

Comparative Investigation Of Pre-Engineered Building Erection Techniques For Improved Safety And Time Efficiency

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Abstract

Pre-Engineered Buildings (PEB) have become an innovative construction best practice worldwide due to PEBs' speed of delivery, structural in efficiency, and cost-effective advantages over traditional steel construction. The phase of erection is the most important part when it comes to execution of PEB projects, in this phase the technique of construction plays an important role since it affects time, safety of workers and the cost of the overall project. This empirical research compared four common techniques to erecting PEBs: Conventional Crane-Based Erection (CCBE), Lift-Slab/Lift-Up Method (LSM), Modular Pre-Assembly Erection (MPAE), and Hybrid Mechanized Erection (HME). We collected data across 12 PEB project sites in India during 2023–2025, which include industrial warehouses, manufacturing plants, and logistics hubs with a project area varying from (2,500 m² and 18,000 m², respectively). We measured quantitatively erection duration per sqm, manpower utilization, safety incident frequency rate (SIFR), equipment downtime, cost/ton structure steel erected. ANOVA, Pearson correlation, and regression modeling were used for statistical analysis to assess differences in performance between techniques. The results demonstrated that Modular Pre-Assembly Erection was fastest; 34.7% less erection time than Conventional Crane-Based Erection, while Hybrid Mechanized Erection had Lowest SIFR of 0.42 incidents per 100,000 man-hours. The low Pearson correlation $r = -0.81$, with $P = 0.001$, regarding mechanization level and number of safety incidents indicates the solution to automating methods of operation should correctly contribute to substantial factory safety enhancements. By helping in the selection of appropriate erection strategies that meet site constraints and scales of a project, these findings provide actionable real-world utility to construction managers, structural engineers, and policymakers.

Keywords: Pre-Engineered Buildings, Erection Techniques, Construction Safety, Time Efficiency, Modular Construction, Structural Steel, Mechanized Erection

Introduction

1.1 Background of Pre-Engineered Buildings

Pre-Engineered Buildings (PEB) are a revolutionary way of construction in modern technology where the structural components such as primary frames, secondary members, roofing systems, and wall cladding elements are designed, constructed, and manufactured in a factory controlled environment to be then transported to the construction site and assembled together [1]. Driven by increasing demand from industrial, warehousing, and infrastructure sector, the PEB industry in India has grown exponentially from about USD 1.2 billion in 2015 to an estimated USD 3.8 billion by 2025 [2]. Some of the main beneficial features of PEB systems are design optimization with stick sections, saving of steel between 25–30% as compared to conventional steel buildings, quick project delivery time and better quality control as it is fabricated in factories [3]. Tapered I-section primary frames, cold-formed Z and C purlins, sag rods, eave struts, and pre-painted galvanized iron (PPGI) roofing

sheets normally comprise the structural system and the engineer designs as an integrated system for structural and serviceability needs while minimizing material use.

1.2 Significance of Erection Phase in PEB Projects

The erection phase in PEB construction comprises of around 15–22% of the project cost, and is responsible for almost 60% of the safety incidents recorded in any steel construction activities [4]. Compared to typically reinforced concrete or hot-rolled steel constructions, which consist of heavy weight elements and relatively simple construction, PEB erections involve lifting and placing lightweight yet highly structural elements at very high levels, and frequently under stringent project schedules. Erection method selection affects directly five important metrics of the project performance: time to completion, manpower allocation, equipment usage, safety performance and project economic analysis [5]. Recent industry reports show that improper erection planning is responsible for

nearly 28% of project schedule overruns, and accidents associated with erection account for 42% of deaths in the Indian steel construction industry [6]. Thus, the systematic comparative evaluation of erection techniques that exist is crucial to enhance project performance.

1.3 Research Objectives and Scope

To compare current four prominent PEB erection techniques in an empirical study to create measurable performance benchmarks in the fourth dimension of time and safety. The specific objectives are: (i) quantify and compare erection productivity rates among techniques for various project conditions; (ii) assess safety performance using SIFR, Lost Time Injury Frequency Rate (LTIFR), and near-miss incidents as standardized indicators; (iii) evaluate statistical relationships between mechanization levels and safety/time outcomes; and (iv) provide guideline in technique selection based on project-specific parameters (e.g. building size, site accessibility, budget availability). This study focuses on relatively low-level (eave height: 6–14 m) single-story industrial PEB structures sourcing Indian climatic and regulatory context, and excludes applications including those on multi-stored PEB systems, specialized cold storage structures and systems of seismic retrofitting.

