

Life Cycle Cost Structure of a High-Rise Office Building and Its Conceptual Integration with Digital Twin Technology

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Article Information	ABSTRACT
Article History Received : August 13, 2026 Revised : August 29, 2026 Published : October 02, 2026	Investment decisions for building projects remain dominated by initial construction cost, while operational, maintenance, and replacement costs accumulating over decades receive limited attention. This study analyses the life cycle cost (LCC) structure of a 27,288 m² high-rise office building over a 25-year service period and examines conceptually how digital twin technology could address the limitations of conventional LCC practice. Cost data were obtained from the building management unit and projected using annual escalation rates of 12% for operational and 10% for maintenance cost under a constant-currency approach. Initial cost accounts for only 21.8% of total LCC, operational cost 46.9%, and maintenance and replacement cost 31.3%, so post-occupancy expenditure represents 78.2% of total ownership cost. Energy (24.6%) and security (24.3%) dominate operational cost, while air conditioning (25.6%) and generator sets (20.4%) dominate maintenance and replacement cost. A conceptual framework is proposed in which digital twin capabilities transform LCC from a static design-stage estimate into a continuously updated decision instrument. The framework was neither implemented nor empirically validated. Because the analysis rests on a single case and projected costs, the proportions are context-specific, although sensitivity analysis confirms the dominance of post-occupancy cost is robust.
Keywords: <i>Digital Twin; Operational Cost; Life Cycle Cost.</i>	

INTRODUCTION

Buildings are long-lived capital assets whose economic performance cannot be judged from construction cost alone. The decision to procure a building commits its owner to several decades of expenditure on energy, cleaning, security, technical servicing and the periodic replacement of components that wear out long before the structure does. Despite this, investment appraisal in many developing construction markets remains anchored on the initial contract sum, because that figure is contractually visible, occurs early and is easily compared between bids. Future expenditure, by contrast, is diffuse, uncertain and often borne by a different organisational unit. The predictable consequence is a bias towards options that minimise capital outlay while transferring cost to the operational phase.

This bias has a physical expression. Where specification is reduced to lower the contract sum, equipment of shorter service life is installed, deterioration accelerates, and the frequency of repair and replacement rises across the service period. The saving realised at handover is therefore not a saving but a deferral, and frequently an amplification, of cost. Life cycle costing (LCC) was developed to make this transfer visible. It determines the total cost attributable to an asset over its whole life, including acquisition, operation, maintenance, renewal and disposal, so that alternatives may be compared on total ownership cost rather than first cost. The approach is codified internationally in ISO 15686-5.

The analytical importance of LCC is concentrated at the design stage. Once the structural system, envelope and mechanical and electrical strategy are fixed, most subsequent expenditure is effectively determined, even though little of it has yet been spent. This asymmetry between commitment and payment is the central argument for early LCC, and it has motivated work coupling cost modelling to digital design tools. Altaf et al. (2024) demonstrated BIM-integrated optimisation of life-cycle energy and cost for the building envelope; Fazeli et al. (2022) integrated BIM with multi-criteria decision analysis for component selection; and Ghadbhan Abed et al. (2022) reviewed machine-learning approaches to construction cost estimation.

Empirical studies consistently confirm the dominance of the post-occupancy phase, although reported proportions vary with building type, service density and horizon. Katić and Tadić (2023) analysed an office building and found capital cost at 42.6% and operation and maintenance at 57.4% over thirty years, the two becoming approximately equal only over twenty years. In Indonesia, Kaming et al. (2019) applied LCC to a training facility over twenty-five years and obtained 39.12% for initial cost, 44.61% for operational cost and 16.28% for maintenance and replacement. Islam et al. (2021) identified design-related factors driving maintenance cost, while Desbalo et al. (2024) proposed a conceptual framework for built-asset information management.

