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Cost-Optimized Pre-Engineered Buildings: A Bim-Based Meta-Analysis

Dinki[1], Prof. Rajesh Chouhan[2]
[1]Research Scholar, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh, India.
[2]Professor, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh, India.
Email: chouhanrajesh49@gmail.com [2]
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Abstract
In recent times, the usage of Pre -engineered buildings (PEB), a method exists that provides benefits for building structures quickly and efficiently while using materials effectively and economically. However, to fully realize the potential of PEBs, advanced design optimization tools and stringent cost efficiency frameworks must be incorporated. The aim of this paper is to discuss a systematic review and meta-analysis of articles that were published from 2010 until 2024 focused on the implementation of Building Information Modelling (BIM) or specific structural software such as STAAD. In terms of a literature review, the following are traffic or software analysis used in different research papers: Pro, ETABS, SAP2000 and Tekla Structures and other PEB systems status prediction that has taken its place comfortably for an optimal use of figures based on some economic parameters. The evidence is drawn from 30 peer reviewed studies, and covers several dimensions such as structural mass reduction, material use efficiency, load distribution optimization, fab costs savings etc. It was discovered that design processes involving PEB integration with BIM material savings ranged from 15–30% lower in weight than the conventional process and optimization software for structures reduced steel consumption by up to a maximum of 25%. Using BIM along with structural tools has also been indicated to yield consistent reductions in project delivery timelines and lifecycle costs, as illustrated in the meta-analysis. Some of the key barriers identified are limited interoperability between software platforms, talent shortage and lack of well defined PEB-BIM integration frameworks in developing economies. In this paper, we present AI-Driven Design Optimization for an Effective parametric Metal Structure which is a better dimensional strategy to achieve economic viability and cost efficiency in PEB Design while ensuring minimum information loss and time in the design process though further incorporating effective parametric structures by integrating Ai-driven Parametric optimization embedded with real-time structural health monitoring systems integrated into the BIM environments as future directions of research.

Keywords: *Pre-Engineered Buildings; Building Information Modeling (BIM); Structural Optimization; STAAD. Pro; Cost Efficiency; Steel Frame Design; Parametric Analysis*

1. Introduction

1.1 Background and Significance of Pre-Engineered Buildings

Rapid changes to the global construction industry over last 30 years due to pressures for speed and cost control. Pre-engineered buildings haracterized by factory-fabricated structural steel components assembled on-site as a construction system for industrial, commercial institutional facilities. Unlike traditional building, PEBs are manufactured as a complete system; every structural member primary frames, secondary members, roof and wall cladding, roof and wall cladding connections is designed is achieved in specialized factory facilities. It maximizes off-site labor, minimizes material waste, and exponentially shortens project timelines. As per industry estimates [1], PEBs can accelerate construction by 30–50% over conventional structural systems and this advantage makes them a preferred option for time-sensitive industrial and logistics projects. The market for PEBs has witnessed steady growth owing to industrialization in various regions such as South and Southeast Asia, the Middle East, and Africa; The global PEB industry was worth USD 18.6 billion in 2022 which is estimated to reach a value of around 34.4 billion by 2030 according to a report by "Fortune Business Insights". Though such procedures contain these advantages, determining an optimal structural design of PEBs that is closest to material efficiency whilst retaining full structural safety remains a trilemma in engineering and has only been accommodated with advanced analytical tools. A body of work that has focused on transitioning from empirical rule-based design to software-driven optimization has been foundational in realizing the economic potential of PEB systems, and a final frontier in this evolution concerns the integration of Building Information Modeling with structural-analysis platforms into seamless, data-rich design workflows [2] [2].

1.2 Role of BIM and Structural Software in PEB Design

Building Information Modeling (BIM), a complete digital solution to planning, designing, producing, and managing built assets. BIM platforms like Autodesk Revit, Tekla Structures and Bentley Open Buildings Designer allow users to model entire building systems as parametric, data-rich 3D objects for PEBs. Such integration enables design teams to visualize structural performance, identify clashes, coordinate multi-disciplinary inputs and produce accurate fabrication drawings, all in a unified environment [3]. At the same time, software focused solely on structural analysis and design such as STAAD. Moreover, software such as Pro or ETABS or SAP2000 and RISA-3D have a star FEA solver engine flexibility that can be used in the analysis of the frame subjected to a combination of load cases like dead load case, live load case, wind case, seismic loads due to some place for certain period of time with thermal effects. When using interoperability formats like IFC, CIS/2, and direct API-based links between BIM and structural software synergetic design workflows emerge in which design changes propagate across disciplines automatically, analysis results are encapsulated within the BIM model [4] (e.g., as 3D models), and accurate quantities for cost estimations can be derived. Arguably, this combination has the highest impact in PEBs as standardization of components greatly enhances parametric BIM modeling. Studies have continuously reported a 60–80% reduction in drawing errors, a 30–40% reduction in design-cycle time and ±10-2.5% improvement of accuracy on cost estimates for PEB projects of the same scale and complexity when integrating BIM-structural 5.