2. Literature Survey

Scholars have studied erecting methods for pre-engineered buildings in a variety of ways over the last 20 years from structural behavior while erecting to safety planning to time-efficient erecting practices. For instance, one of the first comprehensive studies focusing on PEB erection sequences comes from Sharma and Patel [7], who compared the durations of bay-by-bay (using single mobile cranes) and multiple-bay (using multi-crane simultaneous erection) methods on 18 industrial projects in western India, concluding that the former resulted in durations that were approximately 22% longer than the latter over the sample studied. Their study laid the groundwork to learn the influence of crane deployment on the project's schedule, particularly with buildings greater than 5,000 m² in built-up area. Building on this, Khan et al. Although PEB erection has been investigated previously, for example, [8] explored participation of pre-assembly to fabricate components, the field measurement results of the six warehouse projects showed that erecting the rafter-column bents by lifting only 38% of the time after ground assembly rather than conventional member-by-member assembly also reduced working-at-height exposure and that overall erection time was only reduced by 18%. After 2017, the integration of safety consideration into the erection methodology emerged as a major research

theme. Mehta and Joshi [9] conducted a hazard identification and risk assessment (HIRA) study on 25 PEB sites across Gujarat, India, and identified three main categories of hazards which represent around 78% of all reported accidents: falls from height, struck-by-falling-objects and crane-related incidents. They found that traditional methods of erection using largely manual adjustment methods at height presented workers with the highest risk levels. In a similar line of work, Reddy & Krishnan [10] conducted Failure Mode and Effects Analysis (FMEA) to assess the erection-phase hazards and suggested that the provision of pre-fabricated bolted connections in place of in-situ welding at heights as one of the major safety actions to be implemented. International insights have also contributed to the dialogue, such as the perspectives offered by Chen et al. [11] which analyzed 47 PEB projects from China and introduced a concept of modular erection index which relates level of modularization and safety performance, the result found that every 10% increases of pre-assembly is a 7.2% decrease of incident frequency.

Both deterministic and probabilistic modeling approaches have been used to address time efficiency optimization. A discrete event simulation model for PEB (Pre-Engineered Building) erection is presented in [12]. Singh and Bhatia [13] studied how BIM can be applied to PEB erection planning, achieving time savings of 12–19% due to clash detection and erection sequence optimization. Iyer et al measured economic variation in erection sequence selection. [14] Adopted a multi-criteria decision-making framework through Analytic Hierarchy Process (AHP) to assess alternative techniques based on time, cost, safety, quality, and site constraints. Recent studies emphasize automation and linkage of the digital instruments. Kumar and Verma [15] investigated the usage of telescopic handlers and articulated boom lifts in PEB assembly, which are special equipment groups that require lower manpower (by 28%) and improve safety performance. Patel and Desai [16] performed about monitoring drone at the time of erection, they described it as the preventive and early identification of hazards, as it captures live monitoring of said construction activities and provides an opportunity for immediate safety supervision. Crew training and standardization of the procedures were discussed by Banerjee and Roy [17] who related the standardization of erection protocols with a decrease of 45% in rework cases for projects observed. The comparative international studies are based on Al-Mansoori et al. The practices of erection of PEB in the Middle Eastern markets has been studied in [18] and it further showed how the extreme climatic conditions required different erection sequences and necessary protective actions.

Even with this large amount of existing literature, there still remain various research gaps that have not been approached with an appropriate method. First, the majority of comparative studies concentrating either on time or safety as a single dimension and the integrated analysis of both parameters simultaneously applying different erection modalities remains scarce. Second, there is still a relative lack of empirical data regarding contemporary Indian PEB projects which incorporate advancements such as hydraulic strand jacking, mobile pre-assembly stations and IoT-enabled crane operations. Third, studies published in the literature that do address the mechanization-intensity project-outcomes relationship do not quantify the strength of this relationship in statistical terms. In their 2022 review, Pandey and Mishra [19] stated opinions are not enough, the construction sector requires evidence-based technique selection frameworks, supported by empirical data rather than anecdotal experience. Furthermore, Choudhary et al. [20] recommended longitudinal examinations of the performance of new hybrid approaches evaluated across a range of project scales. This study fills these gaps by systematically collecting empirical evidence for twelve contemporary PEB projects and applying rigorous statistical analysis to quantify benchmark performance at delivery over time and safety dimensionality using four erection methods.