Conventional LCC practice nevertheless carries a structural limitation. It is typically performed once, near the design stage, and is deterministic. Service lives are taken from handbooks or supplier data, escalation is assumed constant, and maintenance is assumed to follow a fixed calendar. The resulting model is a projection made at a single moment and never subsequently corrected. Actual buildings deviate continuously, because equipment degrades at rates dependent on load, occupancy and maintenance quality. Part of the problem is informational: asset data generated during design and construction is rarely transferred to operations in usable form, a discontinuity documented by Abdelkarim et al. (2024) and Wijeratne et al. (2023).

Digital twin (DT) technology has emerged as a candidate remedy for this discontinuity. A digital twin is a virtual representation of a physical asset, synchronised with it through a continuous flow of data, that can monitor, diagnose, predict and simulate the behaviour of the asset. Sepasgozar (2021) set out the distinction between a digital model, in which no automatic data exchange exists; a digital shadow, in which data flows only from the physical to the virtual object; and a true digital twin, in which the flow is bidirectional. Opoku et al. (2021) reviewed digital twin applications across the construction industry, and Deng et al. (2021) traced the evolution from BIM to digital twins. Applications to building operation are documented by Hosamo et al. (2022), who developed a predictive maintenance framework for air handling units based on automatic fault detection; by Bouabdallaoui et al. (2021), who proposed a machine-learning framework for building installations; and by Hodavand et al. (2023). The field has been surveyed by Almatared et al. (2022) and Mousavi et al. (2024).

Although life cycle costing and digital twin research both address the operational phase, they have developed largely in parallel. LCC studies quantify where money goes but stop at the boundary of the cost model; digital twin studies demonstrate technical capability, most often on a single system, without asking whether that system is economically the one that matters most. What is missing is an analysis that begins from a measured cost structure and uses it to determine which capabilities offer the greatest economic leverage. This study therefore quantifies the twenty-five-year life cycle cost structure of a high-rise office building and, on that basis, constructs a conceptual framework linking its dominant cost drivers to specific digital twin capabilities. The objective is

explicitly not to test the effectiveness of a digital twin, nor to implement one on the building studied, but to use a measured cost structure to develop a conceptual framework that identifies where such technology would offer the greatest economic leverage and that can subsequently be tested empirically.

RESEARCH METHODS

This study adopts a descriptive quantitative approach based on a single case, with the individual cost categories treated as embedded units of analysis. The case-study design was selected because life cycle cost structure is meaningful only in relation to a specific building configuration, service level and management regime, and because the required data exist only at the level of an operating asset.

The object of analysis is a high-rise office building located in a metropolitan area of Indonesia. In accordance with a confidentiality undertaking, the building is not identified. Its relevant characteristics are a gross floor area of 27,288 m² across four basement levels, sixteen upper floors and a rooftop, a raft foundation, and a services configuration typical of a certified environmentally rated commercial tower, including centralised air conditioning, standby generation, sewage treatment and building automation. It is operated by a professional in-house management unit supported by outsourced vendors and occupied by multiple tenants under a full-service lease.

The analysis period was set at twenty-five years, consistent with the technical service life adopted by the building management unit and with comparable studies. The initial cost was recorded at Rp 170,000,000,000. Cost data were collected through structured field study and comprised payroll records for in-house and outsourced personnel, energy accounts, service contracts, and maintenance schedules and equipment inventories for each mechanical and electrical system.

The life cycle cost model follows the standard formulation in which total cost is the sum of initial, maintenance, operational and replacement components, less the residual value of the asset:

$$LCC = C + M + O + R - S \quad (1)$$

Where C is the initial cost expressed as a present cost, M the annual maintenance cost, O the annual operational cost comprising energy and personnel expenditure, R the annual cost of replacement and functional alteration, and S the salvage value. In this study S was set to zero, since no reliable estimate of residual value was available and disposal was not expected within the horizon considered. This slightly overstates net life cycle cost but does not affect the relative proportions between categories, which are the principal object of the analysis.

