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An Activity-Based Costing Framework for Occupational Safety and Health Management Costs in Modular Building Installation

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Research Article

Keywords: Activity-based costing, Modular construction, Occupational safety and health management cost, Work package, Cost driver, Traceability

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Abstract

Modular building installation concentrates lifting, landing, stabilization, and connection hazards into short, repeated cycles, whereas Korean occupational safety and health management cost (OSHMC) is administered mainly by statutory resource category. This study develops an activity-based costing (ABC) framework that preserves the legal eligibility boundary and links eligible resources to five installation work packages, fourteen safety activities, measurable drivers, owners, due points, and evidence. The model was constructed from legislation, official guidance, modular-safety studies, and ABC literature, then tested with a normalized 100-unit case. Cost conservation, driver causality, responsibility, timing, traceability, and four controlled change scenarios were examined. Resource, activity, and work-package totals were identical (100.0 = 100.0 = 100.0; error = 0.0), and all activity records contained an owner, due point, and evidence field. Increases in modules, lift-hours, connections, and shifts produced totals of 113.6, 114.5, 108.5, and 102.2, while unaffected activities remained unchanged. The framework therefore supports internally consistent, selective, and traceable allocation. The normalized values demonstrate model behavior rather than observed project costs or recommended spending ratios; actual project records are required for rate calibration and external validation.

Keywords: Activity-based costing; Modular construction; Occupational safety and health management cost; Work package; Cost driver; Traceability

1 Introduction

1.1 Research background

Modular construction transfers production to a factory, but site installation still requires large three-dimensional units to be received, rigged, lifted, landed, aligned, temporarily stabilized, and connected in rapid sequence. Falls, load movement, temporary instability, access conflict, and communication failure therefore remain prominent site hazards (Fard et al. 2017; Ahn et al. 2020; Mohandes et al. 2022). Repetition allows standard work packages, yet cost demand changes with lift duration, module geometry, connection quantity, weather, work shifts, and specialist-contractor interfaces. These conditions favor an activity-level view of safety resources rather than a uniform allocation based only on total project progress.

1.2 Research problem

Article 72 of the Korean Occupational Safety and Health Act requires appropriation and proper use of OSHMC, and the applicable notice controls eligible purposes and evidence (Republic of Korea 2026; Ministry of Employment and Labor 2025). This item-based ledger is essential for legal control, but an item total does not by itself identify which installation control consumed the resource, which workload caused a change, who had to prepare it, or whether it was ready before exposure. One resource may support several activities, and one activity may consume labor, facilities, equipment, training, and inspection simultaneously. The core problem is therefore a missing causal and traceable path from eligible cost item to activity, driver, work package, responsibility, timing, and evidence.

1.3 Research objective and scope

The objective is to develop and internally test a dual-ledger ABC framework for modular-installation OSHMC without changing the statutory boundary. The scope begins with site arrival and ends after rigging, lifting, landing, alignment, stabilization, permanent connection, inspection, and crane release. Factory production and long-distance transport are excluded except where they produce an interface requirement at site receipt. The study asks how the item/activity mismatch arises, which causal drivers and work packages are suitable, how management criteria change under ABC, and whether the model is numerically consistent and selectively responsive.

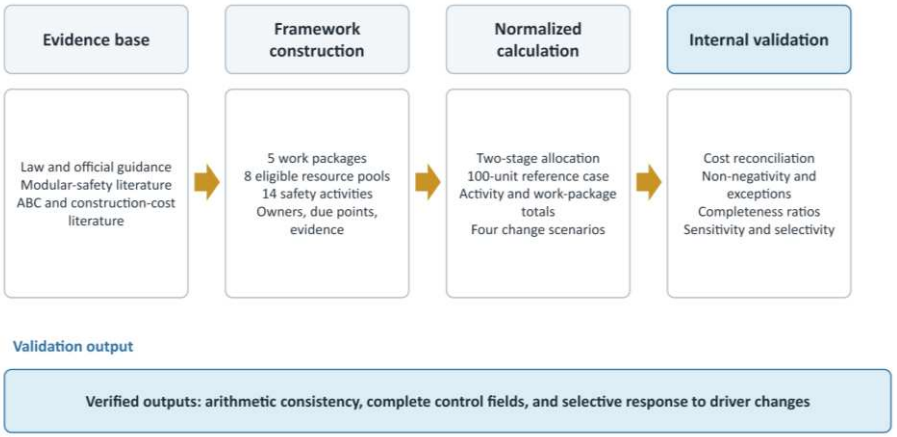


Fig. 1 Research design for developing and internally validating the ABC framework

