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Evaluating Construction Machinery Management from a Socio-Technical Systems Perspective: Current Practices and Industry Challenges

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Abstract

Construction machinery management involves multiple interconnected lifecycle stages that influence overall project performance; however, research has generally examined machinery acquisition, operation, and maintenance stages as separate managerial activities. This study investigates construction machinery management across three lifecycle stages, namely acquisition, operation, and maintenance, through the lens of socio-technical systems theory to understand how organizational, technical, and human-related factors shape machinery management practices across these three stages. A quantitative survey was administered to professionals working in construction firms, and the data were analyzed using reliability analysis, the Relative Importance Index (RII), Principal Component Analysis (PCA), Pearson correlation, Chi-square tests, and independent-samples *t*-tests. The findings indicate that firms generally implement structured practices in equipment selection, operational monitoring, and maintenance. However, the observed cross-stage relationships highlight the need for stronger organizational coordination and information exchange between acquisition, operation, and maintenance activities. Consequently, the findings demonstrate that effective machinery management depends not only on technical optimization but also on stronger organizational coordination and information-sharing practices that connect acquisition, operation, and maintenance activities. Overall, the findings provide a socio-technical perspective for understanding construction machinery management across acquisition, operation, and maintenance, offering practical guidance for organizations and extending existing construction machinery management literature.

Keywords: construction machinery management; equipment management; socio-technical systems; operational decision-making; organizational practices

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1. Introduction

Construction machineries as heavy equipment are indispensable vehicles for effective project management. These machines are used for a wide range of operations such as earth-moving, material handling and transportation in the execution of different infrastructure and superstructure projects. The rapid progress and technological developments in the construction sector increase the usage of construction machineries [1]. These machineries are also very costly assets affecting key performance indicators (KPIs) of the projects [2]. For example, Yeo and Ning [3] noted that major equipment may account for nearly 36% of total procurement cost in major engineering projects and the costs of construction machinery constitute

a significant portion of the total cost of a construction project. Furthermore, construction machineries have a big effect on worker safety on site [4]. Aghazadeh et al. [5] showed that the numerical distribution of work accidents according to accident types and accidents caused by construction machinery emerged as the third most common accident type. Consequently, these machineries should be addressed within construction equipment management [6].

Construction equipment management has received considerable attention in the construction management literature owing to its significant influence on project productivity, cost-efficiency, and operational performance. Existing research has addressed various aspects of machinery management, including equipment selection, maintenance strategies, replacement decisions, market characteristics, and lifecycle cost analysis. For instance, studies have investigated equipment selection using multi-criteria decision-making methods [7]; maintenance management and its influence on project performance [8]; replacement decision-making through analytical models [9]; and acquisition, maintenance, and replacement practices within different industry contexts [10]. Collectively, these studies have contributed to improving machinery performance by developing management approaches and decision-support techniques across different stages of the equipment lifecycle.

Despite these valuable contributions, the existing research has predominantly examined construction machinery management through individual lifecycle stages rather than as an interconnected process. Studies commonly focus on specific activities such as equipment selection, acquisition, operation, maintenance, or disposition/replacement [8,11,12]. However, this stage-specific treatment offers limited understanding of how decisions made during one stage influence subsequent stages. In particular, operational performance and maintenance experience may generate important information for future acquisition and equipment selection decisions, while acquisition choices directly shape subsequent utilization, maintenance requirements, and lifecycle costs [13,14]. Consequently, effective construction machinery management requires continuous information exchange and feedback across lifecycle stages rather than treating them as separate managerial functions [15,16].

Beyond the fragmentation across lifecycle stages, previous studies have predominantly conceptualized construction machinery management as a technical or operational problem. The existing research has identified various factors influencing machinery performance, including planning practices, operator competence, equipment utilization, maintenance activities, managerial decisions, site conditions, and inspection practices [7,8,17]. These findings demonstrate that construction machinery performance is shaped not only by technical characteristics but also by organizational processes and human capabilities. Although Zhou et al. [18] adopted a socio-technical systems perspective to investigate tower crane safety, their study focused on a single type of construction equipment and safety management rather than construction machinery management across the equipment lifecycle. Consequently, previous research has continued to examine these factors primarily in isolation or from technical and operational perspectives, providing limited understanding of how their interactions collectively influence construction machinery management.

Considering these gaps identified in the literature, this study aims to investigate construction machinery management across three lifecycle stages, acquisition, operation, and maintenance through the lens of Socio-Technical Systems (STS) Theory. Disposition or replacement is recognized as a distinct stage within broader machinery-lifecycle models [12]. However, relocation, redeployment, disposition, and replacement were outside the inferential scope of the present study because the questionnaire did not include a dedicated and systematic item set for evaluating these processes. The empirical analysis therefore focused on the three pre-specified stages for which comparable organizational and perceptual measures were available: acquisition and selection, operation, and maintenance.

Rather than examining acquisition, operation, and maintenance as independent managerial functions, the study explores how these three stages are implemented and what relationships are observed among them in current construction machinery management practices by considering technological, organizational, and human elements. By adopting a socio-technical perspective, the research seeks to provide a more comprehensive understanding of current construction machinery management practices and the challenges affecting their effectiveness within construction organizations. Accordingly, this study addresses the following research question:

- How are construction machinery management practices implemented across acquisition, operation, and maintenance, and what socio-technical challenges are evident across these stages?

To address this research question, this study adopts a quantitative survey design based on responses from construction professionals to examine machinery management practices across acquisition, operation, and maintenance. The findings are interpreted through the lens of Socio-Technical Systems Theory to explain how technical, human, and organizational elements interact across these stages. In doing so, the study demonstrates that machinery management is shaped by complementary organizational mechanisms rather than isolated practices and provides practical guidance for developing more coordinated management strategies within construction organizations.

This paper first presents the theoretical background and research methodology, followed by the empirical findings on construction machinery management across acquisition, operation, and maintenance. The findings are then discussed through a socio-technical systems perspective. The paper concludes by outlining the study's theoretical and practical implications, limitations, and directions for future research.

2. Theoretical Background

2.1. Construction Equipment Management

Construction equipment management is commonly recognized as an umbrella concept encompassing both heavy construction machinery and light equipment within a unified management framework [19]. While heavy equipment management primarily concerns construction machinery used for earthmoving, lifting, transportation, and production activities, light equipment refers to portable tools and small-scale construction devices that support daily site operations. Despite this broad classification, heavy construction machinery represents the most capital-intensive component of construction projects and has a substantial influence on productivity, project cost, safety, and schedule performance [1]. From a broader lifecycle perspective, construction machinery management extends beyond equipment ownership or operation [20]. Previous studies generally identify four major lifecycle stages: planning and acquisition, operation, maintenance and repair, and disposition or replacement [12]. Each stage involves distinct managerial decisions that collectively influence equipment utilization, lifecycle cost, and project performance [21,22].

Among these stages, planning and acquisition, operation, and maintenance and repair are particularly critical because they are closely interconnected and continuously influence one another throughout the equipment lifecycle [23]. Acquisition decisions determine equipment suitability, capacity, and long-term economic performance, directly affecting operational efficiency [10]. The operation stage focuses on maximizing equipment productivity through scheduling, utilization monitoring, operator management, and performance evaluation, thereby contributing to improved lifecycle return on investment (ROI) [24]. Maintenance and repair aim to preserve equipment reliability, minimize downtime, reduce lifecycle costs, and extend service life through preventive and corrective interventions [25]. Importantly, the technical, human, and organizational dimensions are treated as cross-

cutting and interdependent rather than as stage-specific or mutually exclusive categories. Acquisition, operation, and maintenance each involve combinations of technical information, human judgment and capability, and organizational arrangements, although the relative emphasis of these elements may differ across activities.

2.2. Construction Machinery Management from a Socio-Technical System Perspective

Construction machinery management can also be understood through the lens of Socio-Technical Systems Theory, which proposes that organizational performance emerges from the joint optimization of technological and social subsystems rather than the independent optimization of either component [26]. Early socio-technical research conceptualized organizations as integrated systems in which technologies, work processes, organizational structures, and human capabilities continuously interact to influence operational performance [27]. Subsequent developments further argued that effective organizational performance depends on maintaining alignment between these technical and social subsystems rather than improving individual components in isolation [28].

Applied to construction machinery management, this perspective suggests that the technical performance of machinery is inseparable from the organizational and human systems through which it is managed. Machinery utilization is influenced not only by equipment specifications and maintenance technologies but also by operator competence, organizational decision-making, planning practices, communication structures, and management policies [22]. Consequently, machinery performance cannot be fully understood through purely technical indicators, such as utilization rates, fuel consumption, or maintenance frequency. Instead, equipment performance emerges from the interaction between technological capabilities and organizational practices throughout the machinery lifecycle [9].

Accordingly, each stage of the construction machinery can be viewed as a socio-technical system in which technological resources, organizational processes, and human capabilities jointly shape management outcomes [18]. During acquisition, machinery selection depends not only on technical specifications and economic evaluation but also on organizational objectives and managerial judgment [7]. During operation, equipment performance is influenced by operator competence, communication, and machinery capability [6]. Likewise, maintenance effectiveness depends not only on technical interventions but also on maintenance planning, workforce skills, coordination, and information management [8]. From this perspective, effective construction machinery management requires the coordinated interaction of technical and social subsystems across lifecycle stages to achieve sustainable equipment performance [24].