Because the components of Equation (1) are expressed on different time bases, present and future costs were converted to equivalent annual values using the standard discrete compounding relationships (Pujawan, 2009). A present cost is converted to an annual cost through the capital recovery factor:

$$A = \frac{P[i(1+i)^N]}{[(1+i)^N - 1]} = P\left(\frac{A}{P}, i\%, N\right) \quad (2)$$

a future cost is converted to an annual cost through the sinking fund factor:

$$A = \frac{F[i]}{[(1+i)^N - 1]} = F\left(\frac{A}{F}, i\%, N\right) \quad (3)$$

and a future cost is converted to a present cost through the single payment present worth factor:

$$P = \frac{F}{(1+i)^N} = F\left(\frac{P}{F}, i\%, N\right) \quad (4)$$

in which A denotes an annual cost, P a present cost, F a future cost, N the number of periods and i the annual interest rate.

Two escalation rates were applied to represent the real growth of the two dominant cost accounts rather than general price inflation. Operational cost was escalated at 12% per annum. Because personnel expenditure, and not energy, constitutes the larger part of that account, the rate was derived from the average annual growth of the statutory regional minimum wage in the province concerned over the period 2009–2016 (from Rp 908,824 to Rp 1,494,000, equivalent to an average of about 12% per annum), a policy-driven trajectory that is the principal determinant of the building's labour cost and that consistently exceeded general consumer-price inflation over that period. Maintenance and replacement cost was escalated at 10% per annum, a rate set above the prevailing time-deposit rate so that the projection would not understate the real cost of deferring the renewal of ageing mechanical and electrical equipment. Following the constant-currency convention, general price inflation was not modelled separately, so both figures are interpreted as real escalation over and above inflation. Because these rates exert a substantial influence on the twenty-five-year result, their effect, together with that of the other principal assumptions, is examined explicitly through the sensitivity analysis described below.

To establish how far the results depend on these assumptions, a one-way (*ceteris paribus*) sensitivity analysis was carried out. Each of the parameters identified as most influential was varied in turn across a plausible range while all others were held at their base values, and the total life cycle cost and the resulting initial-cost and post-occupancy shares were recomputed. The parameters examined were the operational escalation rate (6–18% per annum), the maintenance and replacement escalation rate (4–16% per annum), a real discount rate applied to the projected cash flows (0–10% per annum), the effective service life of the dominant mechanical and electrical components (represented as a $\pm 20\%$ change in accumulated replacement cost), and the asset residual value (0–20% of initial cost). This procedure allows the stability of the study's central conclusion to be assessed against the range of inputs that could reasonably have been chosen.

The cost breakdown structure distinguished six operational categories, namely building management personnel, engineering personnel, security, housekeeping, office services and energy, and eleven maintenance and replacement categories corresponding to the principal building systems. For each category the annual cost was projected across the horizon and accumulated, and the totals were expressed as proportions and ranked to identify the concentration of expenditure.

Finally, the conceptual component was developed by narrative synthesis. The cost categories found to dominate the empirical result were mapped against digital twin capabilities reported in the reviewed literature, and organised into a three-layer framework comprising a physical layer, a digital twin layer and a decision layer. This component is analytical rather than experimental, no digital twin was implemented, and the framework is offered as a structured hypothesis for subsequent testing.

RESULTS AND DISCUSSION

Composition of Life Cycle Cost

Over the twenty-five-year period the total life cycle cost of the building amounted to Rp 780.71 billion. Table 1 sets out its composition across the three principal categories.

Table 1. Life cycle cost composition of the building over 25 years

Cost category	Amount (Rp bn)	Share (%)
Initial cost	170.00	21.8
Operational cost	366.13	46.9
Maintenance and replacement	244.57	31.3
Total life cycle cost	780.71	100.0

Source: analysis of building management data

represents only 21.8% of total ownership cost, whereas operational and maintenance costs together account for 78.2%. Every rupiah invested in constructing the building is therefore associated with approximately 3.6 rupiah of subsequent expenditure over the following quarter century. Normalised by floor area, total life cycle cost corresponds to roughly Rp 28.6 million per square metre, or about Rp 1.14 million per square metre per year.