2 Analysis of Previous Studies and Current Practice

2.1 Definition and scope of safety management cost

Korean OSHMC is a statutory, earmarked construction-project account: only costs satisfying the accident-prevention purpose, eligible-use rule, project period, and evidence requirements enter the ledger. International research uses a broader functional concept, examining prevention, control, monitoring, training, inspection, and sometimes accident consequences according to the jurisdiction and study purpose (Pellicer et al. 2014; Kim and Kim 2023). In this study, Korean law determines eligibility and international literature informs activity and causality design. ABC begins only after an eligibility gate and cannot expand the legal account.

2.2 Modular-site installation characteristics and safety-resource demand

The installation process was divided at observable work transitions and changes in the dominant control objective. WP1 covers arrival, laydown, and preparation; WP2 rigging and pre-lift inspection; WP3 lifting and load transfer; WP4 landing, alignment, and temporary stabilization; and WP5 permanent connection and closeout. The sequence reflects modular-safety studies that emphasize lifting, temporary states, access control, inspection, and coordination (Jun et al. 2021; Choi et al. 2023; Sadeghi et al. 2025).

Table 1 Modular installation work packages, principal hazards, and control objectives

Code / work package	Principal hazards	Required control objective
WP1 Arrival and laydown	Vehicle contact, unstable laydown, access conflict	Secure route, laydown capacity, exclusion boundary, and delivery sequence before entry
WP2 Rigging and pre-lift	Rigging failure, incorrect lifting point, communication error	Verify module data, rigging configuration, inspection status, roles, and the pre-lift hold point
WP3 Lifting and load transfer	Falling load, collision, wind, blind spot	Maintain the exclusion zone, signaling and communication, wind monitoring, and a controlled load path
WP4 Landing, alignment, and temporary stabilization	Pinch point, fall, overturning, premature release	Control personnel access, alignment tools, temporary restraint, and stability verification
WP5 Permanent connection and crane release	Fall, hot work, incomplete connection, premature crane release	Complete connection, fire prevention, inspection, and release authorization

Each package requires a bundle rather than one cost item. Lifting, for example, combines signal labor, communication and wind monitoring equipment, exclusion-zone facilities, briefing, PPE, and inspection. Conversely, safety-management labor and shared facilities serve several packages. This many-to-many relationship is the operational reason for two-stage allocation.

2.3 Current execution structure under modular-installation conditions

Current execution was examined as a documentary structure, not as observed expenditure shares from sampled projects. The statutory ledger can confirm appropriation, eligible item, amount, period, voucher, and balance, but it does not routinely aggregate resources as pre-work control bundles or retain module count, lift-hours,

connection points, controlled time, and shifts as common causal drivers. Specialist contractors execute high-risk work while the prime contractor coordinates the account, creating another gap between financial control and activity readiness. The ABC activity owner clarifies preparation and evidence without transferring statutory or contractual responsibility.