1.3 Objectives and Scope of the Review

This review paper aims to consolidate, critically evaluate, and synthesize the body of research published between 2010 and 2024 on the application of BIM and structural software to the design optimization and cost efficiency analysis of pre-engineered buildings. The specific objectives are: (i) to document and categorize the methods, software tools, and structural parameters studied in published literature; (ii) to quantify the material savings, cost reductions, and performance improvements reported across studies through a meta-analytic lens; (iii) to identify the critical gaps, methodological limitations, and inconsistencies in existing research; and (iv) to propose a framework for future research and practice integration [7]. The scope encompasses studies on single-story and multi-bay PEB systems for industrial and commercial applications, covering portal frame design, column and rafter optimization, secondary structural member design, connection design, and whole-building cost analysis. Studies involving precast concrete, timber frame, or modular construction systems without a PEB steel framing focus are excluded. The review follows a systematic literature review methodology aligned with PRISMA guidelines, with elements of narrative meta-synthesis applied to address both quantitative and qualitative dimensions of the evidence base, recognizing the significant heterogeneity in research contexts, methodologies, and outcome metrics that characterizes this field.

2. Literature Survey

However, there is a wealth of literature available on PEB design optimization and integration with Building Information Modeling (BIM), covering several technical areas such as structural engineering, construction management, and digital design technology. The early foundational work on PEB structural optimization typically occurred earlier than available BIM tools were present, employing classical methods of modelling the structure and deterministic algorithms for optimization. Sable and Gupta [4] has carried out one of the earliest comparative experimental studies using the STAAD under Indian Standards for PEB portal frames As per analysis from PRO, tapered I-section columns and rafters gain 18–22% steel weight economy when compared with prismatic sections for the same span. In the same context, Wakchaure and Sagade [5] examined the structural behavior of PEB frames for different eave heights and bay spacings, and found that the best-weight-to-span ratios in terms of industrial warehouse layout resulted from ideal bay widths of 6–8 meters. These initial studies provided empirical benchmarks that informed later BIM-supported workflows since then and are still a basis for citations in the PEB optimization literature.

With the increase of BIM implementation in the construction industry, researchers started focusing on its application related to PEB systems. Wang et al. [6] proposed the initial framework of BIM-based structural coordination by introducing a federated model that supports all disciplines (i.e., structural, architectural and MEP) working under a common data environment (CDE). This concept has been put to work for PEB systems by researchers, e.g., Abanda and Byers [7] showed that BIM-based energy-structural co-simulation can eliminate unnecessary structural members (which would still be retained in a conservative approach using conventional design. They carried out their study on a 40m span industrial PEB and reported that they could reduce total steel tonnage by 14.7% from integrated BIM-structural analysis source. Refer to the following work by Agarwal et al [10] reported an extension of this finding into fabrication management by noting that Tekla Structures-based

PEB detailing can lead to a 60%+ reduction in drawing production time and eliminate dimensional errors (a leading cause of out-of–scope rework and cost overruns) in shop drawings, a common aspect of traditional building approaches.

ETABS and SAP2000 are used at the design stage for many multi-story and multi-bay PEBs, especially under seismic and wind performance contexts. In Kaur and Singla [8] assessed the seismic performance of PEB frames using ETABS in Zone IV of the Indian seismic zonation map, reporting a significant improvement in inter-story drift control, with a moment-resisting function performed by semi-rigid connections (SRC) within a frame outperforming traditional pinned-base frames under four different loading conditions or response types as defined by four different loading conditions. This has obvious cost-influencing aspects because the less drift, the less requirements on secondary structural members and smaller connection plates. Simultaneously, Duggal [9] using SAP2000 nonlinear analysis shown that PEB frames with corner connections having haunched rafters reduce the demand of bending moment at critical section by 31% and also permit substantial reduction in cross-section. Such structural adaption to maximize efficiency offers quantifiable cost perspectives: optimized frames demonstrated reduced per-square-metre structural costs of INR 420–650, approximately 12–18% of the baseline structural cost for a specific case from [12] in Indian market settings.

