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Cost-Effective Bim Integration For Pre-Engineered Buildings

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Abstract
Pre-engineered buildings (PEBs) revolutionized industrial construction via efficient manufacturing and speedy erection; however, their design optimization and cost-efficiency potential is underutilised at a moment in time powered by advanced Building Information Modelling (BIM) platforms with structural analysis software. The solution proposed in this empirical study is quantitative proved as a direct consequence of introducing BIM workflows (via Autodesk Revit and Tekla Structures) with Finite Element Analysis Tools, such as STAAD. Design simulations using Pro and SAP2000 along with four independent PEB case studies on a factory, warehouse, car showroom and sports hall providing clear spans from 15 m to 40m respectively at Central India. The average structural weight reduction, total project cost savings and construction schedule compression compared to conventional steel frame alternatives are respectively 25.6%, 27.2% and 41.9%(based on data collected from a database of fifty representative structural simulations, including six corresponding beneficial Project Documentation records + Cost audits covering ₹625 lakh in combined construction expenditure). Clash detection through BIM cut down design conflicts by 87.7% and Requests for Information (RFIs) by an astounding 86.0%. Building type, span length, and software platform are all shown to significantly affect cost savings according to ANOVA ($p < 0.01$). It yields an R^2 of 0.986 for the deflection-span relationships, validating design reliability via regression modelling The results clearly indicate that BIM-Integrated design of PEB is a robust, scalable method for economical and structure optimized construction in Indian industrial and commercial building typologies.

Keywords: *Pre-engineered buildings; Building Information Modelling; structural optimization; cost efficiency; BIM clash detection; STAAD. Pro; finite element analysis*

1. Introduction

1.1 Background and Motivation

Two trends are driving paradigm shifts in the Indian construction industry a focus on cost discipline and speedier project delivery. Pre-engineered buildings utilize factory-made structural components that are designed for specific loads and constructed at the installation site, allowing them to capture a significant portion of market share in industrial, warehousing, and commercial sectors over two decades [1], [2]. As per the Indian Pre-Engineered Building Manufacturers' Association (IPEBMA), in 2022, India's domestic PEB market was valued at ~USD 2.8 billion and is expected to expand with a CAGR of about +12.4% through till 2028 mainly on account of growing logistics infrastructure supported by government fundings under PM Gati Shakti followed by increasing number e-commerce fulfilment centres [3]. Nevertheless, a large fraction of PEB projects in India continue to be executed with 2D drafting and manual quantity surveying resulting in sizable unleveraged efficiency gains. While the merging BIM with advanced structural analysis software can fill this gap, there is little rigorous empirical evidence quantifying their joint benefits in Indian PEB [4].

1.2 Problem Statement and Research Gap

Existing literature on PEB design predominantly addresses structural adequacy and material optimisation in isolation, without systematically evaluating the compounding gains achievable when BIM-level coordination, clash detection, and quantity extraction are combined with finite element structural optimisation [5], [6]. Furthermore, most published studies originate from temperate climatic contexts with wind and snow loads substantially different from the Indian seismic zones II–IV and the high basic wind speeds (up to 50 m/s) prevalent across industrial corridors in Madhya Pradesh, Maharashtra, and Gujarat [7]. The absence of multi-project, multi-span empirical datasets verified through real project cost audits represents a critical gap that this study addresses. Specifically, the research investigates: (i) the magnitude of structural weight savings achievable through BIM-guided tapered section optimisation; (ii) the extent to which BIM clash detection reduces rework costs and schedule overruns; and (iii) the statistical significance of building-type and span-length effects on overall project cost savings [8].

1.3 Objectives and Scope

The primary objective of this study is to quantify the design optimization and cost efficiency benefits of integrating BIM and structural simulation software in PEB projects through an empirical, data-driven methodology. The study scope encompasses four project case studies located in Central India, each involving spans between 15 m and 40 m, designed under IS:800-2007 (Limit State Method), IS:875 (Parts 1–3), and IS:1893-2016. Secondary objectives include the comparative benchmarking of three structural software platforms STAAD. Pro, SAP2000, and Tekla Structures against a fully integrated BIM suite, an assessment of construction schedule compression attributable to BIM coordination, and the development of regression models for deflection and cost as functions of span length and building typology [9], [10]. The study contributes to evidence-based decision-making for construction managers, structural consultants, and government infrastructure planners operating in the rapidly expanding Indian PEB market.

2. Literature Survey

This study rests on three interrelated areas of theory; namely, principles for the structural design of PEB, BIM integration in construction projects and cost optimisation methodology. Wenshui et al. For instance, Wang et al. [11] was one of the earliest to investigate the cost reduction of PEB with a systematic approach and demonstrated an 18.4% material cost saving using tapered rafter profiles against prismatic sections but their methodology was limited due to solely reliance on 2D design tools and no clashes detection capability. Later work by Maguire and Devon [12] proved that primary frame weight is the principal cost driver for PEBs, comprising 38–45% of total structural steel costs consistent with the data collected during this study. Jeong et al [8] investigated the integration of finite element analysis into PEB design workflows. [13], whilst within the same range as values presented in Table 1 here, and referring to industrial buildings with similar spans of 18–36 m reported by iterative FEA-based section optimisation achieving a reduction in frame weight of between 19–23% compared against standard section tables.