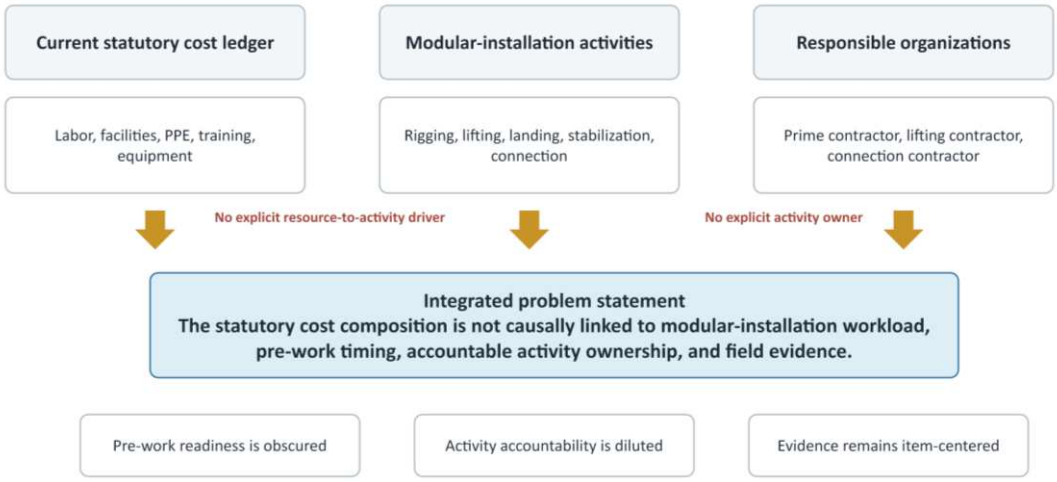


Fig. 2 Mismatch among statutory cost items, installation activities, drivers, and accountable parties

2.4 Previous studies on safety cost and ABC

Safety-cost research has examined appropriation standards, eligible-use categories, risk-based distribution, and estimation (Baek et al. 2020; Yeom et al. 2015; Lim et al. 2023). Modular research has identified hazards, checklists, crane factors, and training needs, while construction ABC has improved the explanation of overhead, manufacturing, and quality cost (Di Gregorio and Soares 2013; Kim 2017; Lee et al. 2015). However, these streams do not jointly provide a legal-boundary gate, a resource-to-activity-to-WP path, causal change drivers, and linked responsibility and evidence for modular safety cost.

2.5 Research gap and questions

The unresolved task is not to estimate a universal safety-cost ratio, but to explain an eligible project total through operational units that can be planned, changed, executed, and settled. Accordingly, the model must conserve the legal total, react only to affected drivers, assign complete ownership and timing, and retain documentary traceability. These requirements form the internal validation criteria used below.

3 Research Method and Framework Design

3.1 Research design and evidence base

Four evidence groups were used: legislation and official notices for eligibility and responsibility; Korean modular guidance and peer-reviewed modular-safety studies for process boundaries and controls; ABC and construction-cost studies for allocation logic; and WBS/OBS and construction-management studies for aggregation and accountability. Sources were retained when they directly supported site installation, safety-cost boundaries, measurable cost causality, or work-package management. The evidence defines constructs and candidate drivers; it does not supply universal activity rates.

3.2 ABC concept and dual-ledger allocation logic

ABC represents two consumption relationships: activities consume resources and cost objects consume activities (Cooper and Kaplan 1988; Kaplan and Anderson 2004). The statutory ledger remains the control account for eligibility, source documents, and balance. A linked activity ledger records the consuming activity, resource and activity drivers, WP, owner, due point, and evidence. Eligible resources are first grouped by similar consumption patterns, allocated to activities, and then assigned to WPs. Costs failing the eligibility gate or lacking a causal driver are excluded or held in an exception account rather than distributed arbitrarily.

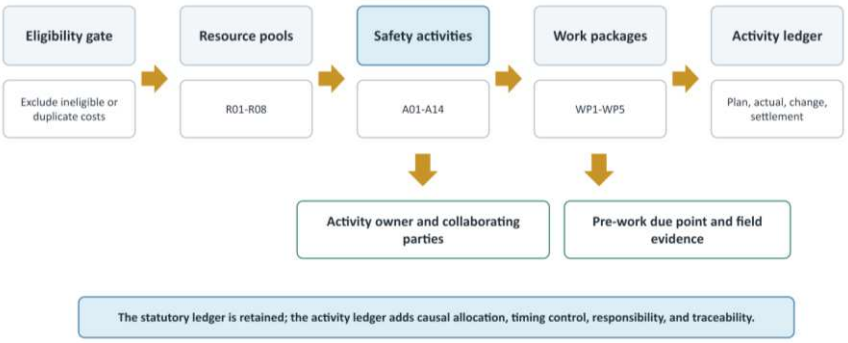


Fig. 3 ABC-based activity-responsibility linkage framework for modular installation safety costs

Let RC_r be eligible resource-pool cost, x_ra the resource-driver quantity consumed by activity a, AC_a activity cost, D_a total activity-driver quantity, AR_a the activity rate, d_aj the activity-driver quantity consumed by WP j, and SC_j the WP safety cost.

$$\text{alpha_ra} = \text{x_ra} \,/\, \text{sum_a x_ra} \tag{1}$$

$$\text{AC_a} = \text{sum_r (RC_r x alpha_ra)} \tag{2}$$

$$\text{AR_a} = \text{AC_a} \,/\, \text{D_a} \tag{3}$$

$$\text{SC_j} = \text{sum_a (AR_a x d_aj)} \tag{4}$$

For every resource pool, allocation coefficients are non-negative and sum to one; the same requirement applies when activity cost is aggregated to WPs. These identities establish cost conservation. Activity rates are kept separate when the causal units differ, such as lift-hour, module, connection point, stability check, controlled hour, or shift.