3. Materials and Methods

3.1. Research Design

A structured questionnaire was developed to investigate construction machinery management practices across the acquisition, operation, and maintenance stages of the equipment lifecycle. The original questionnaire, developed as part of Turkyilmaz's master's thesis [29], comprised four administrative sections and covered a broader range of construction machinery management issues. For the present study, only selected items relevant to machinery acquisition, operation, and maintenance were analyzed and reported. The initial questionnaire items were generated through a review of the relevant literature. The machinery acquisition and selection section was informed primarily by studies addressing construction equipment selection and acquisition practices [30,31]. The machinery operation section drew on research concerning equipment management and productivity, machinery-related safety issues, and operational risk factors [1,5,6,17]. The machinery

maintenance section was informed by studies addressing equipment maintenance practices, maintenance costs, and maintenance-related decision-making [8,25,31].

Following the literature-based development of the initial questionnaire, the instrument underwent an informal practitioner-informed refinement process. The draft was shared with engineers and project managers with relevant industry experience in construction-equipment procurement, machinery-related decision-making, and project execution. The practitioners provided feedback on question clarity, the appropriateness of industry terminology, the relevance of response options, and practical applicability. Based on this feedback, the wording of several questions was clarified, technical terminology was refined, and selected response options and questionnaire instructions were adjusted to better reflect industry practice. Because no contemporaneous consultation log, standardized expert-review form, or complete item-by-item revision history was retained, the exact number of practitioners consulted and their individual qualifications could not be documented retrospectively with sufficient confidence. Accordingly, this stage is described as informal practitioner-informed questionnaire refinement rather than a formal expert-panel or content-validity procedure. A separate formal pilot study was not conducted.

The original questionnaire comprised 39 questions in four sections; the present article reports selected items grouped under three analytical lifecycle stages, Machinery Acquisition and Selection, Machinery Operation, and Machinery Maintenance, as illustrated in Figure 1. By combining factual and perceptual questions across these sections, the questionnaire captured both organizational practices and respondents' evaluations of construction machinery management, including technical and socio-organizational aspects.

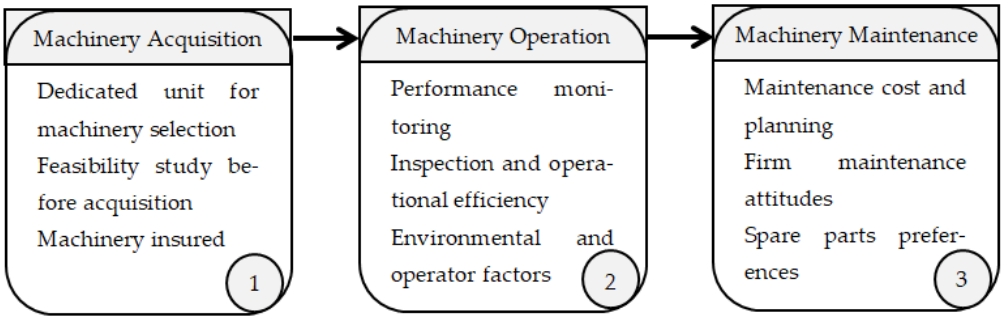


Figure 1. Questionnaire Flow across Acquisition, Operation, and Maintenance Stages.

Consistent with STS theory, the questionnaire variables were interpreted in relation to the interacting technical, human, and organizational elements of machinery management rather than being assigned to mutually exclusive categories [27]. For example, acquisition decisions combine machinery characteristics and economic considerations with managerial judgment and organizational procedures; operation involves machinery capability together with operator behavior, supervision, communication, inspection, and performance monitoring; and maintenance combines technical interventions with workforce involvement, maintenance planning, cost considerations, and service-related decisions. Thus, STS theory provided the theoretical lens for interpreting how these elements interact within and across the three machinery-management stages.

The original questionnaire covered a broader range of construction-machinery management issues than those examined in the present article. Supplementary Material S1 therefore presents only the selected questionnaire items analyzed in this study, covering machinery acquisition and selection, operation, and maintenance.

3.2. Participant Selection and Sampling Strategy

Participants were purposively recruited from contractor, consultant, and client organizations operating within the Turkish construction industry based on their knowledge of and involvement in construction machinery management and equipment-related decision-making. Eligible respondents included project managers, site engineers, site managers, and other managerial, technical, procurement, financial, or supervisory professionals involved in machinery acquisition, operation, or maintenance activities. Purposive sampling was adopted to target knowledgeable respondents who could provide informed assessments of machinery management practices within their organizations [32]. Given that one respondent represented each organization, eligibility was limited to professionals with direct knowledge of or involvement in machinery-related activities and decision-making so that responses were based on first-hand knowledge of organizational practices. Accordingly, the responses were interpreted as informed assessments of firm-level machinery management rather than independently verified organizational measures. Variation was sought across organizational types, professional roles, project sectors, and levels of industry experience to capture a broad range of construction machinery management practices.

The final sample comprised 61 respondents from 61 different construction organizations, with one knowledgeable respondent participating from each organization. Accordingly, no organization was represented by more than one response in the final dataset. The participating organizations covered different construction sectors and levels of industry experience, while respondents represented different professional roles associated with machinery-related activities. Detailed characteristics of the participating organizations and the numerical distribution of respondent roles are presented in Section 4.1.

3.3. Data Collection Procedure

Data were collected through an online questionnaire administered using Google Forms. The questionnaire was distributed via email and professional networks to 120 construction organizations operating across different sectors of the Turkish construction industry. Respondents completed the questionnaire based on their knowledge of and involvement in construction machinery-related activities within their organizations. A total of 61 valid and complete responses were obtained, corresponding to 61 different organizations and representing a response rate of approximately 51%.

Prior to participation, respondents were provided with information explaining the purpose of the study, the voluntary nature of participation, and the intended academic use of the collected data. Participants were informed that completion of the questionnaire would take approximately 30 min and that they could withdraw from the study at any stage without penalty. All responses were collected anonymously, and the data were used only for the associated academic research and publications. Ethical approval was obtained from Cukurova University prior to data collection.

3.4. Data Analysis

The survey data were analyzed using descriptive and inferential statistical techniques to examine construction machinery management practices across the acquisition, operation, and maintenance stages of the equipment lifecycle [33]. The analytical process consisted of four sequential stages. First, preliminary data assessment was conducted to evaluate the reliability and distributional characteristics. Second, descriptive statistics and the Relative Importance Index (RII) were employed to summarize and prioritize respondents' perceptions of machinery management practices. Third, Principal Component Analysis (PCA) was performed to identify the underlying dimensions of construction machinery management represented by the Likert-scale items. Finally, inferential statistical analyses

were conducted to examine the relationships between organizational characteristics and machinery management practices and to test the proposed research hypotheses.

Statistical analyses were primarily performed using IBM SPSS Statistics Version 22, while Microsoft Excel 2010 was used for data preparation, descriptive summaries, and graphical presentation. The bootstrap-based component stability assessment was conducted separately in Python Version 3.11.9 using a custom resampling procedure.

3.4.1. Preliminary Data Assessment

Before conducting the main statistical analyses, preliminary data assessment was performed to evaluate the quality and suitability of the dataset. The initial internal consistency of the Likert-scale questionnaire sections was assessed using Cronbach's alpha coefficient, which is widely used to evaluate the reliability of survey instruments [34]. The obtained alpha values were interpreted according to the criteria proposed by George and Mallery [35], with values of 0.90 and above considered excellent, values from 0.70 to below 0.90 considered good, values from 0.60 to below 0.70 considered acceptable, values from 0.50 to below 0.60 considered poor, and values below 0.50 considered unacceptable in terms of internal consistency.

Following the reliability assessment, the distributional characteristics of the dataset were examined to determine the suitability of subsequent statistical analyses. The Shapiro–Wilk test was examined as a supplementary indicator of normality [36,37]. In addition, skewness and kurtosis values were examined, where coefficients between -2 and $+2$ indicate approximate normality. For the purposes of selecting subsequent statistical tests, skewness and kurtosis were used as the primary indicators of approximate normality. Accordingly, distributions were considered sufficiently approximately normal for parametric analysis when both skewness and kurtosis values remained within the ± 2 threshold, even when the Shapiro–Wilk test was statistically significant ($p < 0.05$) [38]. The same normality criterion was subsequently applied to the composite component scores used in the inferential analyses.

3.4.2. Descriptive Analysis

Descriptive statistical analysis was undertaken to summarize respondents' characteristics and provide an overview of construction machinery management practices across the acquisition, operation, and maintenance stages. Frequencies, percentages, means, and standard deviations were calculated where appropriate to describe organizational characteristics and questionnaire responses.

To prioritize respondents' perceptions regarding construction machinery management practices, the Relative Importance Index (RII) was calculated for all Likert-scale items. RII is widely employed in construction management research to rank variables according to their perceived importance based on respondents' evaluations [39]. The RII was calculated using Equation (1).

$$\mathrm{RII} = (\sum w)/(A \times n)\ (0 < \mathrm{RII} \leq 1) \quad (1)$$

where w represents the weight assigned to each question by respondents (ranging from 1 to 5), A is the highest possible score (5), and n is the total number of responses (61). The resulting RII values range between 0 and 1 and are typically interpreted using defined thresholds: values between 0.80–1.00 indicate high (H) importance, 0.60–0.79 high–medium (H–M) importance, 0.40–0.59 medium (M) importance, 0.20–0.39 medium–low (M-L) importance, and 0.00–0.19 low (L) importance [39]. Overall, this RII method was employed in this study to prioritize items based on their perceived significance by respondents.