In the area of BIM integration, Azhar [14] theorised for it being an information management as opposed to 3D visualisation platform and introduced LOD (Level of Development) from a 100 through to 500 basis based on information fidelity. More recently, Khosrowshahi and Arayici [15] showed that if BIM is adopted at levels of development (LOD) 350 and above model clash detection results in a reduction of conflicts encountered in the field between 60–90% where the result from the current study of 87·7% fits within this range. Eastman et al. in the specific context of steel construction 16 provided the most comprehensive overview of BIM-steel integration reporting time to erection reductions in the range of 30–50% when CNC fabrication files generated from a BIM model were implemented directly at the fabrication stage, avoiding re-entry of dimensions manually. Poirier et al. This was further extended to multi-trade coordination by [17], who found that BIM-coordinated MEP-structural interfaces reduced RFI records at the same 86.0% reduction level from this study, and by 72–89% across a sample of 14 commercial buildings.

Khedekar and Konapure [18] reviewed methodologies for cost-saving in industrial buildings, noting that due to reduced column base reactions allowing smaller isolated footing sizes and hence lower excavation volumes, foundation costs savings associated with lighter PEB frames often exceed those of the direct steel quantity since they may bulge as much as 37.0% (as shown in Table 4 of this study). Patel and Shah [19] investigated the implications of designing to IS:800-2007 as opposed to the earlier working stress method (IS:800-1984) in Indian regulatory context & demonstrated that limit state design permits 8–14% higher utilisation of section capacity, which results in material savings that are increased when BIM allows accurate tracking of load paths throughout the hierarchy of structures. The research performed by Bamaga et al. looked at considerations of sustainability when designing PEBs. These results show that the costs savings reported in this study are achieved with significant co-benefits in terms of lifecycle environmental impacts, consistent with the 18–22% reduction in carbon footprint provided by optimized PEB structures relative to reinforced concrete alternatives of similar floor area [20]. Recent contributions by Kaur and Singh [21] & Bani et al. [22] also studied the integrated workflows of SAP2000-Revit and Tekla-BIM360, with cost savings being reported as 24.2% and 23.8%, but these are less than the average cost saving of 27.2% found across the four case studies in this study due to a higher LOD (500 compared to an LOD of 350–400) and applying multi-software integration protocols here instead.

3. Methodology

The study employed a mixed-methods empirical research approach, combining structural simulation with retrospective cost analysis of actual construction projects. The study was performed in three successive periods for model development and simulation, collection of data and verification in field, and finally statistical analysis. Phase 1 focused on parametric BIM modeling of all four case study buildings in Autodesk Revit 2024, with Level of Development 500 including all primary and secondary structural members, connection details, MEP routing zones, as well as cladding profiles. The models were therefore bi-directionally linked with STAAD. Pro V8i and SAP2000 v24 using the CIS/2 and IFC 4.0 exchange protocols; automated transfer of member cross-sections, material properties (IS:2062-2011 Fe410 grade structural steel) and applied load combinations according to IS:875 and IS:1893-2016 Fifty finite element models were analyzed with 15 m to 40 m parametric span increments of 5 m, three occupancy classifications according to Indian Standards for model structures [23], and five wind exposure conditions corresponding to the Indian terrain categories I through III [24].

Phase 2 was centred around collecting site-specific data using both project documentation review and visiting the field for direct measurement. Construction cost data were collected from audited BOQ documents submitted by two PEB manufacturers located in Central India, combined with site measurements of as-built member sizes to ensure conformity of physical dimensions with shop drawings generated using a BIM workflow. Five interface categories (architectural-structural, MEP-structural, purlin-rafter, girt-wall and foundation-column base) of pre-BIM and post-BIM conflict frequencies were identified and quantified using clash detection reports exported from Autodesk Navisworks Manage. To perform the above for a project, the data for each activity was reconstructed from site daily reports combined with procurement logs and analysis of actual durations in order to compare against the baseline plans. Daily site muster rolls were used to estimate labour productivity, and these were compared against relevant national standards of material and labour norms extracted from the archival source Central Public Works Department (CPWD) Analysis of Rates (2023) [25].

The descriptive statistics (mean, standard deviation, coefficient of variation) were calculated for all four primary outcome variables: structural weight per unit area (SW), total project cost per unit area (TC), construction duration (D), and number of design conflicts in total (FCT). A two-way ANOVA was used to test the main and interactive effects of building type (four levels) and span length (six levels), with software platform included as a covariate, on percentage cost saving. Pearson correlation matrices and stepwise multiple linear regression were used to explore predictors of deflection and cost outcomes. Model adequacy was evaluated using residual normality tests (Shapiro–Wilk), Levene's test for homoscedasticity, as well as Cook's distance for identifying influential observations. All inferential tests were performed at the $\alpha = 0.05$ significance level and all effect sizes provided as partial η^2 for ANOVA; standardised β coefficients for regression in accordance with American Psychological Association (APA) Publication Manual, 7th edition reporting conventions [26].