There have been many comparative studies into cost efficiency analysis of PEBs relative to traditional construction with findings demonstrate continuous association economic advantages for PEB's. Subramanya et al. Chandrahasan et al[11], The objective of this study was to compare the lifecycle cost of PEB systems with reinforced concrete (RC) frame construction for industrial facilities in South India; results indicate that PEB have a 22–28% first-cost savings and a 35% lower annual maintenance cost (over a period of30years), attributed to better corrosion resistance performance from factory-applied coatings, and half-life design concept in which components based on modular flexibility could be replaceable. Another comparative analysis Rajanish et al. [12] Perpendicular to this, Optimization of pre-engineered building designs using BIM for warehouse construction in Rajasthan showed that optimized PEB designs reduced structural steel requirement by 19.3% and were more cost-effective by around INR 1.2–1.8 million per 1000 m2 floor area as compared to Non-optimized PEB design✳. The two studies point out that the complete cost benefit of BIM-optimized PEB construction is only achieved when the benefits of BIM-generated Bill of Quantities (BOQ) accuracy are capitalized upon during procurement, as design-stage cost savings can be reversed by high material-order discrepancies causing busyness or overhaul.

Particularly focus has been while analysing the wind load and its effect on PEB design economy, typically in coastal and tropical scenarios. IS 875 Part-3 (2015) and ASCE 7-22 specify complex wind pressure coefficients specifically for low-rise industrial buildings which have a substantial impact on the design of pre-engineered building (PEB) frames including those adopted for gable end frames or longitudinal bracing systems [21]. Using finite element models validated against wind tunnel test data, Mahendran and Mahaarachchi [15] showed that realistic wind pressure distributions, rather than simplified code envelopes, reduce both design wind demand on PEB frames by 15–20% and lead to reductions in purlin and girt sizes. For this reason, BIM-based wind load modeling tools that import CFD-derived pressure data directly into structural analysis models are increasing in popularity offering such a degree of savings without the risk of errors during manual transfer between different software programs which presents an excellent path forward for future research and adoption by industry.

A frontier research field with important implications for PEB cost effectiveness is the integration of parametric design optimization algorithms with BIM platforms. Mueller and Ochsendorf [13] and Preisinger and Heimrath [14] worked on structural optimization plug-ins in Grasshopper/Rhino and Revit, respectively, showing that the topology optimization size optimization algorithm can be directly applied to PEB frame geometries to reach weight designs that are very close to theoretical minimum weight. The application of these methods to portal frames with 20–60 meter spans yielded designs with steel weights that were 8–12% lower than those obtainable through traditional iterative design (implemented by experienced structural engineers), while also having integrated with Building Information Modeling (BIM) for easy downstream documentation and quantity extraction [13]. Through advancements in GPU-accelerated FEA, the computational efficiency of these methods has significantly improved past a point where real-time parametric optimization is becoming viable for production design environments within BIM.

Seismic Design Integration and Challenges in BIM-PEB Workflows for high-seismicity zone regions of South Asia (Pakistan, India, Nepal and the Asia-pacific) Bhatt and Basu [16]; Bhaskaran et al. While examining the response spectrum analysis performed in STAAD. The Pro and ETABS method consistently yields lower base shear demands than equivalent static methods for building frames which render its use in PEB reconstructions, with more economical designs of column base plate and anchor bolts. BIM models incorporating these refined analyses then automatically document the optimal design, entirely avoiding the version management problems that incur expensive field changes in traditional PEB projects. Bhatt and Basu estimated this value management advantage of versioning to be in the range of 3–5% of project cost for Medium Complexity PEB works, which not only demonstrate a BIM enabled design optimization environmental benefits but shows the benefits to control costs during construction phase also.

The newest and most rapidly growing area of research appears in the recent application of artificial intelligence (AI) and machine learning (ML) into PEB structural optimization in BIM environments. The use of particle swarm optimization (PSO) by Kaveh and Talatahari [18] for steel frame weight minimization was one of the first works to address irregular geometries, producing results that outperform classical gradient-based methods. Later works of Dede et al. Evolutionary algorithms and teaching-learning-based optimization can find near-global optima of multi-bay PEB frames unreachable by traditional optimization [19,20]. Thus, the linkage of these AI algorithms with BIM platforms using Dynamo scripting in Revit or Python APIs in Tekla can create a completely automated design-to-documentation pipeline that aims to dramatically lower human effort and time for PEB design optimization while minimizing material waste to near theoretical mininmum for an arbitrary structural configuration and loading scenario.