3.4.3. Principal Component Analysis (PCA)

Following the RII analysis, principal component analysis (PCA) was applied as a data-reduction method to identify interpretable dimensions among the Likert-scale items [40]. Although the sample comprised 61 respondents, sample-size adequacy was considered in relation to the characteristics of the component solutions rather than solely on the basis of a fixed respondent-to-item ratio. Methodological research indicates that the sample size required for component analysis depends on characteristics such as the magnitude of component loadings, communalities, and the extent to which components are well defined, and that reliable component recovery may be achieved with relatively small samples under favorable conditions [41].

PCA was selected because the analytical objective was to reduce the correlated questionnaire items into a smaller set of interpretable empirical dimensions while retaining as much of the observed variance as possible, rather than to estimate a latent variable measurement model [40]. For multi-component solutions, Varimax rotation was applied to achieve an orthogonal simple structure. For single-component solutions, rotation was not applicable and the unrotated component loadings were reported [42]. The number of components retained was determined by considering multiple criteria, including eigenvalues greater than 1.0, visual inspection of the scree plot, and the substantive interpretability of the component-loading patterns [43]. Items were retained when component loadings absolute loadings of at least 0.32 and when cross-loadings were not problematic; components containing fewer than three items were removed iteratively to obtain stable and interpretable component solutions [44]. The suitability of the data for component analysis was confirmed by the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity (for the final retained solutions KMO > 0.74; $p < 0.001$).

Potential item redundancy was additionally assessed by examining inter-item correlations, with highly correlated item pairs further evaluated through sensitivity analyses of the component solution. As a supplementary check of empirical distinctness between the two item sets, the heterotrait–monotrait ratio of correlations (HTMT) was calculated between General Perceived Risks to Construction Machinery Efficiency (C1) and Perceived Operator-Related Machinery Problems (C2). An HTMT value below the conservative threshold of 0.85 was considered indicative of adequate empirical distinctness between the two item sets [45]. Detailed PCA diagnostics for C1–C6, including eigenvalues, explained variance, component loadings, extraction communalities, and scree plots, are provided in Supplementary Material S2.

Given the relatively modest sample size ($n = 61$), an additional bootstrap-based stability assessment was conducted in Python Version 3.11.9 to evaluate the robustness of the extracted component solutions. For components with complete item-level data corresponding to the final retained-item solutions, 5000 bootstrap samples were generated with replacement [46], and the PCA was repeated for each bootstrap sample using the same extraction and rotation procedures, where applicable. The similarity between the original and resampled component solutions was evaluated using Tucker's component congruence coefficient [47] and the median congruence coefficients and 95% bootstrap ranges were calculated.

Following component extraction, composite component scores were calculated for each respondent using simple composite averaging. Specifically, the arithmetic mean of the retained items assigned to each component was calculated, with all retained items equally weighted. The resulting composite-based component scores remained on the original 1–5 Likert scale. Following the formation of the composite-based component scores, the internal consistency of the retained items defining each component (C1–C6) was reassessed separately using Cronbach's alpha. The distributional characteristics of the component-based composite mean scores were examined using the Shapiro–Wilk test together with

skewness and kurtosis coefficients. The Shapiro–Wilk test did not indicate statistically significant departures from normality for C2–C6, with p-values ranging from 0.061 to 0.114. Only C1 showed a statistically significant Shapiro–Wilk result (p = 0.004); however, its skewness (−0.585) and kurtosis (−0.546) values remained within the ±2 range and did not indicate substantial asymmetry or kurtosis. Taken together, these indicators suggested that the departure from normality for C1 was limited rather than severe [37].

Pearson correlation analysis was subsequently used to examine relationships among the composite-based component scores, while the same composite scores were also used in the independent-samples t-tests. The use of parametric analyses was based on the predefined approximate-normality criterion described above.

3.4.4. Hypothesis Testing

Lastly, to examine the relationships between firms' machinery management activities and relevant organizational components, 18 hypotheses were formulated. Table 1 presents the first 13 hypotheses across three areas: Acquisition (H01–H04), assessing the role of professional units in machinery selection and sustainability practices; Operation (H05–H10), focusing on machinery associations between inspection teams and performance-monitoring practices and reporting; and Maintenance (H11–H13), examining how professional units and associations of inspection teams with insurance, maintenance scheduling, and cost reflection. Together, these hypotheses provide a framework for understanding how organizational structures shape systematic machinery management.

Table 1. Hypotheses on Machinery Management Practices.

Categories	Hypothesis No.	Hypothesis Statement
Acquisition	H01	Project type is not associated with the presence of a dedicated machinery selection unit.
	H02	Firm experience is not associated with the presence of a dedicated machinery selection unit.
	H03	A dedicated machinery selection unit is not associated with conducting machinery acquisition feasibility studies.
	H04	A dedicated machinery selection unit is not associated with adopting sustainable environmental standards.
Operation	H05	Project type is not associated with recording daily machinery performance.
	H06	Firm experience is not associated with the presence of a machinery inspection team.
	H07	A machinery inspection team is not associated with recording daily machinery performance.
	H08	A machinery inspection team is not associated with recording machinery performance from previous projects.
	H09	A machinery inspection team is not associated with greenhouse gas emission calculations.
	H10	Project type is not associated with the presence of a machinery inspection team.
Maintenance	H11	A machinery inspection team is not associated with construction machinery insurance.
	H12	A machinery inspection team is not associated with preparing periodic maintenance schedules.
	H13	A machinery inspection team is not associated with the inclusion of maintenance and repair costs in tender or contract prices.

This study employed inferential statistical methods to test these research hypotheses in Table 1 regarding construction machinery management practices. For hypothesis testing, the multiple-response project-type data were recoded into three mutually exclusive categories: building construction (coded as 1), non-building construction (coded as 2), and both building and non-building construction (coded as 3). Firms reporting projects in both

the building and non-building categories were assigned to the third category. Given the nominal nature of key variables (e.g., yes/no responses), Pearson Chi-square tests (χ^2) were used to evaluate associations between categorical variables, such as firms' project types, experience, and the presence of independent or professional units for machinery selection or performance evaluation [48]. These tests were used to determine whether structural organizational characteristics were associated with acquisition, operational, and maintenance practices.

Moreover, the following five hypotheses (H14–H18) focusing on additional aspects related to maintenance costs and operational components were formulated in Table 2, divided into two main categories. The first category, Maintenance Cost Estimate (H14–H15), examines whether the estimated lifetime maintenance and repair cost as a percentage of total machinery cost differs according to the presence of a dedicated machinery-selection unit or a machinery inspection team. The second, Operational & Maintenance Components (H16–H18), examined whether the operational and maintenance component mean scores differed according to the presence of these organizational arrangements or a periodic maintenance schedule.

Table 2. Hypotheses on Maintenance Cost and Component Scores.

Categories	Hypothesis No.	Hypothesis Statement
Maintenance Cost Estimate	H14	The mean estimated lifetime maintenance and repair cost as a percentage of total machinery cost does not differ between firms with and without a dedicated machinery selection unit.
	H15	The mean estimated lifetime maintenance and repair cost as a percentage of total machinery cost does not differ between firms with and without a machinery inspection team.
Operational & Maintenance Components	H16	The operational and maintenance component mean scores do not differ between firms with and without a dedicated machinery selection unit.
	H17	The operational and maintenance component mean scores do not differ between firms with and without a machinery inspection team.
	H18	The operational and maintenance component mean scores do not differ between firms with and without a periodic maintenance schedule.

For these hypotheses in Table 2, independent-samples *t*-tests were conducted to examine differences in operational and maintenance-management components scores based on firm characteristics [49]. For each independent-samples comparison, homogeneity of variance was assessed using Levene's test. When Levene's test was non-significant ($p \geq 0.05$), the equal-variance-assumed Student's *t*-test result was reported; when Levene's test was significant ($p < 0.05$), Welch's unequal-variance *t*-test result was reported. For consistency, all mean differences and t statistics were expressed as the mean of the "Yes" group minus the mean of the "No" group. The analyses examined whether the component-based composite mean scores differed according to the presence of a dedicated machinery-selection unit, a machinery inspection team, or a periodic maintenance schedule [33]. Specifically, the analysis assessed whether the presence of professional units for machinery selection, performance evaluation teams, or periodic maintenance programs were associated with differences in component mean scores for operational activities, machinery efficiency risks, operator-related issues, and maintenance-related preferences. All reported *p*-values are unadjusted. Given the number of inferential tests relative to the sample size, findings with

p-values close to 0.05 were interpreted as exploratory associations rather than as robust standalone evidence.

4. Results

This section presents the survey findings across the three stages of the construction machinery lifecycle: acquisition and selection, operation, and maintenance. The results begin with an overview of the participating firms, followed by descriptive, exploratory, and inferential statistical analyses of construction machinery management practices.