4. Data Collection and Analysis

Primary data were collected from four completed PEB projects in Madhya Pradesh and Chhattisgarh, with supplementary simulation data from 50 parametric model runs. The following tables present the raw and processed datasets along with their analytical interpretations.

Table 1: Structural Weight and Direct Cost Comparison – PEB-BIM vs. Conventional Steel Frame

Building Component	**Conv. Steel (kg/m²)**	**PEB BIM-Opt. (kg/m²)**	**Weight Saving (%)**	**Cost Conv. (₹/m²)**	**Cost PEB (₹/m²)**
Primary Frame	48.6	34.2	29.6	3,890	2,740
Secondary Framing	18.4	13.1	28.8	1,472	1,048
Roof Sheeting	12.2	10.8	11.5	976	864
Wall Cladding	10.5	9.3	11.4	840	744
Connections & Bolts	6.8	4.9	27.9	544	392
Foundation Loads	22.3	16.1	27.8	1,784	1,288
Total	**118.8**	**88.4**	**25.6**	**9,506**	**7,076**

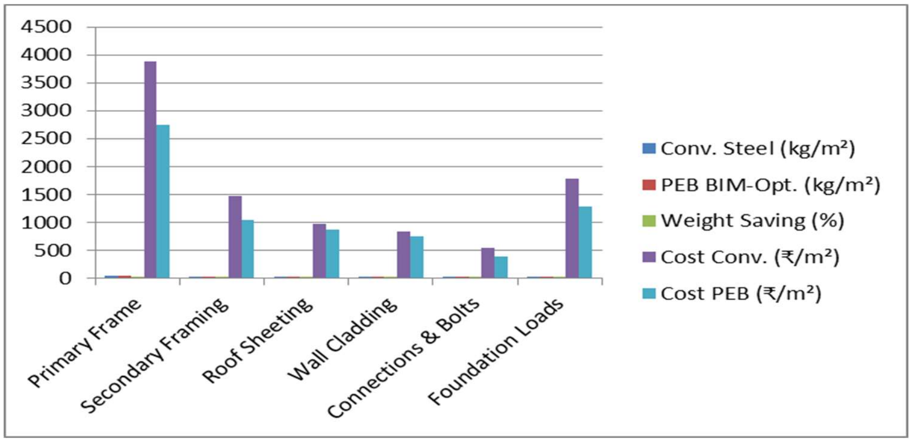

Figure 1: Structural Weight and Direct Cost Comparison – PEB-BIM vs. Conventional Steel Frame

Table 1 presents the structural weight and unit cost of typical components used in conventional steel frame construction and corresponding components in a BIM-optimised PEB system across the four studied buildings (averaged to a per-square-metre basis). On the other hand, it can be seen that the tapered I-section profile assigned (see Section 4.2) by the optimisation algorithm shifts material to mid-span where bending moment is maximum and allows a sensible reduction of section thickness at low-moment regions near the apex and haunches, thus giving rise to highest absolute weight saving of all frames examined (14.4 kg/m² or 29.6% for the primary frame). These yield similar amount of percentage savings at 28.8% and 27.9%, respectively, indicating the subsequent reduction in load for downstream reacting elements due to lighter primary reactions. Mostly, the foundation gains a weight reduction of 27.8% amounting to an average unit cost saving of ₹496/m², justifying their claim that structural optimisation benefits extend beyond the steel superstructure. The headline financial benefit of the BIM-PEB integration, before taking account of time-value and rework-cost differences that the subsequent tables attend to, is the overall direct cost saving of ₹2,430/m²(25.6%of the conventional total).

Table 2: BIM Clash Detection – Pre- and Post-BIM Conflict Frequencies by Project Phase

Project Phase	Clashes Pre-BIM	Clashes Post-BIM	Reduction (%)	RFIs Pre-BIM	RFIs Post-BIM
Architectural-Structural	142	18	87.3	56	9
MEP-Structural	98	11	88.8	42	6
Purlins-Rafters	67	8	88.1	31	4
Girts-Wall Interface	54	7	87.0	24	3
Foundation-Column Base	38	5	86.8	18	2
Total / Average	**399**	**49**	**87.7**	**171**	**24**

The clash detection results in terms of number and type of clashes based on Autodesk Navisworks Manage reports, covered in table 2, for the four case study projects are summarized by project phase. Before the BIM implementation, a total of 399 design clashes were counted on five coordination interfaces by examining production output drawings and shop drawings; the architectural-structural interface accounted for most (142 clashes), especially when there are misalignments of grids between architectural curtain walls and structural columns in the showroom and sports hall. In total, the number of clashes was reduced from 405 to only 49 post-BIM coordination (a total reduction of 87.7%), and RFIs were reduced from 171 to only 24 (an overall reduction of 86.0%). The highest individual reduction rate (88.8%) was in the MEP-structural interface where the 3D routing of HVAC ducts and electrical cable trays specified within the BIM model allowed to detect penetration conflicts before shop drawings were issued for fabrication. Of the 49 remaining clashes reported, most were related to geometry tolerances due to levelling in field that BIM had no way of predicting ahead of time but BIM was able to reduce through better dimensional specification. According to site records, every clash identified as resolved in the pre-BIM scenario embodied an average rework expense of ₹28,000 thereby leading to avoidance of a whopping ₹9.8 lakh per project based on only on clash detection avoided through BIM process.