There is also a wealth of literature reporting considerable regional variation in drivers for PEB adoption, design standards, and costs [19]. The Indian studies, which account for the largest single-country contribution to the corpus reviewed are characterized by an emphasis on a compliance context with respect to the IS 800 and IS 875 code [22]. Research in the Middle East and Southeast Asia emphasizes the significance of wind loading on flat-roof industrial layouts, durable metal coatings for use in high-humidity marine environments, and cost methods. While the European and North American studies, as fewer in number than their developing economy counterparts, are primarily benchmarks for compliance with Eurocode 3 [24] and AISC 360 [23] standards of performance respectively; they do demonstrate the higher baseline level of BIM adoption in these markets that makes continuous integration of PEB into BIM context markedly less challenging than much earlier stages in terms of BIM adoption characterise developing economies.

Connection design and its effect on the rational use of PEBs is a topic that has been increasingly investigated by researchers. Foundational results on the slenderness behavior of PEB frame members with respect to moment connections have been developed by Bradford and Lay [28] and form the basis for current design practice for these types of connections. Recently, Subramanian [29] and Narayanan and Kalyanaraman [30] have reported the cost impact of alternative connection design philosophies, confirming that moment-resisting end plate connections yield structural efficiency advantages (and therefore reduce construction materials used) but increase fabrication for spans greater than 25 meters. Abstract: The ability of BIM platforms to include connection design parameters as parametric attributes of structural objects allows for automated optimization of connection designs as part of an integrated BIM-structural workflow, a potential that we are only beginning to model systematically in the PEB research literature.

3. Methodology

3.1 Literature Search and Inclusion Criteria

This review was conducted according to the systematic literature review protocol and reporting methods in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency, reproducibility, and comprehensiveness. Boolean search strings integrating the words were constructed to perform a comprehensive database search throughout Web of Science, Scopus (Elsevier), IEEE Xplore, ASCE Library and Google Scholar: terms such as pre-engineered building; PEB structural optimization; BIM structural integration; STAAD. Learn more about Work Optimization of Pro portal frame, ETABS steel design, cost efficiency PEB parametric structural optimization The search consisted of Engligh-language, peer-reviewed literature as well as conference proceedings and technical reports published from January 2010 to December 2024. An initial search identified 847 records, of which 124 were duplicates– leaving a total of 723 non-duplicate records; title and abstract screening eliminated 498 irrelevant records while full-text review excluded an additional 195 records following the more stringent criteria requiring that studies addressed PEB systems specifically and/or provided quantitative data on their structural or cost outcomes. The final meta-synthesis included a corpus of 30 peer-reviewed references and the corpus was supplemented by 12 standards documents, government reports and industry white papers for contextual information. The methodology quality of each retained study was assessed using a bespoke scoring rubric (clarity of research design, rigor of validation, specificity of outcome reporting and discussion of limitations); studies with scores below 60% on this rubric are indicated as requiring caution in interpretation in the synthesis.

3.2 Data Extraction and Coding Framework

Nine dimensions were then systematically coded for each retained study, namely: (i) the geographic and climatic context; (ii) building typology and span range; (iii) structural system configuration of single-span or multi-bay or mezzanine; (iv) software tools employed for BIM modeling and structural analysis; (v) design standards applied of IS, AISC, Eurocode or AS; (vi) primary optimization objective as weight minimization, cost minimization, performance maximization or multi-objective; (vii) key quantitative outcomes such as percentage weight savings, cost reductions and time savings; (viii)primary limitations acknowledged by authors in texts and descriptions of any adjustments made by authors to overcome these limitations's been performed by the authors', and with cases where they have been tested vs not tested leaving only results outside 'control', e.g. experimental validation / peer design comparison/ code compliance verification. For studies reporting ranges of outcomes across multiple design scenarios, the median value was used for meta-analytic aggregation to avoid extreme scenario results acting as outliers. Weighted mean effect for material savings and cost reduction outcomes were estimated based on the inverse-variance weighting method, with heterogeneity determined using Cochran's Q statistic and the I-squared index. Cost reduction outcomes were highly heterogeneous ($I^2 = 72\%$) due to the clinical diversity of project scale and geographic market, and ways in which cost accounting methods are applied; therefore, a narrative synthesis for describing cost reduction outcomes along with pooled quantitative estimates. Data coding was independently performed by two reviewers and in order to measure the inter-rater agreement, Cohen's kappa ($\kappa = 0.83$) was computed (indicates strong agreement providing evidence of reliability of the coding framework.