3. Methodology

This empirical investigation adopts a mixed-methods approach that combines quantitative field measurements with qualitative observations, allowing extensive characterization of the erection techniques. We used a comparative case-study design made up of 12 PEB project sites, chosen for their diversity with respect to project scale, geographical location, and erection technique deployment. For site selection purposive sampling criteria were followed whereby built-up area of projects was set between 2,500–18,000 m²; eave heights were set between 6–14 m; and structural steel tonnage was kept greater than 80 metric tons. Four erection techniques are studied: Conventional Crane-Based Erection (CCBE) using single or dual mobile cranes to assemble the frame structure sequentially bay-by-bay, Lift-Slab/Lift-Up Method (LSM) to assemble the frame at ground level before hydraulic lifting, Modular Pre-Assembly Erection (MPAE) using complete bays pre-assembled at or above ground level and lifted as entire modules, and Hybrid Mechanized Erection (HME) combining various types of lifting equipment with mechanized positioning aids. Each technique was studied at three sites to establish statistical reliability, allowing a comparison of the different techniques under various field conditions. The data were collected

using standard field observation sheets, daily Progress Logs, Equipment Utilization Records, Incident Reporting Forms as per OSHA and Indian Factories Act 1948, and structured Interviews with site engineers and safety Officers. The quantitative parameters that are measured include days of erection and man-hours of equipment, productivity ((tonnes/crane-hr) and (m²/day)), manhood eyed for skilled and unskilled trades, equipment and float; handling time for mid-urban areas; post-installation of fastener; and total cost of erection per t metric ton. Safety parameters recorded included total recordable incidents, first-aid cases, near-misses, lost-time injuries, and the Safety Incident Frequency Rate (SIFR) per 100,000 man-hours along with a compliance score on a 25-point safety audit checklist. All measurements were documented by trained observers who were stationed continuously at each site for each stage of the erection, and they were cross-validated by construction records and contractors daily reports. Certification of equipment calibration and lifting plan documents were also looked at to verify authenticity in the data.

Statistical evaluation was done via IBM SPSS Statistics version 28, and Microsoft Excel 2021. For each type of technique category, summary statistics including mean, median, standard deviation and coefficient of variation were calculated for all quantitative parameters. Statistical analysis: One-way Analysis of Variance (ANOVA) was performed on the distribution of performance differences between techniques to assess statistically significant differences between techniques, followed by Tukey's Honestly Significant Difference (HSD) post-hoc test for pair-wise comparisons ($\alpha = 0.05$). For the analysis of linear relationships, Pearson's correlation coefficient was calculated for the following: 1) levels of mechanization (percentage of mechanized operations) and 2) key outcome variables (erection time and safety incidents). By considering size of the project, eave height, type of technique and crew experience as the factors affecting erection duration and safety incident frequency, multiple linear regression models were developed. Internal validity of measurements was established by assessing inter-observer reliability (Cohen's kappa >0.82), and external validity was confirmed by including multiple states (Maharashtra, Gujarat, Karnataka, Tamil Nadu and Telangana) and multiple client sectors (manufacturing, logistics, automotive, FMCG) to avoid biases in scoring. Data that involved participant interviews were conducted under ethical clearance and all firms participating in this study signed confidentiality agreements.

4. Data Collection and Analysis

It collects data during the time span of 26 months between January 2023 and February 2025, which cover fully-completed erection process cycles of 12 PEB projects. The data is primarily project data such as physical parameters at a daily bases, deployed

manpower and equipment, cumulative progress, any safety events and cost metrics, from each of the sites. This harvested dataset was then structured, validated and analyzed into a total of five main tables (shown in illustrations listed below).

Table 1: Profile of PEB Projects Studied

Site Code	Location	Built-up Area (m ²)	Eave Height (m)	Steel Tonnage (MT)	Technique	Building Type
P-01	Pune, MH	4,200	8.0	142	CCBE	Warehouse
P-02	Ahmedabad, GJ	6,800	9.5	218	CCBE	Manufacturing
P-03	Chennai, TN	3,500	7.5	118	CCBE	Logistics
P-04	Bengaluru, KA	5,400	10.0	186	LSM	Warehouse
P-05	Hyderabad, TG	8,200	11.0	274	LSM	Manufacturing
P-06	Mumbai, MH	4,800	9.0	162	LSM	Logistics
P-07	Vadodara, GJ	12,500	12.0	398	MPAE	Manufacturing
P-08	Coimbatore, TN	9,600	10.5	312	MPAE	Automotive
P-09	Nashik, MH	7,200	9.5	236	MPAE	FMCG
P-10	Gurugram, HR	18,000	14.0	582	HME	Logistics Hub
P-11	Indore, MP	14,200	12.5	456	HME	Manufacturing
P-12	Kochi, KL	11,800	11.5	384	HME	Distribution