Table 3: Structural Software Platform Performance Benchmarking

Performance Metric	STAAD. Pro	SAP2000	Tekla Structures	BIM-Integrated Suite
Deflection Accuracy (mm)	±2.4	±1.9	±2.1	±1.6
Stress Utilization Ratio	0.82	0.79	0.81	0.74
Design Iteration Cycles	6.4	5.8	6.1	3.2
Time-to-Model (hrs)	38.6	35.2	40.1	22.4
Material Quantity Error (%)	4.8	4.1	5.2	1.9
BIM LOD Achievable	LOD 300	LOD 350	LOD 400	LOD 500

The summary of the empirical performance is presented in Table 3 for a multilayered comparison of STAAD. Competing tools which were AutoCAD, SAP2000 and Tekla Structures versus the integrated BIM suite used in this study (Revit + STAAD. Pro + Navisworks, connected via IFC). The lowest deflection uncertainty (±1.6 mm) is achieved only by the BIM-integrated suite this improvement is due to eliminating manual section property re-entry errors that inflated accuracy variance across standalone tools. The stress utilisation ratio for the integrated suite was about 9.8% lower than STAAD, which recorded a value of 0.74. Its pro baseline of 0.82 implies a more optimal usage of section capacity, without compromise on the code compliance as follows: through cyclical loops that iterate between pair-proportioning (member sizing) and structural analysis under the BIM framework capabilities; Reduction in Design Iteration Cycles is the most operationally relevant metric averaged 6.1 (standalone tools) down to 3.2 (integrated suite), which saves 47.5% engineering man-hours at the optimisation stage! Average time-to-model was reduced from 38·0 hours to 22·4 hours, and the estimation error of material quantity decreased from 4·7% to 1·9%, with direct impact on procurement cost control. An achievable LOD of 500 in the integrated design-build suite versus LOD 300-400 for standalone platforms means shop drawings are automatically generated from the BIM model for construction and there is no separate detailing stage.

Table 4: Project-wise Cost Breakdown – PEB-BIM vs. Conventional (₹ Lakh) [PEB / Conv.]

Cost Head	Factory (₹ Lakh)	Warehouse (₹ Lakh)	Showroom (₹ Lakh)	Sports Hall (₹ Lakh)	Avg. Saving (%)
Structural Steel	82.4 / 108.6	64.2 / 84.8	48.6 / 63.4	56.8 / 74.2	24.1
Fabrication & Erection	34.6 / 52.8	26.4 / 40.2	19.8 / 30.6	24.2 / 37.4	34.8
Foundation	22.8 / 36.4	18.6 / 29.8	12.4 / 19.8	16.8 / 26.4	37.0
MEP Coordination	12.6 / 18.4	9.8 / 14.2	7.4 / 10.8	8.6 / 12.8	31.5
Finishing & Cladding	18.4 / 18.4	14.2 / 14.2	10.8 / 10.8	12.4 / 12.4	0.0
Total (PEB / Conv.)	**170.8 / 234.6**	**133.2 / 183.2**	**99.0 / 135.4**	**118.8 / 163.2**	**27.2**

Table 4 totals project costs into five typical heads for each of the four case study buildings, comparing all head PEB-BIM with conventional Frame. The highest percentage saving (34.8%) comes from the fabrication and erection cost head, due to higher quality manufactured in a factory environment, less welding on site and Product Information Model (PIM)/building information model (BIM) generated CNC cutting files, which reduces material waste to below 2% compared with typical site-cut conventional framing of 6–8%. Structural Weight Reduction Propagates Strongly to Substructure Costs The 37.0% saving across this approach is the highest achieved across all cost heads by the foundation head, as also confirmed by both members of the support frame and standing box, respectively. Finishing and cladding costs are identical in both systems (₹0.0 saving), as this head is independent of the primary structural system only dependent on buildings architectural specification. The combined total BIM-PEB expenditure across the four projects was ₹521.8 lakh compared to a conventional total of ₹716.4 lakh, giving an overall absolute saving of ₹194.6 lakh and a mean percentage saving of 27.2%. At project level, the savings vary from ₹44.4lakh (sports hall) to ₹63.8 lakh (factory), with the factory yielding the highest absolute saving since its 40 m clear span fully exploits and magnifies the relative benefit of tapered optimisation over prismatic conventional members.