This result is directionally consistent with the literature but more extreme in degree. Katić and Tadić (2023) reported a capital share of 42.6% over thirty years, and Kaming et al. (2019) obtained 39.12% over twenty-five years. The lower capital share observed here reflects several characteristics of the case. The building is a multi-tenant commercial tower under a full-service lease, requiring continuous security, housekeeping and technical presence at a service level well above that of an institutional facility. The escalation rate applied reflects a period of rapid statutory wage growth and compounds the labour-intensive service model. Salvage value was also excluded. The comparison is shown in Figure 1.

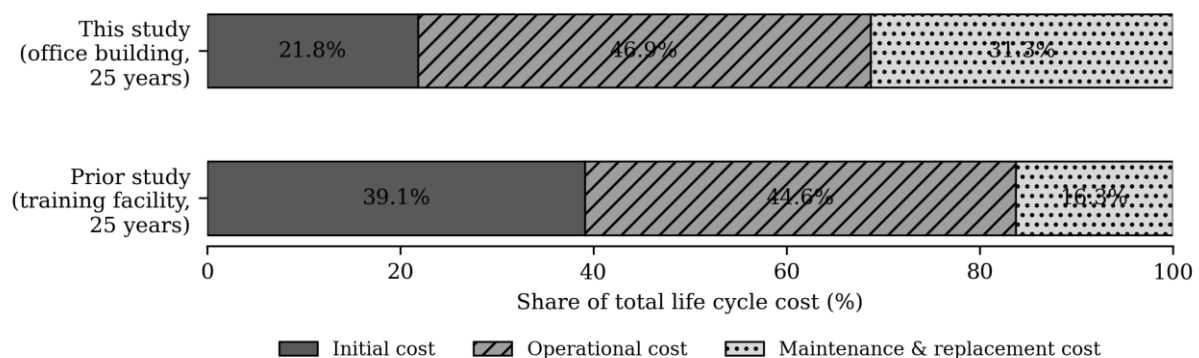


Figure 1. Comparison of life cycle cost composition with a reference study

The practical significance is that the economic identity of this building is determined in operation rather than in construction. A design decision reducing the contract sum by one per cent saves approximately Rp 1.7 billion; a management decision reducing recurrent expenditure by one per cent saves approximately Rp 6.1 billion over the same horizon. Any framework seeking to control the cost of such an asset must therefore act primarily on the operational and maintenance accounts, and must continue acting throughout the service life rather than terminating at handover.

Structure of Operational Cost

Table 2 disaggregates the operational account into its six constituent categories, accumulated across the analysis period.

Table 2. Structure of operational cost over 25 years

Operational category	Amount (Rp bn)	Share (%)
Energy	90.00	24.6
Security	89.04	24.3
Office services	60.10	16.4
Housekeeping	53.02	14.5
Engineering personnel	39.18	10.7
Building management personnel	34.80	9.5
Total operational cost	366.13	100.0

Source: analysis of building management data

Energy is the largest single operational item at 24.6%, consistent with the general finding that energy dominates the running cost of commercial buildings. The more striking feature of Table 2, however, is that the five remaining categories are all personnel-based and together account for 75.4% of operational expenditure, with security alone almost equal to the entire energy account.

The operational cost of this building is therefore first of all a labour cost, governed by wage policy at least as much as by tariff policy or technical efficiency.

This has an important implication for cost-control interventions. Technical measures directed exclusively at energy efficiency address only about a quarter of the operational account, whereas a measure that improves the productivity of deployed personnel acts on a base three times larger. This observation is rarely foregrounded in the digital twin literature, which has concentrated on energy and equipment, and it identifies a substantial and largely unexploited application domain.

Structure of Maintenance and Replacement Cost

Table 3 presents the maintenance and replacement account disaggregated by building system.