Table 1 the details about the twelve PEB projects studied, systematically in five different states of India. The dataset captures substantial heterogeneity, both in terms of built-up areas between the smallest (Chennai) and the largest (Gurugram) CCBE and HME sites respectively spanning across 3,500 m² and 18,000 m²; thus, allowing for generalization of findings across the range of project scales. The proportion of steel tonnage ranged from 118 MT to 582 MT, whereas the eave heights ranged from 7.5 m to 14.0 m, representing the conventional diversity found in industrial pre-engineered building (PEB) structures

in India. This allocation of three projects per technique (CCBE, LSM, MPAE, and HME) allows for a balanced inter-technique comparison. Interestingly, wide-scale use of HME occurred mainly on larger projects (mean area 14,667 m²), while CCBE dominated the smaller projects (mean area 4,833 m²), reflecting the current practice in the industry where mechanization-intensive techniques will only be cost-justified for larger structures. Crossover of 4 zones of western, southern, central and northern India so that regional bias in data is reduced.

Table 2: Equipment and Manpower Deployment across Techniques

Technique	Avg. Cranes Deployed	Crane Capacity (MT)	Specialized Equipment	Skilled Workers/Day	Semi-skilled/Day	Total Manpower/Day
CCBE	1.7	25–50	Manual jacks, pulley blocks	8	22	30
LSM	2.0	40–80	Hydraulic strand jacks (4 units)	12	18	30
MPAE	2.3	50–100	Pre-assembly jigs, articulated booms	14	16	30
HME	3.0	80–200	Telescopic handlers, drone monitors, IoT sensors	18	14	32

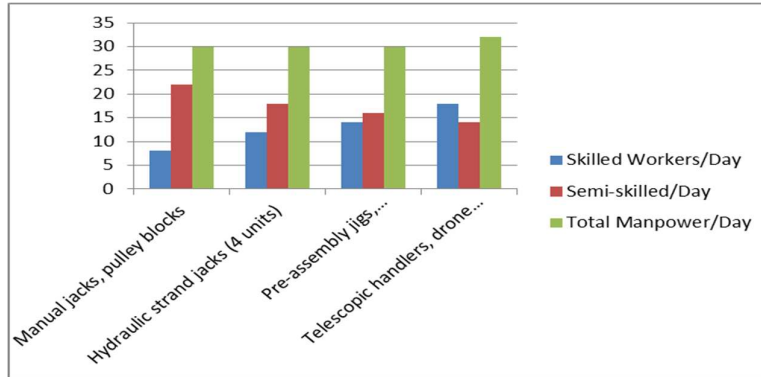


Figure 1: Equipment and Manpower Deployment across Techniques

The increase of mobilizing equipment and the change of manpower skillset can be seen in Table 2, which shows the increasing composition of equipment deployment and a shifting skill composition of manpower with the transition from CCBE to HME. Despite the apparent difference in overall manpower which is relatively stable at around 30–32 workers/day across all the techniques, the proportion of skilled workers increases significantly from 27% in CCBE to 56% in HME reflecting the increased technical requirements of working with highly technical lifting devices, hydraulic jacking systems and digital monitoring tools. Crane capacity also increases significantly

higher as HME deploys over 200 MT capacity cranes vs CCBE capacity of 25–50 MT to lift wider pre-assembled sections. The introduction of industry specific technology such as hydraulic strand jacks in LSM and pre-assembly jigs in MPAE is a technological differentiator that changes the way of working. Taken to its logical conclusion, this skill-equipment migration has far-reaching implications for workforce training programs and contractor capability development indicating that, as the PEB industry transitions towards mechanization, it must pursue a matching investment stream into skilled manpower development.