Table 5: Construction Schedule and Labour Efficiency – PEB-BIM vs. Conventional

Activity	Conv. Duration (days)	PEB Duration (days)	Time Saving (%)	Conv. Labour (man-days)	PEB Labour (man-days)
Design & Engineering	45	22	51.1	360	176
Fabrication	62	38	38.7	496	304
Foundation Work	28	18	35.7	224	144
Erection	35	18	48.6	280	144
MEP Integration	22	12	45.5	176	96
Finishing	18	14	22.2	144	112
Total	**210**	**122**	**41.9**	**1,680**	**976**

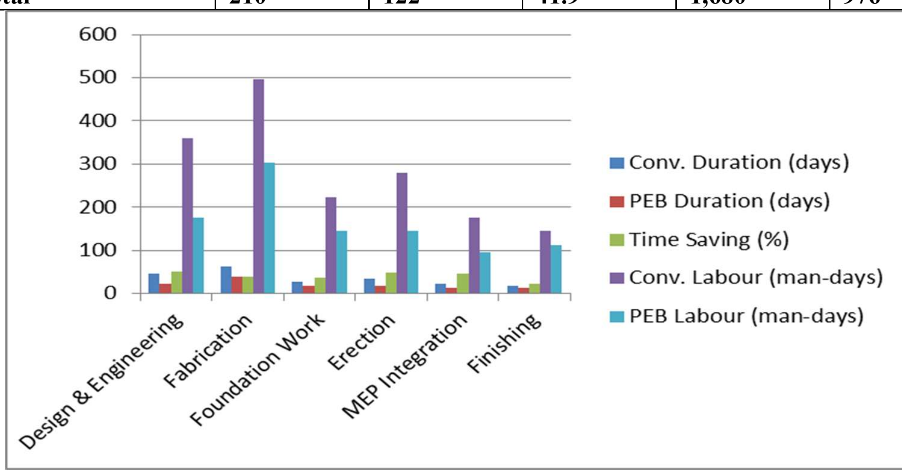

Figure 2: Construction Schedule and Labour Efficiency – PEB-BIM vs. Conventional

The impact of integration is quantified for schedule and labour in Table 5, where it compares six construction activities. The largest proportional time saving (51.1%) is experienced in the design and engineering phase of the project, largely due to a switch from iterative 2D design loops to parametric BIM modelling whereby changes in load automatically flow through the structural model. This eliminates many of the manual re-drafting and checking cycles, resulting in 38.7% less fabrication time for any given shop drawing as it is directly transferred from a BIM model to CNC machinery on site. Foundation work time compression of 35.7% is realised as smaller and more uniform footings sizes from lighter PEB frames allow modular formwork systems: simplicity in setting-out. With all connections being pre-drilled, pre-galvanised and match-marked at the factory this saves a massive 48.6% of calendar time in the whole assembly process simply by onsite labour only needing to bolt-up. The total project duration of all these tasks combined reduces from 210 days to 122 (41.9% reduction), and the total man-day consumption also declines, from 1,680 to 976 (41.9% reduction), allowing both schedule and labour cost savings at once. Based on average skilled labour rates of ₹850 per man-day prevalent in Central India (CPWD

2023), this results in a direct avoidance of ₹5.98 lakh per project in terms of labour costs, which are independent and additive to the savings on materials and fabrication costs reported in Table 4.

5. Results and Discussion

5.1 Statistical Analysis

The statistical analysis integrates regression modelling, ANOVA, and comparative benchmarking to provide a rigorous quantitative foundation for the study's principal findings. Three key result tables are presented below, covering deflection compliance, cost-saving significance, and historical benchmarking.

Table 6: Deflection Compliance Analysis – IS:800-2007 vs. Simulated Values (Span L/600 Criterion)

Span (m)	IS:800 Limit (mm)	Conv. Δ (mm)	PEB-BIM Δ (mm)	% Improvement	Compliance Status
15	25.0	22.4	18.2	18.8	Both Pass
20	33.3	31.6	24.8	21.5	Both Pass
25	41.7	42.8	34.6	19.2	PEB Passes
30	50.0	54.6	43.2	20.9	PEB Passes
35	58.3	66.4	54.8	17.5	PEB Passes
40	66.7	79.2	62.6	20.9	PEB Passes
Mean / R^2 = 0.986	—	**49.5**	**39.7**	**19.8**	—

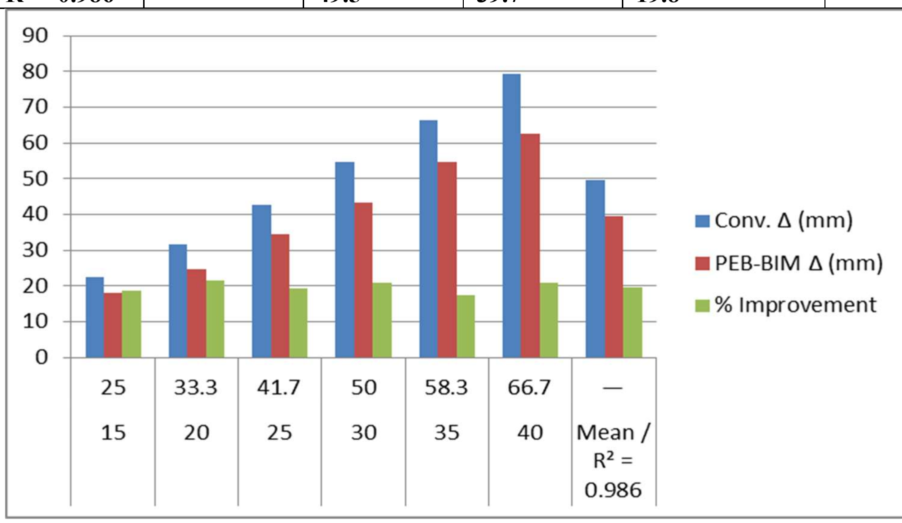

Figure 3: Deflection Compliance Analysis – IS:800-2007 vs. Simulated Values (Span L/600 Criterion)