Table 3. Structure of maintenance and replacement cost over 25 years

Building system	Amount (Rp bn)	Share (%)
Air conditioning	62.63	25.6
Generator set	49.90	20.4
Electrical main equipment	31.23	12.8
Vertical transportation	30.09	12.3
Electronic systems	25.95	10.6
Sewage treatment plant	17.70	7.2
Architectural and lot works	11.80	4.8
Consumable parts	6.92	2.8
Outsourcing	4.87	2.0
Fire fighting	1.77	0.7
Plumbing and drainage	1.72	0.7
Total maintenance and replacement	244.57	100.0

Source: analysis of building management data

The distribution is strongly concentrated. Air conditioning and the generator set together account for 46.0% of the account, and the four largest systems, adding electrical main equipment and vertical transportation, account for 71.1%. At the opposite end, plumbing, drainage and fire fighting together represent 1.4%, and architectural works, which typically attract the greatest attention during design review, account for only 4.8%. Mechanical, electrical and electronic systems collectively govern the renewal account, consistent with the observation that the durable structure of a building outlives its services by a wide margin.

Read together with Table 2, the two accounts identify a small set of systems that jointly determine long-run cost, the air conditioning plant, which is both the largest renewal item and the principal consumer of energy; standby generation and electrical distribution; vertical transportation; and the deployment of service personnel. These are the points at which monitoring or optimisation will have the greatest economic leverage, and they define the scope of the framework developed below.

Sensitivity of the Cost Structure

Because the twenty-five-year projection rests on assumed escalation rates and other parameters that cannot be observed in advance, a one-way sensitivity analysis was performed to establish how far the central finding depends on those assumptions. Each parameter was varied across a plausible range while the others were held at their base values. The results are summarised in Table 4.

Tabel 4. Sensitivity of the 25-year life cycle cost result to key parameters

Parameter	Range tested	Total LCC (Rp bn)	Post-occupancy share (%)
Operational escalation rate	6–18% p.a.	672.7 – 888.7	74.7 – 80.9
Maintenance escalation rate	4–16% p.a.	700.7 – 860.7	75.7 – 80.2
Real discount rate	0–10% p.a.	780.7 – 343.7	78.2 – 50.5
Component service life	–20% – +20%	731.8 – 829.6	76.8 – 79.5
Residual value	0–20% of C	780.7 – 746.7	78.2 – 77.2

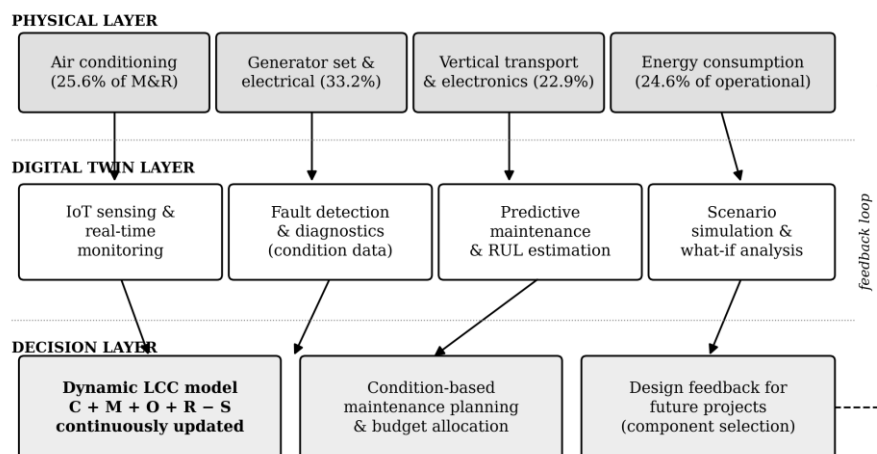
Note: base case total LCC Rp 780.71 billion, initial-cost share 21.8%, post-occupancy share 78.2%. Source: authors' analysis.