3.3 Work-package composition criteria and results

The unit of analysis is the smallest safety activity that consumes an identifiable resource bundle and produces a verifiable control result. A WP was retained when it had (1) observable start and finish transitions, (2) a coherent hazard-control set, (3) at least one measurable driver, (4) a pre-work decision point, (5) a responsibility interface, and (6) evidence closure. Applying these criteria produced the five WPs in Table 1. Each of the fourteen activities was then assigned one primary purpose, a monotonic and collectable driver, one readiness/evidence owner, a pre-work due point, and representative evidence.

3.4 Resource pools, safety activities, drivers, and responsibility

Eight resource pools were organized by consumption pattern rather than by mechanically copying statutory sub-items. The activity register then connects each pool to a control result and driver. The owner is accountable for readiness and evidence, collaborating parties execute or verify work, and the prime contractor retains overall coordination of the statutory account.

Table 2 Eligible resource pools and recommended resource drivers

Code / resource pool	Typical eligible resource	Recommended resource driver
R01 Safety-management and coordination labor	Safety-manager time, task coordination, and documentation	Labor-hours by activity code
R02 Signal and spotter labor	Dedicated signaler, guide, and exclusion-zone observer	Person-hours per lift or control period
R03 Temporary safety facilities	Barriers, signs, guardrails, and temporary access protection	Quantity-days or area-hours
R04 PPE and safety consumables	Harness-related consumables, protective equipment, and fire-prevention supplies	Issue quantity, use-days, or exposure-hours
R05 Training and briefing	Induction, lift-specific TBM, special training, and rescue drill	Participant-hours and session count
R06 Communication and monitoring	Radio, wind meter, alarm, and eligible smart-safety equipment	Equipment-hours or monitored lift-hours
R07 Health, emergency, and rescue support	First aid, rescue readiness, and health-protection resources	Coverage-hours or worker-days

Code / resource pool	Typical eligible resource	Recommended resource driver
R08 Inspection and technical guidance	Rigging inspection, stability verification, and technical guidance	Inspection-hours and inspection count

Table 3 Modular-installation safety activities and causal drivers

Code	Safety activity	Resource pool	Resource driver	Activity driver
A01	Installation-safety planning and interface coordination	R01	Planning labor-hours	Installation day / work package
A02	Task risk assessment, toolbox meeting (TBM), and special briefing	R01/R05	Participant-hours	Crew / session
A03	Delivery-route, traffic, and laydown control	R02/R03	Person-hours; area-hours	Delivery / laydown period
A04	Module data, lifting point, rigging, and pre-lift inspection	R01/R08	Inspection-hours	Lift count
A05	Exclusion-zone establishment and access control	R02/R03	Person-hours; quantity-hours	Controlled lifting time
A06	Signal, guide, and communication control	R02/R06	Person-hours; equipment-hours	Lift-hours
A07	Wind and weather monitoring	R01/R06	Monitoring-hours	Lift-hours / weather event
A08	Fall prevention and safe access	R03/R04	Quantity-days; issue quantity	Worker-hours at height
A09	Landing, alignment, and pinch-point control	R02/R03	Person-hours; tool-use hours	Module count / alignment-hours
A10	Temporary stabilization and stability verification	R03/R08	Facility quantity; inspection-hours	Module count / verification count
A11	Permanent connection and hot-work safety	R03/R04/R07	Coverage-hours; consumable quantity	Connection points / hot-work hours
A12	Emergency, rescue, and health-protection readiness	R01/R07	Coverage-hours	Shift / worker-days
A13	Smart monitoring and safety-evidence capture	R06	Equipment-hours	Monitored lift-hours / alert count
A14	Post-installation inspection, closeout, and learning	R01/R08	Inspection-hours	Module / work-package closeout