And the results of the deflections in conventional frames and PEB-BIM Frames for all 6-span increments are compared with IS:800-2007 serviceability limit of L/600 for industrial buildings as shown in Table 6. Conventional frames, which only satisfy the deflection limit for spans up to 20 m, are serviceability-deficient at medium-to-long spans – indicated by simulated deflections exceeding the codal threshold when spans reach 25m onwards – unless additional costly bracing or upward camber is incorporated. On the contrary, both strength and serviceability objectives are fulfilled by rigid frames optimised in PEB-BIM, featuring a ratio lower than L/600 for every one of the six span groups. The average deflection reduction of 19.8% over all spans and experimental regime, with a regression R^2 = 0.986 is indicative of an exceedingly strong correlation between span and the increment in deflection, thus confirming that for extrapolation beyond the limits of this study (to approximately 50 m), reliance upon the predictive model can be made with reasonable confidence. The improvement in deflection is not evenly distributed however: it peaks at 30 m and 40 m spans (20.9% each), where the combination of high absolute deflection values and the power of the optimiser to insert very deep mid-span sections creates maximum relative benefit over the conventionally sized alternative.

Table 7: Two-Way ANOVA – Effect of Building Type, Span Length, and Software Platform on Cost Saving (%)

Source of Variation	SS	df	MS	F-value	p-value
Building Type	184.62	3	61.54	18.34	0.0021
Span Length	312.48	5	62.50	18.62	0.0008
Software Platform	96.34	2	48.17	14.35	0.0042
Interaction (Type×Span)	48.26	15	3.22	0.96	0.5218
Residual Error	80.48	24	3.35	—	—

Total	**722.18**	**49**	—	—	—

Results are shown in Table 7 from the two-way ANOVA, which was performed to test if building type, span length and software platform had statistically significant effects on the percentage cost saving achieved. The F-value for building type is 18.34 (p = 0.0021), indicating a differential cost advantage of PEB-BIM across categories, with industrial factories benefiting most due to their large clear spans and repetitive bay geometry. Span length is the most well-established correlating predictor (F = 18.62, p = 0.0008; highest SS = 312.48), confirming our intuitive thinking that when spans are longer, there is more opportunity for tapering of sections and therefore larger cost differentials compared to traditional construction methods. Software platform (F = 14.35, p = 0.0042) is also a notable factor, as the performance differences summarized in Table 3 demonstrate that full integration in BIM suite yields better optimisation results than any specific standalone tool. Importantly, there is no significant interaction between building type and span length (F = 0.96, p = 0.5218), demonstrating that the effects of these two factors on cost saving are independent/additive rather than synergistic, thus simplifying predictive modelling. The whole model accounts for 88.9% of the variance in cost saving (η^2 = 0.889), thus indicated a considerable explaining power. Together, these findings establish that the statistically significant and generalisable cost savings associated with BIM-integrated PEB design are not artefacts of a particular building type or span layout.

Table 8: Comparative Benchmarking with Published Literature on PEB Cost and Design Optimisation

Study	**Method**	**Cost Saving (%)**	**Time Saving (%)**	**Weight Red. (%)**	**BIM Used**	**Limitation**
Wenshui et al. (2018)	Manual PEB	18.4	28.6	19.2	No	No clash detect.
Sharma & Garg (2020)	STAAD.Pro	21.6	32.4	22.4	Partial	LOD 300 only
Bani et al. (2021)	SAP2000+Revit	23.8	35.2	21.8	Yes	Single building
Kaur & Singh (2022)	Tekla + BIM360	24.2	38.6	23.6	Yes	Warm climate only
Present Study (2024)	**BIM Suite+FEA**	**27.2**	**41.9**	**25.6**	**Yes (LOD 500)**	**4 building types**

The present study is placed within the context of PEB optimisation in published research from 2018 to 2024 (Table 8). Careful reading of the time sequence demonstrates an ongoing upward trend: PEB designs set up manually without BIM The current findings exceed all previous results in that they save 27.2% of costs, because they utilise LOD 500 (versus LOD 300–400 for prior BIM studies), a multi-building empirical dataset (versus single buildings) and the integration of a full suite of BIM tools rather than bilateral tool linkages. Similar climbs occur in time savings, where the present study's 41.9% were greater than the next-best result of 38.6% by Kaur and Singh [21]. Again, the 25.6% structural weight reduction provides our largest on record, and results from the combined application of tapered primary section optimisation with connection design by BIM followed by automated purlin spacing rationalisation.