The central conclusion, that post-occupancy expenditure dominates total ownership cost, is robust. Varying the operational escalation rate across the wide range of 6% to 18% per annum moves the post-occupancy share only between 74.7% and 80.9%, and varying the maintenance and replacement escalation rate between 4% and 16% moves it between 75.7% and 80.2%. Shortening or extending the effective service life of the dominant mechanical and electrical systems by twenty per cent, and introducing a residual value of up to twenty per cent of initial cost, likewise leave the post-occupancy share above three-quarters. The single parameter capable of materially altering the conclusion is the real discount rate. Under the constant-currency framework adopted here no separate discounting is applied; but if a real discount rate is imposed, the present value of future expenditure falls sharply, so that at 8% per annum the initial-cost share rises to 44.3% and at 10% the post-occupancy share falls to 50.5%. The dominance reported in this study should therefore be understood as a statement about undiscounted, constant-currency ownership cost: it holds under any modest real discount rate but would weaken if a high real rate were considered appropriate. This also shows that, while the escalation rates influence the absolute magnitude of cost, they do not threaten the qualitative result on which the proposed framework is based.

Conceptual Integration with Digital Twin Technology

The cost structure established above was produced by a conventional life cycle cost model and inherits its limitations. Service lives were taken from supplier and management estimates rather than observed degradation; maintenance was assumed to occur on a fixed calendar irrespective of actual condition; escalation was assumed constant across twenty-five years; and energy consumption was treated as a flat charge rather than a variable driven by occupancy, weather and equipment condition. Each assumption is a point at which projection and reality can be expected to diverge, and none is self-correcting.

Digital twin technology addresses these limitations at the level of their common cause, which is the absence of a return channel from the operating asset to the cost model. Following Sepasgozar (2021), what is required is not a digital model or a digital shadow but a genuine twin, in which information flows in both directions. Figure 2 presents the resulting conceptual framework, organised in three layers.

**Figure 2.** Conceptual framework for digital twin-enabled life cycle costing

The physical layer comprises the cost-dominant systems identified in Tables 2 and 3. Restricting the framework to these systems is deliberate, instrumentation is not free, and a twin monitoring every component equally would allocate its own cost inversely to the economic importance of what it observes.

The digital twin layer comprises four capabilities. Real-time sensing replaces assumed operating profiles with measured ones, so that energy consumption is known as a function of occupancy and equipment state. Fault detection and diagnostics identifies deviation from expected performance and attributes it to a component; Hosamo et al. (2022) demonstrated this for air handling units, combining building information models, sensor networks and facility management data, and reported appreciable annual energy savings from removing detected faults. Predictive maintenance converts condition data into an estimate of remaining useful life, allowing intervention to be scheduled by need rather than by calendar, as set out by Bouabdallaoui et al. (2021), Mi et al. (2021) and Hodavand et al. (2023). Scenario simulation permits alternative interventions to be evaluated before commitment.

The decision layer is where the economic contribution is realised. Its central element is a dynamic life cycle cost model in which the terms of Equation (1) are continuously updated from observed data rather than fixed at design. The maintenance term M becomes the accumulation of interventions actually triggered by condition; the operational term O derives from metered consumption and staffing actually deployed; and the replacement term R is governed by estimated remaining useful life. The second element translates these estimates into condition-based maintenance planning and budget allocation, directing resources towards the four systems that determine seventy-one per cent of the renewal account. The third closes the loop back to design, supplying evidence on realised component cost to inform selection in subsequent projects, as anticipated by Altaf et al. (2024) and Fazeli et al. (2022).

The framework also extends digital twin capability into the personnel domain, which the empirical result identifies as the largest element of operational cost. Occupancy and utilisation data captured by the twin can support the deployment of security, housekeeping and office personnel according to observed demand by zone and time of day, rather than fixed shift patterns. Because personnel account for 75.4% of the operational account, modest gains in deployment efficiency would be economically comparable to substantial gains in energy efficiency.

Two qualifications are necessary. First, the benefit of a digital twin is contingent on data that most existing buildings do not possess in usable form: asset registers are incomplete, sensor coverage is partial, and information generated during design and construction is often lost at handover, as Abdelkarim et al. (2024) and Wijeratne et al. (2023) documented. Second, the cost of instrumentation, integration and the required skills must itself enter the calculation. Reviews by Deng et al. (2021), Almatared et al. (2022) and Mousavi et al. (2024) identify interoperability, data quality, standardisation and cost as binding constraints, and note that many implementations described as digital twins operate only as digital shadows.

