time model of the building facade, providing insights into wear and tear, and thermal performance that are critical for preemptive maintenance (Alizadeh et al., 2022). When augmented by AR technologies, this allows for real-time, location-based data visualization. Facility managers and engineers can overlay structural and performance data onto the physical asset, making both routine checks and complex repairs far more efficient (Clark et al., 2022).

These emerging trends signal a future where the lines between design, construction, and maintenance are increasingly blurred, driving toward more sustainable, efficient, and user-centric building facades.

Challenges and Strategies in Facade Engineering with BIM

Challenge: Data Management and Interoperability

As demonstrated in the three case studies, effective data management is central to the seamless functioning of BIM in facade engineering projects. The issue is further complicated when interoperability between various BIM platforms and design applications comes into the picture.

Case-Study Insights: In the Melzo school project, one of the limitations was the absence of a Contractual Information Exchange Platform, leading to traditional methods for material approval and acceptance. This impediment is a direct reflection of the data management and interoperability challenges prevalent in the industry.
Strategies for Resolution: Open data exchange standards like Industry Foundation Classes (IFC) can serve as a solution for these interoperability issues, enabling seamless information sharing between diverse BIM platforms and applications (Jiang et al., 2018). Fostering the adoption of these standards can significantly streamline BIM-enabled facade engineering workflows.

Challenge: Integration of Analysis Tools

Despite the robust capabilities of BIM software in aiding design and visualization, the integration of specialized facade analysis tools remains an operational bottleneck.
Case-Study Insights: In the Signal House project, a lack of pre-existing standards for integrating different facade materials within BIM software was noted. The Alto Tower project, with its complex double-skin facade, required advanced parametric tools for design, which are not universally integrated into BIM software.
Strategies for Resolution: To fully utilize BIM's potential in facade engineering, developing integrated analysis tools and plug-ins is crucial (Li et al., 2018). These will facilitate real-time performance analytics, allowing for dynamic adjustments to the design, thereby improving the overall efficiency and building performance.

Challenge: Skilled Workforce and Training

The successful implementation of BIM in facade engineering calls for a workforce that is well-versed in both domains.

Case-Study Insights: The Alto Tower's case showed a good example of stakeholder involvement and collaboration but didn't delve into the challenge of skill set availability. Nevertheless, given the complexities involved, it's easy to deduce that a specialized skill set was a necessity.
Strategies for Resolution: Training programs targeting both facade engineering and BIM technology must be developed (Sacks et al., 2018). Academic institutions can collaborate with the industry to ensure curriculum alignment with practical needs, better preparing future professionals for the integrated disciplines.

Conclusion

The convergence of facade engineering and Building Information Modeling (BIM) carries a spectrum of both opportunities and obstacles for stakeholders in the architecture, engineering, and construction (AEC) sector. The study elucidated the manner in which BIM can enrich the various stages of facade design, from conceptualization and detailing to fabrication and performance analytics. Notable advantages that ensue from this integration encompass heightened collaboration, streamlined visualization, and more sophisticated analytical functionalities. These synergies pave the way for facade systems that are not only more efficient but also sustainable.

Nevertheless, there exists a set of challenges that inhibit the full capitalization on these advantages. Among them are hurdles related to data governance, software interoperability, and the lack of specialized skills to employ BIM in facade engineering practices. Open data exchange protocols like IFC, coupled with the advent of bespoke analytical tools and software plugins, are posited as potential solutions. Skill acquisition and enhancement could further be facilitated by academic-industrial partnerships and specialized training curricula.

The findings of this investigation serve to educate stakeholders in the AEC domain about the latent potential of BIM in facade engineering. They also offer insights into the complexities involved and propose strategies for the efficacious incorporation of BIM, aiming to catalyze its wider acceptance across the industry. In doing so, the aspiration is to encourage more robust, efficient, and sustainable design strategies for building facades.

Future Research

The sphere of future research can be broad and should aim to scrutinize the integration of emergent technologies like generative design, machine learning, and digital twins into BIM-enabled workflows for facade engineering. The AEC industry stands to gain significantly from the articulation of guidelines, best practices, and demonstrative case studies regarding the application of BIM in facade engineering. Additionally, it is essential to explore the compatibility and synergistic effects of integrating BIM with nascent construction paradigms such as robotic manufacturing and automation. These avenues for future exploration could serve to further enrich the discourse on optimizing facade engineering workflows through technological advancements.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Chat GPT in order to improve language and readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Conflict of interest

The author declares no conflict of interest. All views and opinions expressed in this article are solely those of the author, and no external party had any influence over the research, results, or interpretations presented in this paper.

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Data availability

The findings of this research are exclusively based on secondary sources which are publicly accessible and cited within the manuscript. No primary raw data was collected or utilized for this study.

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