Table 3 (continued) Activity owners, due points, and evidence

Code	Activity owner	Pre-work due point	Representative evidence
A01	Prime contractor	Before mobilization	Approved plan; coordination minutes
A02	Prime contractor	Before each shift or changed task	Attendance; briefing sheet; risk assessment
A03	Installation contractor	Before module entry	Route check; barrier photograph; guide attendance
A04	Lifting contractor	Before hook-up / ground departure	Rigging checklist; certificates; inspection photograph
A05	Installation contractor	Before lifting starts	Zone layout; barrier photograph; observer record
A06	Lifting contractor	Before and during each lift	Radio test; signal assignment; attendance
A07	Lifting contractor	Before and during lifting	Wind log; weather decision record
A08	Connection contractor	Before work at height	Guardrail/access photograph; PPE issue record
A09	Installation contractor	Before personnel enter the landing zone	Landing procedure; observer record; photograph
A10	Installation contractor	Before crane-load release	Brace record; stability checklist; release approval
A11	Connection contractor	Before and during connection	Permit; extinguisher photograph; fire-watch record
A12	Prime contractor	Before high-risk work begins	Emergency plan; rescue-equipment check
A13	Prime contractor	Before monitoring activation	Equipment log; alert history; data file
A14	Prime contractor	Before progress confirmation	Closeout checklist; corrective-action record

3.5 Internal-validation and management procedure

The framework was tested against eight requirements: legal-boundary consistency; conservation across resource, activity, and WP views; causal drivers; complete responsibility; pre-work timing; selective and monotonic response to controlled changes; complete traceability; and cross-validation against authoritative Korean and international sources. The numerical reference case used 20 modules and lifts, 12 lift-hours, 8 alignment-hours, 20 stability checks, 80 connection points, and five installation shifts. Eligible resource cost was normalized to 100.0 so the test addressed accounting behavior rather than field-calibrated rates.

Planning begins with eligible resources, forecast drivers, activity budgets, owners, and due points. Before each WP, the required activity bundle is checked for readiness. Actual workload and evidence are recorded during execution; material driver changes trigger selective recalculation; and settlement reconciles statutory vouchers with activity-coded records. Figures 4 and 5 summarize the procedure and common-code traceability chain.