Implications and Limitations

Three implications follow for practice. Procurement evaluation for mechanical and electrical packages should be conducted on a life cycle rather than a first cost basis, since these systems govern the renewal account while representing a much smaller share of the contract sum. Owners should specify the transfer of structured asset information at handover as a contractual deliverable. Long-range budgeting should be constructed around the concentration revealed in Table 3, with renewal reserves accumulated against the service lives of the four dominant systems.

The study has several limitations. It rests on a single case, and its proportions should not be generalised without adjustment. Salvage value was excluded, and its inclusion would reduce net life cycle cost by an amount not estimated here. Escalation was applied linearly rather than compounded, which renders the reported dominance of operational cost conservative. The cost figures are projections rather than observed outcomes. Most importantly, the digital twin component is conceptual, no twin was implemented, and no empirical measurement of cost reduction was undertaken. As shown by the sensitivity analysis in Table 4, however, the finding

that post-occupancy expenditure dominates total ownership cost is robust to plausible variation in the escalation rates, component service life and residual value, and is sensitive only to the choice of real discount rate, to which the constant-currency framework adopted here is deliberately agnostic.

CONCLUSION

This study quantified the twenty-five-year life cycle cost structure of a high-rise office building and used the result to construct a conceptual framework linking the dominant cost drivers to digital twin capabilities. Total life cycle cost amounted to Rp 780.71 billion, of which initial cost represented 21.8%, operational cost 46.9% and maintenance and replacement cost 31.3%. Post-occupancy expenditure therefore accounted for 78.2% of total ownership cost, approximately 3.6 times the initial investment.

Within the operational account, energy was the largest single item at 24.6%, but personnel categories together accounted for 75.4%, with security alone at 24.3%. Within the maintenance and replacement account, air conditioning and generator sets together represented 46.0% and the four largest systems 71.1%, while architectural works accounted for only 4.8%.

On this basis a three-layer conceptual framework was proposed in which real-time monitoring, fault detection, predictive maintenance and scenario simulation are applied selectively to the cost-dominant systems, feeding a dynamic life cycle cost model, condition-based maintenance planning and a feedback channel to design. The contribution of the framework is to reverse the customary order of reasoning, rather than asking what a digital twin can technically monitor, it asks what the cost structure indicates should be monitored, and it identifies the deployment of service personnel as an economically significant and largely neglected application domain. Subsequent research should implement and validate the framework on an operating asset, incorporating the cost of the twin within the calculation.

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REFERENCES

- Abdelkarim, S. B., Ahmad, A. M., & Naji, K. (2024). A BIM-based framework for managing handover information loss. *Journal of Management in Engineering*, 40(5). <https://doi.org/10.1061/JMENEAE.MEENG-5623>
- Almatared, M., Liu, H., Tang, S., Sulaiman, M., Lei, Z., & Li, H. X. (2022). Digital twin in the architecture, engineering, and construction industry: A bibliometric review. In *Construction Research Congress 2022* (pp. 670–678). American Society of Civil Engineers. <https://doi.org/10.1061/9780784483961.070>
- Altaf, M., Alalaoul, W. S., Musarat, M. A., Abdelaziz, A. A., & Thaheem, M. J. (2024). Optimisation of energy and life cycle costs via building envelope: A BIM approach. *Environment, Development and Sustainability*, 26(3). <https://doi.org/10.1007/s10668-023-03001-w>
- Bouabdallaoui, Y., Lafhaj, Z., Yim, P., Ducoulombier, L., & Bennadji, B. (2021). Predictive maintenance in building facilities: A machine learning-based approach. *Sensors*, 21(4), 1044. <https://doi.org/10.3390/s21041044>
- Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of*