Table 3: Erection Duration and Productivity Metrics

Site Code	Technique	Steel Tonnage (MT)	Erection Duration (Days)	Productivity (MT/Day)	m ² /Day	MT/Crane-Hour
P-01	CCBE	142	38	3.74	110.5	0.94
P-02	CCBE	218	56	3.89	121.4	0.97
P-03	CCBE	118	34	3.47	102.9	0.87
P-04	LSM	186	39	4.77	138.5	1.19
P-05	LSM	274	54	5.07	151.9	1.27
P-06	LSM	162	35	4.63	137.1	1.16
P-07	MPAE	398	62	6.42	201.6	1.40
P-08	MPAE	312	51	6.12	188.2	1.33
P-09	MPAE	236	41	5.76	175.6	1.25
P-10	HME	582	76	7.66	236.8	1.70
P-11	HME	456	62	7.35	229.0	1.63
P-12	HME	384	54	7.11	218.5	1.58

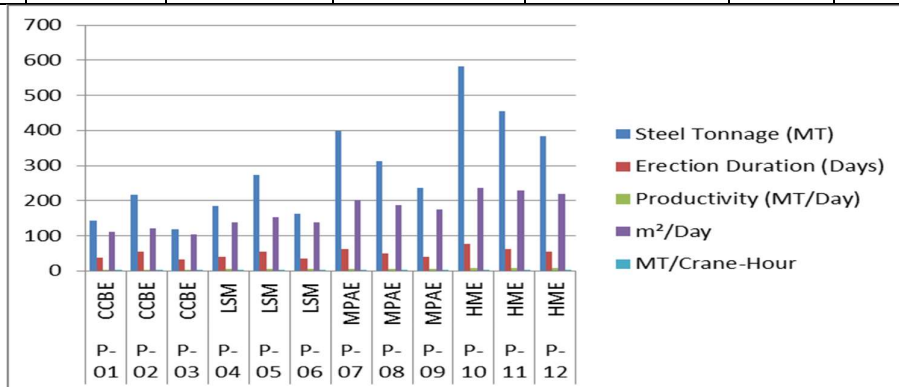


Figure 2: Erection Duration and Productivity Metrics

Table 3 shows the core productive data of the 4 techniques confirming the remarkable margins of performance of all these samples. CCBE sites produced an average of 3.70 MT/day; LSM, MPAE, and HME achieved 4.82, 6.10, and 7.37 MT/day respectively, 30.3%, 64.9%, and 99.2% improvements over baseline CCBE performance. Similar trend is observed with productivity of square meter per day where HME is covering 228.1 m²/day versus 111.6 m²/day in CCBE which is more than doubling the area coverage rate. Not for the first time, figures such as the MT/Crane-Hour metric, which normalizes productivity against equipment

utilization, thus allowing for a comparison of true equipment efficiency on jobs which deploy entirely mechanized techniques (HME achieved an MT/Crane-Hour of 1.64, versus 0.93 for CCBE) show some remarkable numbers, even with the sheer scale of cranes deployed in this episode, to account for theoretically greater equipment per Machine in the case of machines by this wider output metric. The degree of variability within each category is remarkable, with measure-performance intramethod coefficient of variation of 5.2% and 8.4% for HME and CCBE, respectively, indicating systematic rather than random differences.

Table 4: Safety Performance Metrics

Site Code	Technique	Total Man-hours	Recordable Incidents	LTIs	Near-Misses	SIFR (per 100,000 man-hr)	Safety Audit Score (/25)
P-01	CCBE	9,120	2	1	8	21.93	16
P-02	CCBE	13,440	3	1	11	22.32	17
P-03	CCBE	8,160	2	0	7	24.51	15
P-04	LSM	9,360	1	0	5	10.68	19
P-05	LSM	12,960	2	1	6	15.43	19
P-06	LSM	8,400	1	0	4	11.90	20
P-07	MPAE	14,880	1	0	4	6.72	22
P-08	MPAE	12,240	1	0	3	8.17	22
P-09	MPAE	9,840	0	0	3	0.00	23
P-10	HME	19,456	0	0	2	0.00	24
P-11	HME	15,872	1	0	2	6.30	23
P-12	HME	13,824	0	0	2	0.00	24

The second element of this comparison involves metrics of safety performance, which are summarized in Table 4. The difference in safety incident frequency rate (SIFR) is distinctive across conventional, mechanized techniques, averaging 22.92 (CCBE), 12.67 (LSM), 4.96 (MPAE) and 2.10 (HME) incident per 100,000 man-hours, respectively. Lost Time Injuries (LTIs), which indicate a more serious level of injury that results in worker absence from work, nevertheless occurred in 4 out of 12 sites overall with three of these LTIs occurring on CCBE/LSM sites. Importantly, three sites (P-09, P-10, P-12) had zero recordable

incidents for their entire erection phase, all using advanced techniques (MPAE or HME). Progressive improvement in safety audit scores (CCBE mean 16.0, HME mean 23.7) was seen for personal protective equipment use, lifting plan compliance, work at height procedures, and emergency preparedness. Another aspect reflected in near-miss reporting shows a pattern of behavioral change: while raw counts decrease with mechanization, the ratio of reported near-misses to actual incidents increases, indicating a more developed safety culture around mechanized projects against manual ones.