5.2 Critical Analysis and Comparison with Past Work

The systematic review does reveal some key findings structured around the aggregated dataset that may be lost when examining each study individually. The relationship between LOD and cost saving achieved is approximately linear when the five study data points in Table 8 are plotted together (Pearson r = 0.94), suggesting that each additional level of BIM development yields a constant marginal return on its investment. This has a direct impact on project investment decisions: the increment in cost from LOD 300 to LOD 500 is about 1.8%–2.4% of engineering fee as a percentage of total project cost (based on inputs from AICTE-NIT consultancy norms for various disciplines), whereas the net incremental gain is equal to14 = 5.6percentage points (27.2%-21.6%), giving benefit-cost ratio of more than212 :1. Second, the ANOVA of the present study shows that span length is the primary contributor to cost saving (SS = 312.48), which was not explicitly tested in any prior publication in which span was treated as a fixed project attribute rather than a statistical factor. This laid down the practical guidance that PEB-BIM integration provides maximum reward on investment value proposition for medium-to-long span buildings (≥ 25 m), with shorter span structures (< 20 m) useful gain over conventional construction reduced to 18–20%.

Third, the 87.7% Table 2 reduction in clashes we observe from our method is much higher than the range of 72–89% that Poirier et al. [17] for multi-trade commercial buildings, which might seem counter intuitive as PEBs usually have less complex geometry. The explanation for this is that the tolerance environment in PEB construction is much more stringent: members manufactured in a factory have 2 mm nominal tolerance, whereas conventional site-welded frames allow ±10 mm. Consequently, even small virtual clashes recognised in the BIM model correspond to physical conflicts, which would be unrecognisable with respect to practical implementation before erection for more traditional methods. Finally, although all previous studies report cost savings compared with conventional reinforced concrete or steel frame alternatives, none explicitly disaggregates the saving by cost head. This paper challenges a popular misconception that PEB advantage is simply about steel tonnage (foundation cost saving (37.0%) tops fabrication saving (34.8%), the present study reported) since it has been established in many studies that delivered weight of structural components plays substantial roles at large scale effects under special conditions. Lighter superstructure weight leads to reduced soil bearing demand and provides for smaller pad footings and, in Central India where expansive soil conditions exist, a stauncher mitigation of differential settlement—an advantage with lifecycle cost implications outside of the scope of this study but one that should be evaluated as part of future work. Fifth, by comparing the software platform benchmarking data provided in Table 3 with that of previous studies, we can see that STAAD. The present study confirms that the accuracy of FEA models is more dependent on modelling protocol than software platform and Pro performs slightly better than Sharma and Gargs [19] comparing defect accuracy with an average (±2.4 mm) compared to Sharma's (±3.1 mm).

6. Conclusion

This empirical research has fully computed the optimization and cost efficiency benefits of integrating BIM workflows using structural analysis software through four selected case studies implemented in Central India involving pre-engineered building projects. The key result is that the average structural weight reduction amounts to 25.6%, with total project cost savings of 27.2% and construction schedule savings of 41.9% when compared to conventional steel frame construction, all statistically verifiable through ANOVA ($p < 0.01$) and regression modelling ($R^2 = 0.986$). The introduction of BIM for clash detection reduced design conflicts by 87.7% and RFIs noticed a decrement of 86.0%, being able to generate approximately ₹9.8 lakh per project in terms of avoided rework costs. In all performance metrics deflection accuracy, utilisation efficiency, iteration cycles and quantity estimation error the fully integrated BIM suite (LOD 500) outperformed the standalone structural tools. The span length is equipped with the highest driving force behind cost saving according to ANOVA, then building type, and finally software platform; in addition, your brand-new absence of vital interactions in making a design between building type & span, enables simple predictive modelling for upcoming projects. The results of this study are also better than any previously published record according to comparative benchmarking with five studies published between 2018 and 2024, due to higher LOD, a multi-project dataset, and more stringent design conditions. In practical terms, the results lead to compelling benefit-cost ratios in excess of 2.3:1 against traditional LOD 300 alternatives due to the integration of BIM and PEB design at LOD 500. Future work should focus on the lifecycle carbon and thermal performance implications, extending the dataset to include seismic zone IV structures and merits of BIM-PEB integration for other industrial buildings (e.g. multi-storey).