3.3 Analytical Framework and Synthesis Approach

The synthesis was structured according to the main four thematic clusters, based on the coding analysis which were derived from (1) structural optimization for weight reduction, (2) cost efficiency evaluation and analysis, (3) interoperability of BIM-structural software, and last but not least, (4) emerging computational technologies. Studies are then organized by span category (short-span, ≤20m; medium-span 20–40m; long-span >40m) and software platform within each cluster to facilitate meaningful cross study comparisons. For the weight optimization cluster, results were summarized to represent reported weight savings across studies in a density plot, with effect sizes defined as % reductions relative to each study's respective control or baseline design. For the cost-effectiveness cluster effects were standardized to a common metric the net cost savings in USD per 100 square metres of floor area using 2024 purchasing power parity (PPP) factors where base study data allowed exchange. Methods The qualitative analysis of the BIM interoperability cluster was performed using thematic coding that reduced raw data into a taxonomy of integrations and reported benefits and disadvantages classifications. Computational methods supporting these modalities were narratively reviewed, focusing on maturity proof-of-concept vs. applied and validated of each approach. We synthesized the evidence using a multi-method strategy; we selected quantitative meta-analysis for weight optimization outcomes and narrative synthesis for cost and interoperability outcomes in order to optimize the utility of our heterogeneous evidence base while enabling full methodological transparency that allows readers to trace findings back to primary sources.

4. Critical Analysis Of Past Work

A thorough review of the studies identified strengths, weaknesses and methodological issues that form the contours of an evolving body of knowledge on PEB design optimization within BIM-structural integration research. The most common strength found across the reviewed studies was that they validated finite element models and used them as a basis for structural optimization. Studies employing STAAD. Pro and ETABS generally exhibit good assembly of load combinations following the provisions of their respective design codes (IS 800 or AISC 360 or Eurocode 3), and most incorporate validation against experimental results, or independently verified benchmark analyses. The methodological rigor here lends credibility to the reported weight savings and cost efficiencies for each of which cluster consistently in the 15-30% range for materials with respect to benchmark baseline designs and 10-25% ranges for costs versus conventional design baselines. The variety of geographic contexts represented (India, Southeast Asia, Middle East, Europe and North America) bolsters external validity because the efficiency benefits of BIM-structural integration are not merely artifacts of local market conditions or design standards.

But here, a number of major limitations make it difficult to generalize and compare findings across the corpus. First, about 40% of studies reviewed use single case-study buildings and sensitivity analysis is conducted for fewer than half the studies to determine whether studied outcomes would be consistent across different spans, loading conditions or site contexts. Due to this case-study dependency, some studies find quite large effect sizes (i.e., savings of more than 30%) which may either simply be a result of good site-specific or project-specific conditions rather than design optimization gains which are valid across architectures. Second, and related to the first, there is a wide variety in the conservatism of baseline designs used as comparators in cost and weight analyses; designs optimized with BIM compared with unoptimized but over-conservative conventional designs will naturally yield larger apparent savings than studies using well-optimized conventional baselines. This average baseline difference is inflated in the literature and should be treated with caution when interpreting results of meta-analyses. Third, the handling of non-structural costs the broad category that includes foundation systems, cladding, mechanical and electrical services, and site works is inconsistent among studies as cost efficiency analyses containing only structural steel costs report proportionately greater savings than whole-project analyses. Yet still many studies either do not specify their cost boundary clearly neither hence inter-study comparison is tricky so findings may ultimately confuse practitioners looking for research-supported features with which to improve decision-making on projects.

Interoperability between BIM platforms and structural analysis software is recognized in the literature as a major practical challenge, but those analyses tend to be shallow and anecdotal. Most studies characterize interoperability as a constraint on pass, but none of the studies systematically quantify the concurrent information loss, geometric simplification or error propagation in property transfer from BIM model to analysis models. Some critical limitations are that there is almost no longitudinal analysis of real cost and performance outcomes of BIM-optimized PEB projects all the way through construction, commissioning and early operation. Almost all included studies are design stage analyses, the assumption that savings manifest perfectly in construction practice from a design stage analysis have been qualitative and left unproven as empirical question in PEB-BIM literature which is an essential evidence gap of the field. Finally, reviewed literature is overrepresented by South Asia studies (i.e., India) with few studies from Southeast Asia or Sub-Saharan Africa and Latin America where regionally generalizable findings on BIM the level of effort necessary to promote this technology in regions undergoing PEB construction expansion will likely be very different than the Indian context dominating the literature.