4.1. Profile of Participating Firms

Table 3 summarizes the participating firms by construction experience and project type. Most firms had at least 15 years of industry experience (75.41%). Residential and mass housing projects were reported by 52.46% of the participating firms, followed by industrial buildings (47.54%). Because multiple responses were permitted, the project-type percentages do not sum to 100%.

Table 3. Participating Company Profile Summary.

Category	Subcategories/Values	*n*	%
Years of Experience in the Construction Sector	15 years and above	46	75.41
	10–14 years	9	14.75
	5–9 years	3	4.92
	1–4 years	3	4.92
Project Types	Residential and mass housing projects	32	52.46
	Industrial buildings (factories, warehouses, etc.)	29	47.54
	Special buildings (hospitals, schools, cinemas, etc.)	21	34.43
	Infrastructure projects	21	34.43
	Commercial buildings (offices, shopping centers, etc.)	20	32.79
	Road projects (highways, bridges, viaducts, etc.)	17	27.87
	Hydraulic structures (dams, ports, regulators, etc.)	15	24.59
	Other (energy structures, rail systems)	4	6.56

Note: Multiple responses were permitted for project type. For hypothesis testing, firms were classified as undertaking building construction, non-building construction, or both building and non-building construction.

Tables 3 and 4 summarize the profiles of the participating organizations and respondents. The 61 responses represented 61 different organizations operating across 23 provinces and all seven geographical regions of Türkiye, with the highest representation from Istanbul (24.59%) and Ankara (11.48%). Respondents represented a diverse range of professional roles within their organizations. Site managers constituted the largest group (31.15%, n = 19), followed by site engineers (19.67%, n = 12) and project managers (14.75%, n = 9). The remaining respondents represented technical office, project management, planning, coordination, safety, and other construction-related roles, as summarized in Table 4.

Table 4. Professional Positions of Survey Respondents.

Position	*n*	%
Site Manager	19	31.15
Site Engineer	12	19.67
Project Manager	9	14.75
Other *	21	34.43
Total	61	100.00

* Other includes technical office, project planning and management, coordination, OHS, project control, tender, accounting, and other supervisory roles.

4.2. Reliability and Normality Test Results

Table 5 presents the reliability results for the Likert-scale questionnaire parts. All Cronbach's alpha coefficients exceeded the acceptable threshold, ranging from 0.779 to 0.971, indicating good-to-excellent internal consistency.

Table 5. Initial Internal Consistency of the Pre-PCA Analyzed Item Sets.

Questionnaire Part	Questionnaire Reference	Number of Sub-Questions	Cronbach's Alpha (α)	Interpretation
Maintenance Activities	Questionnaire Part 1, Question 23	8	0.779	Good
Operation Activities	Questionnaire Part 2, Question 1	13	0.971	Excellent
Maintenance Activities	Questionnaire Part 2, Question 4	12	0.876	Good
Operation Activities	Questionnaire Part 2, Question 8	6	0.866	Good

Table 6 presents the preliminary distributional characteristics of the pre-PCA item-set scores. The Shapiro–Wilk tests were statistically significant for Questionnare Part 1, Question 23; Questionnare Part 2, Question 1; and Questionnare Part 2, Question 4, with p-values ranging from 0.001 to 0.004. In contrast, the Shapiro–Wilk test was non-significant for the six-item set in Questionnare Part 2, Question 8 (p = 0.061). All skewness and kurtosis coefficients remained within the ±2 range, indicating that none of the item-set scores exhibited severe asymmetry or kurtosis. These results describe the preliminary distributional characteristics of the broader questionnaire item-set scores before PCA and are reported for descriptive completeness. They were not used as the direct basis for the subsequent Pearson correlation and independent-samples t-test analyses. The suitability of the parametric analyses was evaluated primarily using the distributional characteristics of the final C1–C6 component-based composite mean scores used in the subsequent inferential analyses.

Table 6. Normality Test Results of Likert Scale Questions.

Questionnaire Part	Questionnaire Reference	Number of Participants	Significance Values of Shapiro–Wilk	Skewness	Kurtosis
Maintenance Activities	Questionnaire Part 1, Question 23	61	0.002	−0.840	1.346
Operation Activities	Questionnaire Part 2, Question 1	61	0.004	−0.585	−0.546
Maintenance Activities	Questionnaire Part 2, Question 4	61	0.001	0.581	1.665
Operation Activities	Questionnaire Part 2, Question 8	61	0.061	−0.730	1.840

4.3. Machinery Acquisition and Selection

Table 7 summarizes firms' organizational practices related to construction machinery acquisition. Overall, dedicated machinery selection units were relatively uncommon, whereas feasibility studies and machinery insurance were adopted by most firms. These findings suggest that firms place greater emphasis on procurement decisions and asset protection than on establishing formal organizational structures for machinery selection.

Table 8 provides further information on the organization of machinery selection within the participating firms, including responsibility for machinery-selection and acquisition decisions and the size of dedicated machinery-selection teams.

Table 9 presents the professional composition of machinery-selection teams and the types of construction machinery used by the participating firms. As these questions

allowed multiple responses, the results are reported based on the number and percentage of markings; accordingly, the percentages describe the distribution of selections rather than the proportion of firms.

Table 7. Organizational Practices Regarding Construction Machinery Acquisition.

Category	Response Option	*n*	%
Existence of a specific unit for machinery selection	Yes	19	31.15
	No	42	68.85
Feasibility study before machinery acquisition	Yes	36	59.02
	No (based only on past experience)	25	40.98
Machinery insurance status	Yes	44	72.13
	No	17	27.87

Table 8. Machinery-Selection Organization of Participating Firms.

Category	Response Option	*n*	%
Responsibility for machinery selection and acquisition decisions	Civil Engineer/Architect	28	45.90
	Board Member/Firm Owner	25	40.98
	Procurement Officer	3	4.92
	Other (Project Manager, Machine Operators, Assistant Project Manager, Logistics Manager)	5	8.20
Machinery-selection team size *	1–3 persons	8	42.11
	4–6 persons	5	26.32
	7–10 persons	1	5.26
	More than 10 persons	5	26.32

Note: Percentages are based on valid firm responses to each question. * Machinery-selection team size is reported only for the 19 firms with a dedicated machinery-selection unit.

Table 9. Machinery-Selection Team Composition and Equipment Use.

Category	Grouped Response Option	*n* of Selection	% of Selection
Professional roles in machinery-selection teams	Project leadership (Project Manager, Project Coordinator, Project Director)	21	41.18
	Site/technical roles (Site Manager, Site Engineer, Technical Office Engineer, Project Planning Engineer, Design Office Engineer)	19	37.25
	Commercial/administrative roles (Procurement Officer, Accountant)	5	9.80
	Other specialist roles (Machinery Maintenance, Supply and Logistics Director)	6	11.76
Construction machinery used	Excavation and loading (crawler excavator, wheeled excavator, wheel loader, crawler loader, backhoe loader)	152	34.31
	Lifting and handling (telescopic mobile crane, loader mobile crane, tower crane, gantry crane, forklift)	145	32.73
	Hauling and earthmoving (dump truck, grader, bulldozer, scraper)	38	8.58
	Compaction and other equipment (pneumatic-tired roller, steel-drum roller, vibratory tamper)	108	24.38

Note: Frequencies represent selections rather than numbers of firms, personnel, or machines. Percentages were calculated separately for professional roles (51 selections) and machinery types (443 selections). A firm could select multiple options within each group. Percentage totals may differ slightly from 100% due to rounding.

4.4. Machinery Operation

This section presents key operational practices related to the use of construction machinery in firms. In this regard, Table 10 shows that operational performance monitoring and data recording were commonly adopted, whereas dedicated inspection teams and greenhouse gas monitoring were implemented by considerably fewer firms, indicating that environmental performance management remains limited.

Table 10. Overview of Construction Machinery Operation Practices in Construction Firms.

Practice Description	Yes (%)	No (%)
Daily performance data is recorded	65.57	34.43
Performance data from past projects is archived	54.10	45.90
Firms have a dedicated machine inspection team	36.07	63.93
Firms calculate greenhouse gas emissions related to machinery operation	11.48	88.52

In addition, Table 11 summarizes firms' approaches to idle machinery management and machinery service life. Idle equipment was primarily retained for future use rather than disposed of, while most firms reported moderate service lives, reflecting long-term utilization of construction machinery.

Table 11. Idle Machinery Utilization Methods and Average Service Life of Construction Machinery.

Category	Response Option	*n*	%
Idle Machinery Management	Stored in depot/yards	37	60.66
	Rented out	19	31.15
	Sold	1	1.64
	Other (e.g., repair, return to lessor)	4	6.56
Average Machinery Service Life (all machinery types combined)	≤5 years	18	29.51
	5–10 years	20	32.79
	11–15 years	17	27.87
	16–19 years	2	3.28
	≥20 years	4	6.56

The RII results presented in Table 12 indicate that machinery productivity was primarily influenced by operational and site-management risks. Operating machinery beyond its design limits received the highest importance rating, whereas equipment documentation was perceived as comparatively less influential.

To further investigate the component structure of risks affecting construction machinery productivity, PCA extracted a single component representing general perceived risks to construction machinery efficiency (eigenvalue = 9.708), explaining 74.68% of the total variance (Table 13). As only one component was retained, rotation was not applicable.