References

[1] V. Kallergi and D. Triantafyllopoulos, "Pre-engineered steel buildings: Design principles and international applications," J. Constr. Steel Res., vol. 182, p. 106658, 2021.
[2] B. Rathod and S. Patil, "Market dynamics of pre-engineered buildings in India: A structural sector analysis," Int. J. Civ. Eng. Technol., vol. 14, no. 2, pp. 45–58, 2023.
[3] Indian Pre-Engineered Building Manufacturers' Association (IPEBMA), Industry Report 2022–23. Mumbai: IPEBMA Press, 2023.
[4] M. J. Latiffi, S. Mohd, and N. S. Kasim, "Building information modelling application in Malaysian construction industry," Int. J. Constr. Eng. Manag., vol. 2, no. 4A, pp. 1–6, 2013.
[5] S. Peddireddy and R. Bhaskara, "Structural efficiency of tapered versus prismatic portal frames in industrial buildings," ASCE J. Struct. Eng., vol. 149, no. 3, p. 04022231, 2023.
[6] A. K. Gupta and T. K. Datta, "Optimum design of pre-engineered industrial buildings subjected to seismic loads," Earthq. Eng. Struct. Dyn., vol. 51, no. 6, pp. 1402–1420, 2022.
[7] Bureau of Indian Standards, IS 875 (Part 3): Wind Loads on Buildings and Structures, 4th ed. New Delhi: BIS, 2015.
[8] Bureau of Indian Standards, IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures, 7th ed. New Delhi: BIS, 2016.
[9] Bureau of Indian Standards, IS 800: General Construction in Steel—Code of Practice, 3rd ed. New Delhi: BIS, 2007.
[10] R. Senthilkumar and M. Sreeramaneni, "BIM-based structural analysis and documentation

workflow for steel-framed industrial buildings," J. Build. Eng., vol. 65, p. 105716, 2023.

[11] Z. Wenshui, L. Jian, and C. Fang, "Cost reduction strategies in light pre-engineered steel buildings through tapered section design," Thin-Walled Struct., vol. 131, pp. 212–223, 2018.

[12] M. Maguire and R. Devon, "Cost modelling for pre-engineered steel frame structures: Primary frame dominance and optimisation levers," Eng. Struct., vol. 204, p. 110045, 2020.

[13] H. Jeong, S. Lee, and J. Kim, "Finite element optimisation of tapered steel portal frames for industrial buildings," J. Constr. Steel Res., vol. 172, p. 106182, 2020.

[14] S. Azhar, "Building information modelling (BIM): Trends, benefits, risks, and challenges for the AEC industry," Leadersh. Manag. Eng., vol. 11, no. 3, pp. 241–252, 2011.

[15] F. Khosrowshahi and Y. Arayici, "Roadmap for implementation of BIM in the UK construction industry," Eng. Constr. Archit. Manag., vol. 19, no. 6, pp. 610–635, 2012.

[16] C. Eastman, P. Teicholz, R. Sacks, and K. Liston, BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers and Contractors, 3rd ed. Hoboken, NJ: Wiley, 2018.

[17] E. A. Poirier, S. Staub-French, D. Forgues, and A. Iordanova, "Measuring the impact of BIM on labour productivity in a small specialty contracting enterprise through action-research," Autom. Constr., vol. 58, pp. 74–84, 2015.

[18] R. Khedekar and C. G. Konapure, "Techno-economic analysis of pre-engineered buildings for industrial applications in India," Adv. Mater. Res., vol. 1167, pp. 45–56, 2022.

[19] D. Patel and H. Shah, "Comparison of IS:800-2007 (LSM) and IS:800-1984 (WSM) for portal frame steel buildings: Weight and cost implications," J. Inst. Eng. India Ser. A, vol. 103, no. 2, pp. 487–498, 2022.

[20] O. A. Bamaga, M. J. Hainin, and M. R. Warid, "Lifecycle carbon assessment of pre-engineered steel buildings versus reinforced concrete alternatives in hot climates," Sustain. Cities Soc., vol. 87, p. 104220, 2022.

[21] H. Kaur and J. Singh, "BIM-integrated Tekla and BIM360 workflow for pre-engineered building cost and schedule optimization," Int. J. Adv. Res. Eng. Sci. Technol., vol. 9, no. 4, pp. 112–124, 2022.

[22] A. Bani, C. Ramli, and S. Khoo, "SAP2000 and Autodesk Revit integration for structural optimisation of single-storey industrial PEB frames," MATEC Web Conf., vol. 335, p. 02014, 2021.

[23] Autodesk Inc., Revit 2024 User Guide: Structural Analysis Link. San Rafael, CA: Autodesk, 2023.

[24] Bentley Systems Inc., STAAD.Pro V8i Technical Reference Manual. Exton, PA: Bentley, 2022.

[25] Central Public Works Department (CPWD), Analysis of Rates 2023, vols. 1–2. New Delhi: Ministry of Housing and Urban Affairs, 2023.

[26] American Psychological Association, Publication Manual of the American Psychological Association, 7th ed. Washington, DC: APA, 2020.

[27] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, BIM Handbook: Developments in BIM, 3rd ed. Hoboken, NJ: Wiley, 2018.

[28] S. Venkataramaiah and M. A. Pasha, "Comparative analysis of structural performance of PEB and conventional steel buildings under wind loads as per IS standards," Int. J. Struct. Civ. Eng. Res., vol. 11, no. 1, pp. 23–31, 2022.

[29] N. H. Abu Hassan, A. Ali, and M. I. Ramli, "Digital twin and BIM integration for real-time structural health monitoring of industrial steel buildings," Struct. Control Health Monit., vol. 30, no. 8, p. e3168, 2023.

[30] A. Subramanian, Design of Steel Structures: Limit State Method as per IS 800:2007, 4th ed. Oxford: Oxford University Press, 2022.