5. Discussion

Conclusion This review highlights the fact that integration of BIM and structural software is a truly innovative approach to PEB design optimization as it leads statistically significant and practically meaningful material savings and cost efficiency gains. The abundant evidence for material savings of 15–25% from a wide range of contexts suggests that the existing gaps between design practice and integrated BIM-structural workflows in PEB SHOULD BE justified on an economic basis. The biggest gains seem to be from two linked mechanisms: first, the greater accuracy of load take off and quantity extraction based on BIM as a reduction in the conservatism driven by uncertainty in design; second, the ability of specialized FEA software for structural optimization to identify minimum weight designs that manual iterative design can never achieve reliably for complex multi-bay or long span frames. When these mechanisms are integrated into a single workflow, evidence indicates that their effects are not necessarily additive, but synergistic: eliminating version management errors and automating various design-to-documentation workflows magnify the baseline efficiency improvements generated by each technology in isolation.

In addition, the discussion indicates some major implementation barriers that need to be overcome in order to realize the full potential of BIM-PEB integration. The interoperability gap between mainstream BIM platforms and good structural analysis programs is still large, either forcing an iterative re-modeling of the results computed in a specialized environment back into the modeled BIM; or providing only partial (and low fidelity) information transfer due to abstraction in automated data exchange. High/low-quality data integration skills, coupled with investment in BIM capability and software integration expertise, pose as yet an additional barrier for small and medium-sized PEB manufacturers to contractors, especially within the context of developing economies where the majority of the growing demand is based. Solving these issues require concerted action some may come from software vendors themselves, but others will require industry association and government agency collaboration to coordinate technical standard developments such as PEB-BIM object libraries and interoperability protocols. In this regard, approaching fully closed-loop PEB design and management systems by seamlessly integrating AI-driven parametric optimization with digital twin technology alongside real-time structural health monitoring in BIM environments may provide far more massive efficiency gains than any one of the technological interventions reported in the present literature.

6. Conclusion

Here, we provide the first systematic review and meta-analysis of 30 (of 624 articles) peer-reviewed studies on design optimization and cost efficiency analysis of pre-engineered buildings (PEBs) using BIM and structural software since providing strong evidence for integrated digital optimized local workflows successfully constructing digitally designed PEBs. Main findings: Between 15–30% material (mass) savings and about 10–25% cost efficiency improvements (in comparison to conventional design baselines) can be achieved by integrating BIM in PEB design workflows; For long-span increasingly multi-bay configurations with greater structural complexity, the magnitude of benefit increases. Structural analysis software particularly STAAD. A solid understanding of specialized software such as Stru Cad, Pro, ETABS and SAP2000 is crucial to realizing these gains within the process through accurate load modeling, finite element optimization and code compliance verification. BIM platforms generate additive value based on optimized design coordination and clash detection, precise quantity extraction, and fabrication-ready documentation. It is the combined use of BIM and structural software in an integrated workflow that delivers synergistic benefits beyond what either technology can achieve independently, a conclusion with immediacy for PEB practitioners, providing direction for construction project management strategies.

Important gaps in the literature include lack of studies longitudinally following post-construction to validate design-stage savings over the life-cycle of a real project, inconsistent treatment of whole-project versus structural-only costs in cost efficiency analyses, and limited geographic diversity within the evidential base. Future work should focus on conducting multi-project empirical studies monitoring an outcomes trajectory through construction and operation; establishing unified interoperability formats across international markets for BIM-PEB; and integrating history-capturing artificial intelligence/ML based digital twin capabilities into the BIM-PEB process. It is recommended to adopt integrated BIM-structural analysis workflows as standard practice for PEB design, particularly the need to develop internal competences in using interoperable software applications, parametric design and data-driven quantity management that are necessary prerequisites if planners are to realise the efficiency potential documented by this review. Policymakers in fast-industrializing economies who wish to sustain productivity growth in quality, cost, and completion time should acknowledge that BIM-PEB integration promises significant returns — via the separate development of integrative standards; workforce training and procurement incentives.

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