Inter-item correlations among the 13 retained items ranged from 0.530 to 0.911, with only two pairwise correlations exceeding 0.90 and none exceeding 0.95. Although these results indicated some localized item overlap, sensitivity analyses showed that the single-component solution remained stable after removing alternative items from the highly correlated pairs, supporting the robustness of the retained component structure. As a supplementary item-level check of empirical distinctness, the HTMT ratio between the retained item sets defining General Perceived Risks to Construction Machinery Efficiency (C1) and Perceived Operator-Related Machinery Problems (C2) was 0.383, below the

conservative reference threshold of 0.85, indicating limited empirical overlap between the two item sets.

Table 12. Evaluation of Risks Affecting Construction Machinery Productivity.

Risk Description	RII	Importance Level
Operating machinery beyond its design limits	0.744	High–Medium (H–M)
Irregular use of machinery on-site	0.731	High–Medium (H–M)
Insufficient space for machinery setup/manoeuvring on-site	0.718	High–Medium (H–M)
Lack of site layout and traffic planning	0.718	High–Medium (H–M)
Insufficient knowledge of machinery by responsible personnel	0.702	High–Medium (H–M)
Inadequate quality of machinery or components	0.692	High–Medium (H–M)
Inadequate inspection and maintenance practices	0.689	High–Medium (H–M)
Poor supervisory competence of personnel in charge	0.685	High–Medium (H–M)
Incorrect calculation of required machinery capacity	0.675	High–Medium (H–M)
Communication and information gap between the site and the office	0.672	High–Medium (H–M)
Communication breakdown between the firm and the supplier	0.669	High–Medium (H–M)
Inadequate contractual agreements with suppliers	0.666	High–Medium (H–M)
Missing documentation related to equipment	0.613	High–Medium (H–M)

Table 13. Component Loadings for General Perceived Risks to Construction Machinery Efficiency.

Item	General Perceived Risks to Construction Machinery Efficiency (C1)	Communality (h^2)
Incorrect calculation of required machinery capacity	0.919	0.845
Poor supervisory competence of personnel in charge	0.919	0.845
Insufficient knowledge of machinery by responsible personnel	0.918	0.842
Inadequate inspection and maintenance practices	0.896	0.802
Inadequate quality of machinery or components	0.883	0.780
Operating machinery beyond its design limits	0.880	0.774
Lack of site layout and traffic planning	0.869	0.755
Irregular use of machinery on-site	0.862	0.742
Communication and information gap between site and office	0.843	0.711
Communication breakdown between firm and supplier	0.832	0.692
Insufficient space for machinery setup/manoeuvring on-site	0.820	0.672
Inadequate contractual agreements with suppliers	0.815	0.664
Missing documentation related to equipment	0.765	0.585

KMO = 0.923; Bartlett's test: χ^2 = 949.864, df = 78, $p < 0.001$.

Table 14 indicates that operator-related problems were mainly associated with excessive fuel consumption, tire wear, and engine failures, while electrical failures were perceived as comparatively less influential.

The six operator-related variables formed a single component (eigenvalue = 3.636), explaining 60.61% of the total variance (Table 15). As only one component was retained, rotation was not applicable.

4.5. Machinery Maintenance

This section presents firms' practices, attitudes, and cost awareness regarding construction machinery maintenance and spare parts management. In this regard, Table 16 summarizes firms' maintenance practices and cost awareness. Planned maintenance sched-

ules were commonly adopted; however, 18 respondents (29.51%) were unable to estimate lifetime maintenance and repair costs as a percentage of total machinery cost. This pattern indicates uneven maintenance-cost visibility among the participating organizations despite the widespread use of scheduled maintenance.

Table 14. Operator-Induced Common Mechanical Problems in Construction Machinery.

Problem Description	RII	Importance Level
Excessive fuel consumption in construction machinery	0.748	High–Medium (H–M)
Frequent tire replacement in wheeled construction machinery	0.738	High–Medium (H–M)
Occurrence of engine failures	0.725	High–Medium (H–M)
Leakage of oil, fuel, or water	0.715	High–Medium (H–M)
Problems in the braking system	0.652	High–Medium (H–M)
Electrical component failures	0.620	High–Medium (H–M)

Table 15. Component Loadings for Perceived Operator-Related Machinery Problems.

Items	Perceived Operator-Related Machinery Problems (C2)	Communality (h^2)
Leakage of oil, fuel, or water	0.860	0.739
Occurrence of engine failures	0.848	0.719
Problems in the braking system	0.777	0.604
Excessive fuel consumption in construction machinery	0.761	0.579
Electrical component failures	0.748	0.559
Frequent tire replacement in wheeled construction machinery	0.660	0.436

KMO = 0.815; Bartlett's test: $\chi^2 = 180.051$, df = 15, $p < 0.001$.

Table 16. Firms' Practices and Cost Awareness Regarding Construction Machinery Maintenance.

Category	Response Option	*n*	%
Estimated Lifetime Maintenance and Repair Cost (% of Total Machinery Cost)	Low (0–10%)	14	22.95
	Medium (11–30%)	20	32.79
	High (31–50%)	6	9.84
	Very high (51% and above)	3	4.92
	No idea	18	29.51
Maintenance Scheduling	Yes—maintenance schedule/calendar is prepared	40	65.57
	No—no schedule/calendar is prepared	21	34.43

The RII results indicate a clear preference for preventive maintenance practices over reactive approaches, as seen in Table 17. Regular servicing and scheduled maintenance received the highest importance ratings, whereas maintenance performed only after equipment failure was considered the least important practice.

To further examine the component structure of elements related to construction machinery maintenance, a PCA was conducted on the eight items. Initially, the analysis yielded two components, with six items loading on the first component and two items on the second. The two items loading on the second component were "Maintenance is carried out upon the request of operators and/or site workers" (loading = 0.896) and "Maintenance is performed only after a malfunction occurs" (loading = 0.834). Although both items showed substantial loadings, they formed a separate component comprising only two items. As the adopted retention criterion required components to contain at

least three items [50], these two items were sequentially removed from the analysis, and the analysis was repeated. The six retained maintenance items formed a single component (eigenvalue = 3.912), explaining 65.20% of the total variance (Table 18). As only one component was retained, rotation was not applicable.

Table 17. Attitudes of Firms on Construction Machinery Maintenance (Based on RII Analysis).

Maintenance Attitude Statement	RII	Importance Level
Regular maintenance, such as cleaning, lubrication, and bolt tightening is performed.	0.800	High (H)
Maintenance at 250, 500, 1000, and 2000 h is conducted.	0.780	High–Medium (H–M)
Operators are informed about the maintenance and operation of construction machinery.	0.757	High–Medium (H–M)
Tires are replaced based on the tread thickness check.	0.718	High–Medium (H–M)
Maintenance schedules are arranged so as not to affect workers' operation time.	0.708	High–Medium (H–M)
Machinery yards are available for the protection and maintenance of construction equipment.	0.698	High–Medium (H–M)
Maintenance is carried out upon the request of operators and/or site workers.	0.603	High–Medium (H–M)
Maintenance is performed only after a malfunction occurs.	0.528	Medium (M)

Table 18. Component Loadings for Planned and Preventive Maintenance Practices.

Items	Planned and Preventive Maintenance Practices (C3)	Communality (h^2)
Regular maintenance such as cleaning, lubrication, bolt tightening is performed.	0.915	0.837
Operators are informed about the maintenance and operation of construction machinery.	0.905	0.819
Maintenance schedules are arranged so as not to affect workers' operation time.	0.799	0.638
Maintenance at 250, 500, 1000, and 2000 h is conducted.	0.784	0.615
Tires are replaced by checking the tread thickness.	0.714	0.509
Machinery yards are available for the protection and maintenance of construction equipment.	0.702	0.493

KMO = 0.866; Bartlett's test: $\chi^2 = 207.703$, df = 15, $p < 0.001$.

Table 19 shows that firms generally preferred quality-oriented maintenance strategies, particularly the use of original spare parts and authorized service providers. In contrast, non-original spare parts and aftermarket alternatives received comparatively lower importance ratings.

Table 19. Firms' Attitudes toward Spare Part Preferences (Based on RII Analysis).

Spare Part Preference Statement	RII	Importance Level
I prioritize the originality of spare parts obtained from authorized services.	0.741	High–Medium (H–M)
I prefer using authorized service centers for machinery repairs.	0.705	High–Medium (H–M)
I value the proximity of spare part dealers.	0.659	High–Medium (H–M)
Cost is my primary concern when procuring spare parts.	0.656	High–Medium (H–M)
I prioritize purchasing domestic machinery for the firm.	0.616	High–Medium (H–M)
I prefer using private service centers for machinery repairs.	0.616	High–Medium (H–M)
I prioritize purchasing domestic spare parts.	0.613	High–Medium (H–M)

Table 19. *Cont.*

Spare Part Preference Statement	RII	Importance Level
I believe domestic machinery has higher spare part standardization.	0.584	Medium (M)
I keep a spare part storage area at construction sites.	0.580	Medium (M)
I prefer equivalent (compatible) spare parts provided by services.	0.574	Medium (M)
I believe domestic spare parts perform better.	0.561	Medium (M)
I prefer aftermarket (non-original) spare parts provided by services.	0.548	Medium (M)

The 12 maintenance preference items produced a three-component solution with eigenvalues of 5.187, 2.009, and 1.580, together explaining 73.14% of the total variance. These components represented cost-oriented, domestic product-oriented and quality-oriented preferences, respectively. Varimax rotation was applied to improve the interpretability of the solution (Table 20).