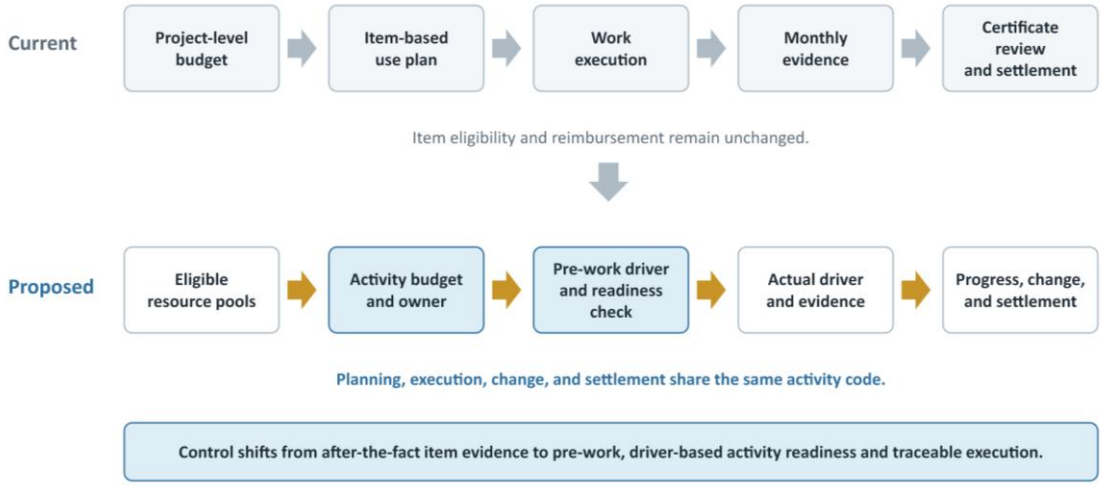


Fig. 4 Comparison of the current item-based and proposed ABC-based procedure

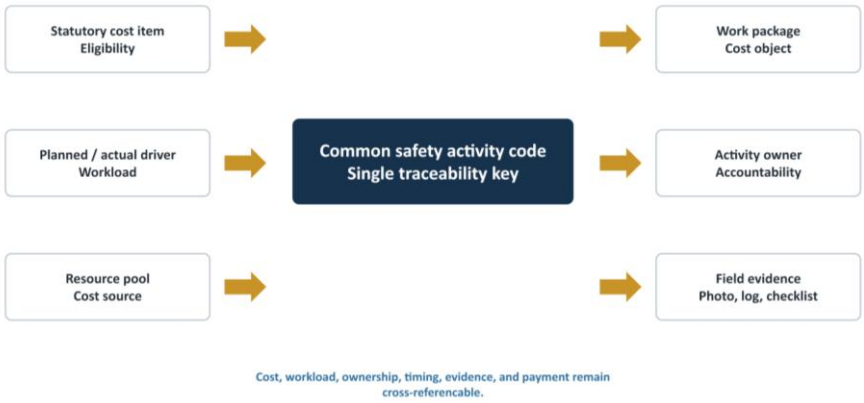


Fig. 5 Traceability using a common safety-activity code

4 Results

4.1 ABC application and safety-cost allocation changes

The baseline ABC application preserved the 100.0-unit eligible total and changed only its managerial representation: eight resource pools became fourteen activity costs and five WP totals. All activity costs were non-negative. The complete vector in Table 4 sums to 100.0; aggregation produced WP1 13.8, WP2 17.4, WP3 28.6, WP4 23.7, and WP5 16.5 (Table 5). Thus, ABC exposes consumption and accountability without creating or removing eligible cost.

Table 4 Normalized activity-cost vector

Code	Safety activity	Primary normalized driver	Baseline cost index
A01	Installation planning and coordination	Installation days	4.0
A02	Risk assessment, TBM, and briefing	Sessions / shifts	5.0
A03	Delivery-route and laydown control	Modules / deliveries	4.8
A04	Rigging and pre-lift inspection	Lift count	7.0

Code	Safety activity	Primary normalized driver	Baseline cost index
A05	Exclusion-zone and access control	Controlled lift-hours	8.0
A06	Signal and communication control	Lift-hours	12.0
A07	Wind and weather monitoring	Monitored lift-hours	4.0
A08	Fall prevention and safe access	Work-at-height units	7.0
A09	Landing and alignment control	Module count	12.0
A10	Temporary stabilization verification	Module count / checks	9.0
A11	Connection and hot-work safety	Connection points	10.0
A12	Emergency and rescue readiness	Shifts	6.0
A13	Smart monitoring and evidence capture	Monitored lift-hours	5.0
A14	Post-installation inspection and closeout	Module count	6.2
	Total		100.0

Table 5 Normalized allocation by work package

Work package	Allocated cost index	Dominant cost-causing activities	Primary activity owner
WP1 Arrival and laydown	13.8	A01 planning; A02 TBM; A03 route/laydown; A12 readiness	Prime / installation contractor
WP2 Rigging and pre-lift	17.4	A02 briefing; A04 inspection; A05 zone preparation; A06 communication check	Lifting contractor
WP3 Lifting and load transfer	28.6	A05 exclusion operation; A06 signal/communication; A07 monitoring; A12 readiness	Lifting contractor
WP4 Landing, alignment, and stabilization	23.7	A08 access; A09 pinch-point control; A10 stability verification	Installation contractor
WP5 Connection and release	16.5	A08 fall prevention; A11 connection/hot work; A14 closeout	Connection / prime contractor
Total	100.0	All A01-A14 activities	Prime contractor retains overall cost responsibility

The values are hypothetical and are not proposed allocation ratios. WP3 is largest only under the stated reference inputs; another project may produce a different distribution when duration, geometry, connections, shifts, resource prices, and work methods change.

4.2 Driver-change effects on safety-management cost

Four deterministic scenarios held activity rates fixed and changed only specified drivers. The recalculated total is C' = 100.0 + C_affected(m - 1), where C_affected is baseline cost linked to the affected set and m is the driver multiplier. Modules and proportional lift-hours +20% produced 113.6; lift-hours +50% produced 114.5; connections +50% produced 108.5; and shifts from five to six produced 102.2. In every case, unaffected activity cost changed by 0.0.