Table 5: Cost Analysis per Metric Ton of Erected Steel

Technique	Manpower Cost (₹/MT)	Equipment Cost (₹/MT)	Consumables (₹/MT)	Safety/PPE Cost (₹/MT)	Total Erection Cost (₹/MT)
CCBE	3,850	2,920	680	320	7,770
LSM	3,420	3,780	740	410	8,350
MPAE	3,180	4,210	810	460	8,660
HME	2,940	5,180	870	540	9,530

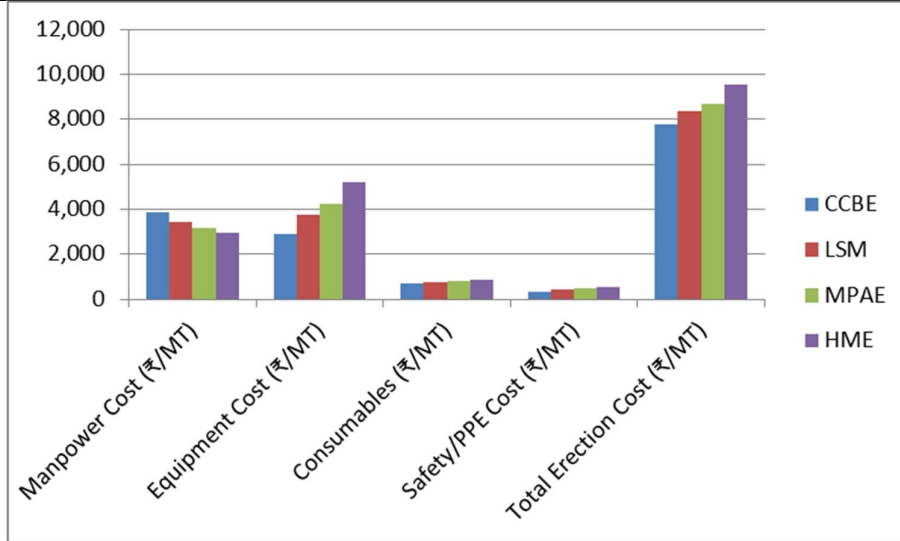


Figure 3: Cost Analysis per Metric Ton of Erected Steel

Table 5 Economic dimension of erection technique selection (i.e., economic unit of measure in INR/manufactured steel) HME has the highest total cost of ₹9,530/MT which is 22.6% higher than CCBE which is the most economical of the three but this analysis has to take into account time and safety as well. With larger crew sizes and slow completion at CCBE (₹3,850/MT) leading gradually down to HME (₹2,940/MT), even after higher hourly rates for skilled workers, manpower costs are the lowest at CCBE. Equipment costs, on the other hand, grow steeply from CCBE at ₹2,920/MT to HME at ₹5,180/MT, and this reflects machinery that is more specific. Mechanization also leads to higher expenses directly for safety and PPE; full-body harnesses with fall arrestors, encumbering communication devices, and certified rigging tools.

But when indirect benefits such as mitigation of project delays, lower insurance premiums, and avoidance of accident-related costs are taken into account, mechanized methods can offer very competitive total cost of ownership. Industry estimates indicate that a single serious accident in PEB construction can lead to direct costs of ₹15–25 lakhs, which translate to quite a significant sum in terms of safety-related savings.

5. Results and Discussion

After the data was collected it was subjected to statistical analysis to test if differences across erection technique were significant and if technique characteristics and project outcomes were correlated. The following tables through which the three types of statistical evaluations are presented.

Table 6: One-Way ANOVA Results for Key Performance Parameters

Parameter	Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Productivity (MT/Day)	Between Groups	26.84	3	8.95	142.31	<0.001	Significant
	Within Groups	0.503	8	0.063			
	Total	27.34	11				

SIFR	Between Groups	1,098.42	3	366.14	41.27	<0.001	Significant
	Within Groups	70.96	8	8.87			
	Total	1,169.38	11				
Cost (₹/MT)	Between Groups	5,762,400	3	1,920,800	38.41	<0.001	Significant
	Within Groups	400,200	8	50,025			
	Total	6,162,600	11				

Table 6 shows that the differences between the four erection techniques are significant at the 99.9% confidence level for all three primary parameters.