Table 20. Component Loadings for Firms' Preferences in Construction Machinery Maintenance.

Items	Companies' Preferences for Technical Services			Communality (h^2)
	Cost-Oriented Service and Spare-Part Preferences (C4)	Domestic-Product-Oriented Preferences (C5)	Quality- and Support-Oriented Preferences (C6)	
I prefer aftermarket (non-original) spare parts provided by services.	0.920	0.123	0.030	0.863
I prefer using private service centres for machinery repairs.	0.810	0.059	0.287	0.742
I prefer equivalent (compatible) spare parts provided by services.	0.790	0.265	0.046	0.696
Cost is my primary concern when procuring spare parts.	0.549	0.366	0.063	0.439
I prioritize purchasing domestic machinery for the firm.	0.049	0.899	0.083	0.818
I prioritize purchasing domestic spare parts.	0.132	0.879	0.228	0.841
I believe domestic spare parts perform better.	0.494	0.744	0.164	0.824
I believe domestic machinery has higher spare part standardization.	0.399	0.645	0.225	0.626
I prioritize the originality of spare parts obtained from authorized services.	−0.031	0.244	0.869	0.815
I prefer using authorized service centres for machinery repairs.	−0.123	0.301	0.864	0.852
I value the proximity of spare part dealers.	0.330	0.036	0.725	0.636
I keep a spare part storage area at construction sites.	0.368	0.036	0.697	0.623

KMO = 0.745; Bartlett's test: $\chi^2 = 469.217$, df = 66, $p < 0.001$.

4.6. Component Reliability, Normality, and Stability Assessment

Following the extraction of the six components, the internal consistency of the retained items and the distributional characteristics of the resulting composite-based component scores were further assessed. Cronbach's alpha was calculated separately for each component

(C1–C6) to evaluate component-specific internal consistency. In addition, the normality of the composite-based component scores was examined using the Shapiro–Wilk test together with skewness and kurtosis coefficients. Table 21 presents the results of these assessments.

Table 21. Reliability and Normality Assessment of Extracted Composite Component Scores.

Lifecycle Stage	Component Code	Number of Items	Cronbach's α	Shapiro–Wilk p-Value	Skewness	Kurtosis	Mean	SD
Operational Activities	C1	13	0.971	0.004	−0.585	−0.546	3.45	1.14
	C2	6	0.866	0.061	−0.730	1.840	3.50	0.80
Maintenance Activities	C3	6	0.810	0.078	−0.640	1.210	3.72	0.99
	C4	4	0.832	0.114	0.333	0.098	2.99	0.93
	C5	4	0.878	0.090	0.130	−0.283	2.97	1.03
	C6	4	0.828	0.114	−0.210	−0.328	3.36	0.95

The component specific Cronbach's alpha coefficients ranged from 0.810 to 0.971, indicating good to excellent internal consistency across the extracted components. For C2–C6, the Shapiro–Wilk tests were not statistically significant ($p > 0.05$), providing no evidence of departure from normality. For C1, the Shapiro–Wilk test was statistically significant ($p = 0.004$); however, its skewness (−0.585) and kurtosis (−0.546) values were well within the predefined ±2 threshold. Moreover, the skewness and kurtosis values of all six composite scores remained within this acceptable range. Accordingly, based on the predefined normality decision rule, all composite-based component scores were considered to demonstrate acceptable approximate normality and were suitable for subsequent parametric analyses [37].

Given the relatively modest sample size, the stability of the extracted component solutions was further examined using bootstrap resampling. Table 22 presents Tucker's congruence coefficients obtained from 5000 bootstrap samples for components with complete item-level data corresponding to the final retained-item solutions.

Table 22. Bootstrap-Based Component Stability Assessment.

Component Code	Component Name	Median Congruence	95% Bootstrap Range
C1	General Perceived Risks to Construction Machinery Efficiency	0.9995	0.9980–0.9999
C2	Perceived Operator-Related Machinery Problems	0.9985	0.9806–0.9998
C3	Planned and Preventive Maintenance Practices	0.9955	0.9732–0.9996
C4	Cost-Oriented Service and Spare-Part Preferences	0.9816	0.9170–0.9952
C5	Domestic-Product-Oriented Preferences	0.9794	0.8962–0.9950
C6	Quality- and Support-Oriented Preferences	0.9797	0.9079–0.9949

The bootstrap results showed consistently high median component congruence, ranging from 0.9794 to 0.9995. In particular, C1–C3 demonstrated very high stability across resamples, while C4–C6 also showed strong similarity between the original and resampled component solutions. Overall, the bootstrap assessment provides additional evidence that the extracted component structures were reasonably stable despite the modest sample size.

4.7. Correlation Analysis of Machinery Operation and Maintenance Components

Table 23 presents the Pearson correlation coefficients among the composite scores derived for the operational and maintenance components identified through principal component analysis.

The correlation analysis revealed generally weak to moderate positive relationships among the extracted components (Table 23). Perceived Operator-Related Machinery Prob-

lems (C2) showed significant positive correlations with both general perceived risks to construction machinery efficiency (C1) and planned and preventive maintenance practices (C3), suggesting that greater operator-related issues are associated with higher operational risks and increased maintenance attention. Within the maintenance dimension, cost-oriented service and spare-part preferences (C4) were positively associated with both domestic-product-oriented preferences (C5) and quality- and support-oriented preferences (C6), while domestic product preferences were also positively correlated with quality and support preferences. These findings indicate that firms' maintenance decisions are influenced by interconnected cost, sourcing, and quality considerations.

Table 23. Pearson Correlations among Machine Management Components.

Management Activities	Variable	Operational Activities		Maintenance Activities			
		C1	C2	C3	C4	C5	C6
Operational Activities	General Perceived Risks to Construction Machinery Efficiency (C1)	1					
	Perceived Operator-Related Machinery Problems (C2)	0.336 **	1				
Maintenance Activities	Planned and Preventive Maintenance Practices (C3)	0.146	0.296 *	1			
	Cost-Oriented Service and Spare-Part Preferences (C4)	−0.003	0.174	0.009	1		
	Domestic-Product-Oriented Preferences (C5)	−0.003	0.227	0.064	0.515 **	1	
	Quality- and Support-Oriented Preferences (C6)	−0.237	0.033	0.210	0.332 **	0.416 **	1

* indicates $p < 0.05$; ** indicates $p < 0.01$ (2-tailed).

4.8. Evaluation of Machinery Management Activities of Construction Companies

The Chi-square test results are presented in Table 24. Significant associations were identified between organizational structures and several machinery management practices. In particular, firms with dedicated machinery selection units and inspection teams were more likely to conduct feasibility studies, adopt sustainable practices, record machinery performance, implement maintenance schedules, provide machinery insurance, and incorporate maintenance costs into tender or contract documents. In contrast, firm experience showed no significant associations, while project type was significantly associated with the presence of a dedicated machinery selection unit (H01, $p = 0.042$), but not with daily machinery performance recording (H05, $p = 0.374$) or the presence of a machinery inspection team (H10, $p = 0.958$). This suggests that project type showed a limited and stage-specific association with machinery management, confined to a particular acquisition-related organizational arrangement rather than extending consistently across other machinery-management practices.

For the subsequent independent-samples *t*-tests, homogeneity of variance was assessed using Levene's test, and the appropriate Student's or Welch's *t*-test result was reported. Table 25 presents the results for H14 and H15. Among the 43 respondents who provided a numerical estimate, respondents representing firms with a dedicated machinery selection unit reported a higher estimated lifetime maintenance and repair cost as a percentage of total machinery cost than those representing firms without such a unit (37.14% vs. 20.34%; mean difference = 16.80 percentage points; Student's $t(41) = 2.518$, $p = 0.016$). No statistically significant difference was observed according to the presence of a machinery inspection team (28.50% vs. 23.48%; mean difference = 5.02 percentage points; Student's $t(41) = 0.751$, $p = 0.457$).

Table 24. Chi-Square Test Results for Hypotheses.

Categories	Hypothesis No.	χ^2	df	*p*-Value
Acquisition	H01	6.330	2	0.042
	H02	1.982	3	0.576
	H03	7.242	1	0.007
	H04	3.994	1	0.046
Operation	H05	1.966	2	0.374
	H06	3.218	3	0.359
	H07	18.065	1	<0.001
	H08	23.700	1	<0.001
	H09	14.018	1	<0.001
	H10	0.085	2	0.958
Maintenance	H11	6.036	1	0.014
	H12	9.784	1	0.002
	H13	4.022	1	0.045

Table 25. Independent-Samples *t*-Test Results for H14–H15.

Hypothesis No	Group	*n*	$\bar{x}$	σ	Mean Difference	Levene *p*	Test	*t*	df	*p*-Value
H14	Yes	14	37.14	19.78	+16.80	0.519	Student	+2.518	41	0.016
	No	29	20.34	20.83						
H15	Yes	20	28.50	16.39	+5.02	0.446	Student	+0.751	41	0.457
	No	23	23.48	25.69						

Note: The H14 and H15 analyses were based on the 43 respondents who provided a numerical maintenance-cost estimate; 18 respondents who selected "No idea" were excluded. Mean differences and t statistics are reported as Yes minus No.