Table 6 Numerical driver-sensitivity results

Scenario	Affected baseline × driver multiplier	Recalculated total	Unaffected-cost change
S1 Modules and proportional lift-hours +20%	68.0 × 1.20	113.6	0.0
S2 Lift-hours +50%; module count fixed	29.0 × 1.50	114.5	0.0
S3 Connection points +50%	17.0 × 1.50	108.5	0.0
S4 Shifts 5 → 6	11.0 × 1.20	102.2	0.0

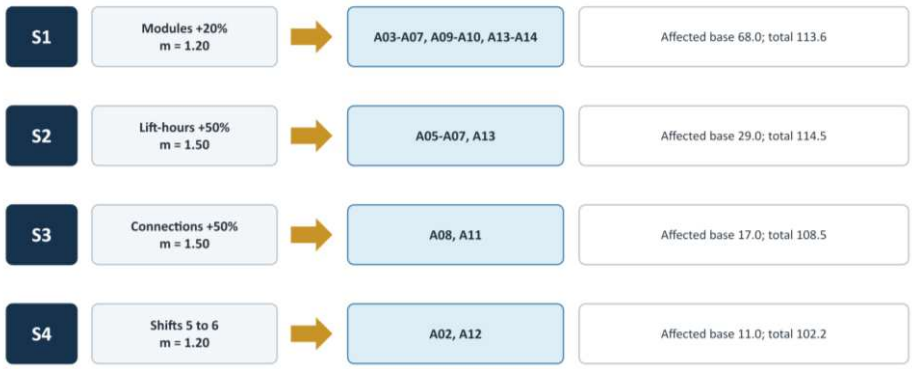


Fig. 6 Selective propagation in four controlled change scenarios

4.3 Changes in management criteria

Statutory appropriation, eligible purpose, proper use, evidence, and balance control remain unchanged. ABC adds causal workload, activity ownership, pre-work due points, planned-actual drivers, exception treatment, and activity-coded settlement. Management therefore shifts from asking only whether an item is eligible and evidenced to also asking which control required it, when it had to be ready, who prepared it, and why the amount changed.

Table 7 Current expenditure control and ABC activity management

Comparison criterion	Current item-based management	Proposed ABC activity-responsibility management	Expected managerial improvement
Primary management unit	Statutory cost item and project period	Safety activity and installation work package	Explains which control consumed the cost
Cost causality	Implicit or estimated after expenditure	Two-stage resource and activity drivers	Causal allocation and activity-rate analysis
Responsibility	Prime-contractor-level total responsibility	Overall responsibility plus one activity owner per activity	No gap in pre-work resource preparation
Execution timing	Monthly or progress-based use and evidence	Pre-work due point and RCR for each high-risk package	Links resource readiness to hazard exposure
Change management	Budget adjustment by item or period	Update only activities affected by changed drivers	Separates module, time, shift, and connection effects
Evidence	Invoices, receipts, attendance, and photographs in separate files	Common activity code links ledger, log, checklist, and photograph	Improved progress-payment and settlement traceability
CM review	Eligibility and expenditure-evidence review	Eligibility plus driver, owner, due point, and evidence consistency	Owner-representative oversight without replacing contractor duty
Legal boundary	Controlled by the statutory ledger	Same statutory ledger plus an eligibility gate	No expansion or duplicate charging of eligible scope

4.4 Internal-consistency results

Resource, activity, and WP totals were each 100.0, so absolute and relative reconciliation errors were 0.0. All fourteen activities had valid owner, due-point, and evidence fields (14/14 for each). Controlled increases were monotonic, remained within the intended activity sets, and left unrelated cost unchanged. Legal eligibility remained an upstream gate, and literature cross-validation supported constructs and driver logic without being used to claim empirical rates.

Table 8 Internal-validation criteria and results

Validation check	Acceptance rule	Numerical / documentary result	Interpretation
Legal-boundary gate	Only eligible, non-duplicate cost enters resource pools	8/8 resource pools retain statutory cross-reference	Project eligibility still checked case by case
Cost conservation	Resource = activity = work-package total	100.0 = 100.0 = 100.0; error 0.0	Pass
Non-negative allocation	No negative activity or work-package cost	14/14 activity costs > 0	Pass for reference case
Responsibility completeness	One owner for every activity	14/14 activities	100% schema completeness
Timing completeness	Due point precedes relevant	14/14 activities	100% schema completeness

Validation check	Acceptance rule	Numerical / documentary result	Interpretation
	transition		
Evidence completeness	At least one evidence key per activity	14/14 activities	100% schema completeness
Scenario monotonicity	Affected cost moves with driver increase	4/4 scenarios increased as specified	Pass
Scenario selectivity	Unaffected activity cost remains fixed	$\Delta = 0.0$ in 4/4 scenarios	Pass



Fig. 7 Analytical and numerical checks for internal model consistency

Together, the tests support internal accounting consistency, responsibility/timing/traceability completeness, and selective change sensitivity. They do not demonstrate typical field expenditure, statistical generalizability, accident reduction, cost savings, or an optimal allocation.