- Information Technology in Construction, 26, 58–83.
<https://doi.org/10.36680/j.itcon.2021.005>
- Dong, K., & Moshood, T. D. (2026). Digital twins across the asset lifecycle: Technical, organisational, economic, and regulatory challenges. *Buildings*, 16(5), 1084.
<https://doi.org/10.3390/buildings16051084>
- Desbalo, M. T., Woldesenbet, A. K., Habtu, T. M., Bargstädt, H.-J., & Yehualaw, M. D. (2024). BIM-enabled built-asset information management conceptual framework: A case of public university buildings in Addis Ababa, Ethiopia. *Heliyon*, 10(12), e33026.
<https://doi.org/10.1016/j.heliyon.2024.e33026>
- Fazeli, A., Jalaei, F., Khanzadi, M., & Banihashemi, S. (2022). BIM-integrated TOPSIS-Fuzzy framework to optimize selection of sustainable building components. *International Journal of Construction Management*, 22(7), 1240–1259.
<https://doi.org/10.1080/15623599.2019.1686836>
- Ghadbhan Abed, Y., Hasan, T. M., & Zehawi, R. N. (2022). Machine learning algorithms for constructions cost prediction: A systematic review. *International Journal of Nonlinear Analysis and Applications*, 13(2), 2205–2218.
<https://doi.org/10.22075/ijnaa.2022.27673.3684>
- Hodavand, F., Ramaji, I. J., & Sadeghi, N. (2023). Digital twin for fault detection and diagnosis of building operations: A systematic review. *Buildings*, 13(6), 1426.
<https://doi.org/10.3390/buildings13061426>
- Hosamo, H. H., Svennevig, P. R., Svidt, K., Han, D., & Nielsen, H. K. (2022). A digital twin predictive maintenance framework of air handling units based on automatic fault detection and diagnostics. *Energy and Buildings*, 261, 111988.
<https://doi.org/10.1016/j.enbuild.2022.111988>
- International Organization for Standardization. (2017). ISO 15686-5:2017 Buildings and constructed assets – Service life planning – Part 5: Life-cycle costing. ISO.
<https://www.iso.org/standard/61148.html>
- Islam, R., Nazifa, T. H., Mohammed, S. F., Zishan, M. A., Yusof, Z. M., & Mong, S. G. (2021). Impacts of design deficiencies on maintenance cost of high-rise residential buildings and mitigation measures. *Journal of Building Engineering*, 39, 102215.
<https://doi.org/10.1016/j.jobe.2021.102215>
- Mi, S., Feng, Y., Zheng, H., Wang, Y., Gao, Y., & Tan, J. (2021). Prediction maintenance integrated decision-making approach supported by digital twin-driven cooperative awareness and interconnection framework. *Journal of Manufacturing Systems*, 58, 329–345.
<https://doi.org/10.1016/j.jmsy.2020.08.001>
- Mousavi, Y., Gharineiat, Z., Karimi, A. A., McDougall, K., Rossi, A., & Gonizzi Barsanti, S. (2024). Digital twin technology in built environment: A review of applications, capabilities and challenges. *Smart Cities*, 7(5), 2594–2615.
<https://doi.org/10.3390/smartcities7050101>
- Nguyen, T. D., & Adhikari, S. (2026). Advancing digital twins for building lifecycle management in construction: A systematic literature review. *Buildings*, 16(6), 1151.
<https://doi.org/10.3390/buildings16061151>
- Opoku, D.-G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, 40, 102726.
<https://doi.org/10.1016/j.jobe.2021.102726>
- Pujawan, I. N. (2009). *Ekonomi teknik* (2nd ed.). Guna Widya.
- Sepasgozar, S. M. E. (2021). Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings*, 11(4), 151.
<https://doi.org/10.3390/buildings11040151>
- Wijeratne, P. U., Gunarathna, C., Yang, R. J., Wu, P., & Hampson, K. (2023). BIM enabler for facilities management: A review of 33 cases. *International Journal of Construction Management*. <https://doi.org/10.1080/15623599.2023.2222962>