Table 26 presents differences in the operational and maintenance component scores according to the presence of a dedicated machinery-selection unit. Respondents representing firms with such a unit reported lower General Perceived Risks to Construction Machinery Efficiency scores (C1; M = 2.93 vs. 3.69; Welch's t(25.600) = −2.175, $p = 0.039$) and higher Planned and Preventive Maintenance Practices scores (C3; M = 4.10 vs. 3.55; Student's t(59) = 2.065, $p = 0.043$). No statistically significant differences were observed for C2 or C4–C6.

Table 27 presents differences in component scores according to the presence of a machinery inspection team. Respondents representing firms with an inspection team reported higher Planned and Preventive Maintenance Practices scores (C3; M = 4.22 vs. 3.44; Student's t(59) = 3.193, $p = 0.002$) and higher Quality- and Support-Oriented Preferences scores (C6; M = 3.74 vs. 3.14; Student's t(59) = 2.449, $p = 0.017$). No statistically significant differences were observed for C1, C2, C4, or C5.

Table 28 presents differences in component scores according to whether firms prepared a periodic maintenance schedule. Respondents representing firms with a periodic maintenance schedule reported higher Planned and Preventive Maintenance Practices scores (C3; M = 4.06 vs. 3.06; Student's t(59) = 4.248, $p < 0.001$). No statistically significant differences were observed for C1, C2, or C4–C6.

Table 26. Independent-Sample *t*-Test Results for H16.

Categories	Component Codes	Group	*n*	$\bar{x}$	σ	Mean Difference	Levene *p*	Test	*t*	df	*p*-Value
Operational Activities	C1	Yes	19	2.93	1.39	−0.76	0.004	Welch	−2.175	25.600	0.039
		No	42	3.69	0.93						
	C2	Yes	19	3.52	0.99	+0.03	0.112	Student	+0.130	59	0.897
		No	42	3.49	0.71						
Maintenance Activities	C3	Yes	19	4.10	0.99	+0.55	0.751	Student	+2.065	59	0.043
		No	42	3.55	0.95						
	C4	Yes	19	3.04	0.98	+0.07	0.583	Student	+0.268	59	0.790
		No	42	2.97	0.92						
	C5	Yes	19	2.83	1.19	−0.20	0.133	Student	−0.699	59	0.487
		No	42	3.03	0.96						
	C6	Yes	19	3.39	1.07	+0.06	0.322	Student	+0.209	59	0.835
		No	42	3.34	0.91						

Table 27. Independent-Samples *t*-Test Results for H17.

Categories	Component Codes	Group	*n*	$\bar{x}$	σ	Mean Difference	Levene *p*	Test	*t*	df	*p*-Value
Operational Activities	C1	Yes	22	3.18	1.28	−0.43	0.225	Student	−1.417	59	0.162
		No	39	3.61	1.05						
	C2	Yes	22	3.45	0.90	−0.08	0.686	Student	−0.371	59	0.712
		No	39	3.53	0.74						
Maintenance Activities	C3	Yes	22	4.22	0.94	+0.78	0.581	Student	+3.193	59	0.002
		No	39	3.44	0.91						
	C4	Yes	22	3.22	1.00	+0.35	0.125	Student	+1.428	59	0.159
		No	39	2.87	0.87						
	C5	Yes	22	3.00	1.08	+0.05	0.661	Student	+0.184	59	0.854
		No	39	2.95	1.02						
	C6	Yes	22	3.74	0.87	+0.60	0.686	Student	+2.449	59	0.017
		No	39	3.14	0.94						

Table 28. Independent-Sample *t*-Test Results for H18.

Categories	Component Codes	Group	*n*	$\bar{x}$	σ	Mean Difference	Levene *p*	Test	*t*	Df	*p*-Value
Operational Activities	C1	Yes	40	3.44	1.09	−0.03	0.224	Student	−0.086	59	0.932
		No	21	3.47	1.26						
	C2	Yes	40	3.61	0.79	+0.34	0.730	Student	+1.583	59	0.119
		No	21	3.28	0.79						
Maintenance Activities	C3	Yes	40	4.06	0.76	+1.00	0.053	Student	+4.248	59	<0.001
		No	21	3.06	1.05						
	C4	Yes	40	3.05	0.91	+0.17	0.764	Student	+0.672	59	0.504
		No	21	2.88	0.97						
	C5	Yes	40	3.01	0.96	+0.11	0.356	Student	+0.404	59	0.688
		No	21	2.89	1.18						
	C6	Yes	40	3.50	0.90	+0.42	0.604	Student	+1.646	59	0.105
		No	21	3.08	1.01						

4.9. Operational Interpretation of the Socio-Technical Framework

To connect the theoretical framework with the empirical findings, STS theory was used to interpret the relationships between machinery-related technical requirements, human knowledge and actions, and organizational arrangements [51]. In the present study, technical aspects were represented by reported machinery problems, operating risks, maintenance routines, and service or spare-part preferences. Human aspects were represented by perceptions concerning operator-related problems, personnel knowledge, supervision, and operator information. Organizational aspects were represented by machinery-selection units, inspection teams, performance records, maintenance schedules, and cost-related practices. These aspects overlap and were not estimated as separate, mutually exclusive statistical constructs. Table 29 links the recorded indicators and selected findings to their corresponding socio-technical interpretations.

Table 29. Operational Linkages between the Socio-Technical Framework and Empirical Findings.

Socio-Technical Interface	Questionnaire Indicators	Selected Empirical Findings	Interpretation Within the Study's Scope
Technical–human interface	General machinery-efficiency risks, including personnel knowledge and supervision; perceived operator-related problems. Part 2, Q1 and Q8; C1 and C2.	C1 and C2 were positively correlated (r = 0.336). Fuel consumption and tire replacement received relatively high operator-related ratings.	Technical problems were associated with human and supervisory concerns; causality was not established.
Organizational–technical maintenance interface	Inspection-team presence, periodic maintenance scheduling, and planned/preventive maintenance items. Part 1, Q13, Q20 and Q23; C3.	C3 scores were higher among firms with inspection teams (4.22 vs. 3.44) and maintenance schedules (4.06 vs. 3.06).	Formal monitoring and planning arrangements were associated with reported maintenance routines; their causal effects were not tested.
Organizational–technical information interface	Daily performance records and records from previous projects. Part 1, Q11 and Q12.	Daily performance recording was reported by 65.57% of firms, and archiving of previous-project records by 54.10%.	These practices indicate the potential information inputs for later decisions, although actual cross-stage use was not measured.
Technical–financial/ service interface	Lifetime maintenance-cost estimates and service/spare-part preferences. Part 1, Q21; Part 2, Q4; C4–C6.	Eighteen respondents (29.51%) could not provide a maintenance-cost estimate. C4–C6 showed positive pairwise correlations.	The findings indicate related cost, sourcing, and service considerations, with limited visibility of lifetime maintenance costs. The effectiveness of financial integration was not established.

Note: Questionnaire references correspond to Supplementary Material S1. The listed interfaces are interpretive categories, not additional PCA components. Inferential findings are based on unadjusted analyses.

The resulting interpretation concerns reported practices and patterns of association. The survey did not directly measure joint optimization, actual information transfer between departments, or the effectiveness of lifecycle-feedback mechanisms. The framework was used to interpret the findings from an STS perspective, not to test cause-and-effect relationships between machinery-management activities.

5. Discussion

This study contributes to the construction machinery management literature by showing that effective machinery management is shaped by the interaction of organizational mechanisms across acquisition, operation, and maintenance, rather than by isolated practices within individual stages. The survey findings consistently showed that different organizational mechanisms were associated with practices across different stages of machinery management, while firm characteristics such as experience and project type showed more limited and less consistent associations. Collectively, these findings suggest that ma-

chinery management should be understood as a coordinated organizational capability rather than a collection of independent technical activities. The following sections discuss these findings through the lens of socio-technical systems theory.

5.1. Organizational Structures and Machinery Management Practices

Within the present sample, selected organizational arrangements were associated with reported machinery-management practices. However, because firm size and financial capacity were not measured, their contribution relative to these organizational arrangements could not be evaluated. Nevertheless, project type showed one notable association at the acquisition stage, being significantly related to the presence of a dedicated machinery selection unit. This suggests that project-specific requirements may be associated with whether firms formalize machinery-selection responsibilities, although the absence of significant project-type associations for the operational indicators examined indicates that this influence is not consistent across machinery-management activities. Dedicated machinery-selection units, inspection teams, and planned maintenance systems were associated with selected management practices in the unadjusted analyses. This finding extends previous research highlighting the importance of equipment planning and coordination [1,29,30] by showing that different organizational mechanisms support different stages of the machinery lifecycle. From an STS perspective, these mechanisms function as organizational structures that coordinate technical decisions, facilitate knowledge exchange, and strengthen interactions between human and technical subsystems [51]. Consequently, machinery management should be viewed as an organizational capability rather than merely a technical function.