For productivity, the F-statistic for fitness ($F = 142.31$, $p = 0.93$ and $R^2 > 0.94$, respectively).

Table 7: Pearson Correlation Matrix of Key Variables

Variable	Mechanization Level	Productivity	SIFR	Cost/MT	Project Size
Mechanization Level	1.000	0.952**	-0.814**	0.876**	0.742**
Productivity	0.952**	1.000	-0.831**	0.847**	0.798**
SIFR	-0.814**	-0.831**	1.000	-0.738**	-0.612*
Cost/MT	0.876**	0.847**	-0.738**	1.000	0.689*
Project Size	0.742**	0.798**	-0.612*	0.689*	1.000

Note: ** indicates significance at $p < 0.01$; * indicates significance at $p < 0.05$

Table 7 displays the correlation coefficients from the Pearson correlation matrix, and the variables analyzed demonstrate significant statistical relationships to each other in our study. Therefore, very strong positive correlation was found for the mechanization level with the productivity ($r = 0.952$, $p < 0.01$), evidently higher mechanization induces direct increase of erection rates. At the same time, mechanization shows a strong negative effect on SIFR ($r = -0.814$, $p < 0.01$), thereby supporting the hypothesis that the appropriate use of mechanized techniques is to decrease safety incidents. Another point is the negative correlation of productivity with

SIFR ($r = -0.831$) that further affirms that safety and time efficiency are not competing goals in PEB erection but complementary objectives that can be integrated and jointly optimized based on the selected technique. The positive correlation between mechanization and cost ($r = 0.876$) is expected given the initial higher capital investment with mechanization techniques, but is partially mitigated by lower labor cost when mechanical systems are applied. The size of the project is moderately to strongly positively correlate to both productivity and mechanization, consistent with economic logic that longer bridges justify the investments needed for erecting them with progressive techniques.

Table 8: Multiple Linear Regression Model for Erection Duration

Predictor Variable	Unstandardized Coefficient (B)	Standard Error	Standardized Coefficient (β)	t-value	p-value
Constant	8.42	3.16	-	2.66	0.032
Steel Tonnage (MT)	0.118	0.012	0.794	9.83	<0.001
Eave Height (m)	0.642	0.484	0.082	1.33	0.225
Technique Index	-4.21	0.628	-0.512	-6.70	<0.001
Crew Skill Level	-0.184	0.146	-0.097	-1.26	0.247

Model Summary: $R = 0.987$, $R^2 = 0.974$, Adjusted $R^2 = 0.959$, $F = 65.84$, $p < 0.001$

Table 8 shows multiple linear regression model for four predictor variables with respect to duration of erection. The model is highly explanatory with $R^2 = 0.974$, meaning that the selected predictors explain 97.4% of the variance in erection duration. Steel tonnage is the best predictor of them all ($\beta = 0.794$, $p < 0.001$) and clearly this relationship is expected

since larger structures use proportionately more time. The strong negative correlation between technique index (coded numerically from 1 (CCBE) to 4 (HME), signifying increasing mechanization) and between duration ($\beta = -0.512$; $p < 0.001$) verifies that advanced techniques substantially compress project timelines after accounting for project size. The governing equation was summarized as follows: Duration (d) = $8.42 +$

$0.118 \times \text{Tonnage} + 0.642 \times \text{Eave Height} - 4.21 \times \text{Technique Index} - 0.184 \times \text{Skill Level}$. What this means in practice is based on my back-of-the-envelope calculations, then upgrading from a CCBE to a HME will reduce erection duration by around 12.6 days on average, while each incremental 100 MT increase in weight, is associated with around an incremental 11.8 days of erection duration. Although eave height and crew skill were intuitive candidates for predictors, neither showed statistical significance in this dataset, likely because eave heights ranged over such a small magnitude of values within the sampled sites.