5 Discussion

5.1 Research significance

The academic contribution is the separation of legal admissibility from managerial causality. Statutory safety-cost studies usually address appropriation and eligible use, modular studies address hazards and controls, and ABC studies explain indirect-resource consumption. The dual-ledger structure links these streams while keeping the legal account intact and making its operational logic testable. The model also distinguishes conservation at fixed workload from selective budget change when a causal driver changes.

Practically, an activity code can link the legal item, resource pool, forecast and actual driver, owner, due point, voucher, labor or equipment record, inspection, photograph, and settlement entry. This allows the prime contractor and construction manager to review control readiness and exceptions without replacing specialist contractors' duties or the competent authority's eligibility determination. Implementation can be limited to an activity budget/responsibility sheet, a pre-work readiness check, a driver log, an activity-coded evidence register, and a reconciliation report.

5.2 Construction-management implications

For pre-work review, the framework converts a general question - whether enough safety cost has been appropriated - into a package-specific question: whether all required controls have an eligible resource, a funded activity budget, an accountable owner, and evidence of readiness before exposure. A construction manager can review this chain at the WP release point without approving the contractor's spending in place of the legally responsible party. Missing drivers or evidence are treated as exceptions, making the basis of review visible rather than embedding it in informal coordination.

For change management, the activity register separates scope growth from duration and price effects. Additional modules propagate to repeated rigging, lifting, landing, stabilization, and closeout activities; longer lifts affect time-driven signaling, exclusion-zone, monitoring, and supervision activities; added connection points affect

only connection-related controls; and additional shifts affect shift-based briefings and inspections. This selective logic supplies an auditable basis for revising a safety activity budget while preserving the statutory account total or documenting a justified project-level revision.

At settlement, the same code connects the original eligible item to forecast driver, actual driver, execution record, and voucher. The resulting audit trail does not make every field document a cost document; it demonstrates why a cost was required, when the associated control was performed, and whether the quantity claimed is consistent with recorded workload. This distinction is useful for identifying duplicate allocation, residual balances, missing closeout evidence, and unassigned responsibility.

5.3 Interpretation and limitations

The results should be interpreted in two layers. At fixed workload, ABC merely explains the same eligible total through activities and WPs. When a driver changes, only causally linked activity budgets change. This prevents general progress from redistributing every item and exposes whether a variance arose from quantity, duration, rate, or consumption. The additional criterion is control readiness: an eligible voucher is necessary, but it does not alone prove that the right resource was available before exposure.

The principal limitation is the normalized hypothetical case. It verifies equations, conservation, completeness, monotonicity, and selectivity but does not estimate actual rates, administrative burden, behavioral effects, or safety outcomes. Eligibility also depends on current rules, primary purpose, use conditions, and evidence. External validation should therefore use eligible ledger and voucher amounts together with modules, lifts, lift/alignment hours, stability checks, connection points, shifts, owners, due points, and evidence. Those data are not required for internal logic but are necessary for calibration and project comparison.

6 Conclusions

Korean OSHMC is controlled through statutory resource items, whereas modular installation is executed through short, interdependent activities and WPs. The proposed ABC framework retains the legal ledger and adds an eligibility gate, eight resource pools, fourteen activities, causal drivers, five WPs, owners, due points, and evidence links. In the normalized case, cost was conserved exactly (100.0 = 100.0 = 100.0), completeness was 14/14 for responsibility, timing, and evidence, and four scenarios changed only affected activities. The framework is therefore suitable as an internally consistent planning and control structure, not as empirical proof of field rates or safety effects. Actual modular-project data should next be used to calibrate rates and test external validity.

Data availability

The equations, normalized inputs, activity-cost vector, scenario multipliers, and results required to reproduce the internal checks are reported in this article. No project-level cost or personal data were used.

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