5.2. Cross-Stage Relationships in Construction Machinery Management

The findings indicate that acquisition, operation, and maintenance are interconnected rather than entirely independent management functions, although the observed relationships are uneven. For example, Perceived Operator-Related Machinery Problems (C2) were significantly associated with Planned and Preventive Maintenance Practices (C3) ($r = 0.296$, $p < 0.05$), while most other correlations between operational and maintenance dimensions were not statistically significant. At the item level, 54.10% of firms reported archiving machinery performance data from previous projects, indicating that operational information was retained in only part of the participating organizations; however, the questionnaire did not directly measure whether such information was subsequently fed back into acquisition or maintenance decisions.

Firms with dedicated machinery selection units reported significantly lower General Perceived Risks to Construction Machinery Efficiency (C1) ($p = 0.039$) and higher Planned and Preventive Maintenance Practices (C3) ($p = 0.043$). Similarly, machinery inspection teams were associated with stronger Planned and Preventive Maintenance Practices (C3) ($p = 0.002$) and Quality- and Support-Oriented Preferences (C6) ($p = 0.017$). These findings suggest that formal organizational practices may be associated with selected cross-stage relationships different machinery-management activities, in line with previous research emphasizing the interaction of human, organizational, and technical factors in maintenance management [52,53]. However, these connections were not consistent across all stages, suggesting partial rather than fully integrated coordination across acquisition, operation, and maintenance.

5.3. Human and Technical Interactions in Machinery Performance

The findings show that machinery performance is shaped not only by equipment condition but also by operator competence, supervision, and communication. The respondents' ratings highlight operator-related concerns alongside technical maintenance issues, indicating that machinery-related problems should not be interpreted solely as

equipment or maintenance deficiencies. Rather, the effective operation of construction machinery also depends on the human conditions surrounding its use, including the knowledge and capabilities of operators and the quality of supervision and communication. Accordingly, maintenance practices may be more effective when considered together with operator-related factors rather than as isolated technical interventions. This interpretation is consistent with the STS perspective, which emphasizes that machinery performance emerges from the interaction between technical systems and human actors rather than from machinery alone [53].

5.4. Maintenance Practices, Cost Visibility, and Organizational Formalization

The findings indicate that maintenance is one of the most structured aspects of construction machinery management. Firms with inspection teams and planned maintenance schedules demonstrated stronger maintenance practices, while quality-oriented preferences, such as using authorized services and original spare parts, further reflected systematic maintenance management. These findings are consistent with previous research highlighting the importance of preventive maintenance for improving equipment reliability and service life [54,55]. A noteworthy finding was that, among the 43 respondents who provided a numerical estimate, those representing firms with dedicated machinery-selection units reported higher estimated lifetime maintenance and repair costs as a percentage of total machinery cost than those without such units (37.14% vs. 20.34%). This cross-sectional association should not be interpreted as evidence that dedicated selection units increase maintenance expenditure. Rather, it may reflect more systematic cost recording, greater recognition of lifecycle maintenance expenditure, investment in planned or preventive maintenance, or unmeasured differences in fleet characteristics and utilization. Previous construction-equipment research has similarly emphasized accurate record keeping, preventive maintenance, and economic analysis as elements of formal equipment-management practice [56]. As these mechanisms were not directly measured, however, they remain plausible interpretations rather than established causal explanations.

The fact that 18 respondents selected “No idea” further indicates uneven visibility of lifetime maintenance-cost information across the participating organizations. While this may point to limitations in the integration of maintenance information with broader financial decision-making, the survey did not directly assess organizational accounting systems, budgeting, or tender-preparation practices. From an STS perspective, the findings therefore highlight the potential importance of coordinating technical maintenance routines with financial and organizational decision-making [57,58].

5.5. Towards a Socio-Technical Framework for Construction Machinery Management

The survey indicates that machinery management involves multiple interrelated practices across acquisition, operation, and maintenance. The observed associations among organizational arrangements, operational activities, and maintenance practices suggest that these activities should not be interpreted entirely in isolation. From an STS perspective, the findings point to potential coordination needs across machinery-management activities and highlight the importance of considering how technical, human, and organizational elements interact across lifecycle stages. This shifts the focus from optimizing discrete management activities towards improving the connections between acquisition, operation, and maintenance decisions [57]. From a socio-technical systems perspective, organizational performance depends on strengthening these interactions through continuous information exchange, coordinated decision-making, and shared organizational responsibility rather than simply introducing additional technical or managerial practices [56,58]. This per-

spective offers a more holistic foundation for future construction machinery management research and practice.

6. Limitations and Future Directions

Despite providing valuable insights into construction machinery management, this study has several limitations. First, although respondents were selected based on their experience, the findings may reflect respondent perceptions rather than objective measures. Future research could strengthen the findings by incorporating objective performance indicators, such as actual downtime records, maintenance cost data, or digital equipment monitoring outputs.

Second, the cross-sectional design captures machinery management practices at a single point in time. Given the dynamic nature of construction projects, longitudinal studies could provide deeper insight into how operational and maintenance strategies evolve and how organizational learning influences long-term equipment performance.

Third, this study focused on machinery acquisition and selection, operation, and maintenance. Although the broader questionnaire included some contextual items on idle machinery and rental practices, relocation, redeployment, disposition, and replacement were not examined through dedicated multi-item measures and therefore fell outside the inferential scope of the study. This reflects the predefined questionnaire and analytical framework rather than the relative importance of these stages. Future research should examine how relocation, redeployment, rental, and replacement decisions interact with equipment planning and subsequent acquisition.

Fourth, as one knowledgeable respondent was obtained from each organization, the reported practices reflect individual informants' assessments and were not independently verified through multiple respondents within the same organization. Future studies could employ multiple informants per organization to assess within-firm agreement and strengthen the reliability of firm-level interpretations.

Fifth, although the inferential analyses were guided by predefined hypotheses, the number of statistical tests should be considered in relation to the sample size. Some categorical subgroup comparisons also involved relatively small numbers of observations, and associations with p-values close to the conventional significance threshold should therefore be interpreted with appropriate caution. In addition, extensive multivariable adjustment was not undertaken given the sample size and the limited organizational covariates available. Future studies with larger samples could further examine the robustness of these relationships using multiplicity-adjusted and multivariable analyses.

Sixth, the external validity of the findings should also be considered in relation to the Turkish construction-industry context. Differences in organizational scale, regulatory requirements, contracting practices, and economic conditions may influence machinery-management decisions and therefore limit the direct transferability of the findings to other national contexts. Although the sample covers firms operating across different project types and geographical regions of Türkiye, it should not be interpreted as statistically representative of the entire Turkish construction industry. The survey did not collect annual turnover, total employee numbers, or machine counts. In addition, the domestic-product items referred specifically to Turkish-made machinery and spare parts, so C5 may be interpreted differently in other national markets.

Finally, while the statistical analyses identified significant associations among organizational, operational, and maintenance variables, they do not explain the underlying causal mechanisms. Future research could explore these mechanisms using longitudinal, mixed-method, or case-based research designs to develop a more comprehensive understanding of construction machinery management.

7. Conclusions

This study investigated construction machinery management across the acquisition, operation, and maintenance stages of the equipment lifecycle through the lens of socio-technical systems theory. The findings indicate that construction firms generally adopt structured practices within individual machinery-management activities, while the observed relationships across these activities are uneven. Selected cross-stage associations were identified, including relationships between operator-related problems and preventive maintenance practices, between dedicated machinery selection units and perceived machinery efficiency risks, and between machinery inspection teams and maintenance-related practices. However, these relationships were not consistently observed across all operational and maintenance dimensions. Accordingly, the findings suggest that coordination among acquisition, operation, and maintenance activities is only partially developed, rather than demonstrating a fully connected management process.

The study contributes to the construction machinery management literature by demonstrating that effective machinery management does not depend on a single organizational practice but emerges from the complementary roles of multiple organizational mechanisms operating across different management activities. Rather than improving acquisition, operation, or maintenance in isolation, the findings suggest that systematic machinery management depends on how these organizational mechanisms collectively support information exchange, coordinated decision-making and continuous improvement. Interpreted through the lens of socio-technical systems theory, this study extends existing equipment management research by conceptualizing machinery management as a coordinated organizational capability rather than a collection of independent technical activities.

The findings suggest three practical priorities. First, firms should strengthen machinery information continuity by maintaining standardized machine-level records covering operating hours, defects, downtime, and completed maintenance, with responsibility assigned for regular updating and review. Second, documented maintenance responsibilities should be formalized through scheduled tasks, designated personnel, completion records, and targeted operator briefings where recurring operational problems are identified. Third, machinery-level lifecycle cost records should be improved by integrating parts, labor, and outsourced repair costs into subsequent procurement assessments. These actions translate the study's socio-technical findings into practical coordination mechanisms across acquisition, operation, and maintenance without implying causal effects not tested in this study.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/buildings16183692/s1, Supplementary Material S1: Selected Questionnaire Items Analyzed in the Present Study; Supplementary Material S2: Detailed Principal Component Analysis (PCA) Diagnostics for Components C1–C6, including eigenvalues, explained variance, component loadings, extraction communalities, and scree plots.

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Informed Consent Statement: Informed consent was obtained from all participants involved in the study. Before completing the survey, participants were informed about the purpose of the research, the voluntary nature of their participation, their right to withdraw at any stage without penalty, the anonymous treatment of the collected data, and the intended academic use of the research findings.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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