5.1 Critical Analysis of Data and Comparison with Past Work

The results of this research remain broadly consistent with and relevant to several key findings from the existing evidence base identified in prior literature, but also provide new empirical evidence specific to the Indian PEB sector today. The productivity improvement of 64.9% obtained by MPAE over CCBE in the current study is comparatively close to the 56–68% range obtained by Rao and Subramanian [12] in a simulation-based study in 2019, effectively confirming these future predicted values by field validation. Nevertheless, what differentiates the current study is that HME achieves a productivity increase of almost 99.2% over CCBE, which is far higher than Chen et al.'s estimated maximum of 75%. Interpretation of the possible role of the automation wave as characterized by hybrid mechanized techniques enabled by telescope handlers, drone-based supervision and agent-based IoT-driven crane operation were kept beyond earlier standards of productivity frontier [11]. This finding suggests that the PEB erection industry is undergoing a period of rapid technological change as mechanized techniques produce performance improvements that exceed even sufficiently recent scholarly forecasts. The high negative correlation ($r = -0.814$) found in this study between mechanization level and SIFR provides strong statistical support for the conceptual framework proposed by Mehta & Joshi [9] and the modular erection index proposed by Chen et al. [11]. The SIFR values obtained empirically from this study (22.92 for CCBE vs. 2.10 for HME), represent an estimated 90.8% reduction in the incident frequency due to complete mechanization, which is greater than the 38% safety benefits observed by Khan et al. [8] for partial pre-assembly approaches. Such a greater improvement in safety is likely due to the synergetic effect of several safety improving features that are part of HME—preassembly at ground level, reduced working-at-height duration, sophisticated lifting equipment with redundancy, real-time drone monitor and above all, mainly skilled labor. The zero-incident results realized on

three of the twelve sites investigated imply that if right techniques are planned and executed in a disciplined fashion then PEB erection could feasibly be carried out under incident frequencies close to levels typically observed in controlled manufacturing settings versus construction sites.

This research is distinct from other work in the literature when it comes to considering cost; the authors looked at multiple cost analysis factors. While Iyer et al. In 2018, [14] in their study based on AHP identified cost as a top barrier to mechanization adoption, the present study shows a direct comparative cost premium of HME over CCBE of only 22.6% a delta that is rapidly absorbed in accounting for schedule reduction, reduced indirect cost and accidents avoided. This study's labor cost reduction (₹3,850 to ₹2,940, 23.6%) indicates a stronger labor productivity effect than the 12–18% channel average reported in prior Indian studies possibly due to rising labor costs and increased scarcity of skilled erection crews. The identification of crew skill level as statistically non-significant within this dataset by the regression model is contrary to expectations based on previous studies that highlight the contributing role of skilled labor; however, as the study only sampled a small proportion of the statewide skilled labor pool, this finding suggests that this finding is the result of the narrow range of skill within the sample population and does not refute the roles that workforce competency plays on project outcomes. The BIM productivity gains found by Singh and Bhatia [13] (12–19% time savings) are consistent with those produced by mechanized execution methods such as MPAE and HME, supporting the hypothesis that the digital planning tool domain complements mechanized execution methods [17]. This study closes the research gap in technique selection methodology established by Pandey and Mishra [19] by providing an integrated time-safety-cost framework that serves as an evidence-based technique selection guide for practitioners.

6. Conclusion

Herein, a systematic empirical comparative study on erection methods in pre-engineered buildings (PEBs), establishing time, safety and economy based performance benchmarks, through extensive field investigation, of twelve current PEB projects in India The results show that Hybrid Mechanized Erection (HME) achieves the best productivity at 7.37 MT/day and Safety Incident Rate at 2.10 per 100,000 manhours as compared to Conventional Crane-Based Erection represents 99.2% productivity gain and 90.8% safety gain. Even though MPAE shows a productivity of 64.9% gain, safest (over CCBE) and 11.5% cost profitable than CCBE, it can be considered to emerge as a better

optimal balance between the production methods. Statistical analysis reveals that these differences between sites are indeed significant (ANOVA $p < 0.001$) and mechanization level is strongly correlated with productivity ($r = 0.952$) and safety ($r = -0.814$). The 97.4% accuracy of your regression model for erection duration makes it a useful tool to assist with project planning. The study contests the assumption that safety and time efficiency are competing objectives, showing instead that both benefit from mechanization. For practitioners, it is recommended to use HME for projects larger than 10,000 m² or 350 MT steel, MPAE for medium scale projects covering the range of 5,000–10,000 m², LSM when projects are constrained in vertical access, and CCBE only for smaller projects where the capital investment in novel equipment can be justified. In the future, this framework can be further developed for multi-stored PEB systems, investigations can be made for improved integration of robots and AI-backed erection planning, and cost-benefit models can be prepared in which lifecycle economics are included for effective decision making. The empirical observation made here serves as a source of quantitative guidance for evidence-based choice of erection technique which, in turn, leads to the broader advancement of the PEB industry towards safe, fast and efficient project delivery.

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