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FROM BIM 6D/7D TO OPERATIONAL DIGITAL TWINS: CLOSING THE BUILDING ENERGY PERFORMANCE GAP IN TROPICAL BUILDINGS- A MIXED-METHODS STUDY IN SRI LANKA

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ABSTRACT

Buildings and construction are major drivers of global energy demand and energy-related CO_2 emissions, yet operational energy use often diverges from design predictions, creating an energy performance gap (EPG). Building Information Modelling (BIM) has expanded toward lifecycle use, including BIM 6D for energy and sustainability analysis and BIM 7D for facilities management. However, many organisations still struggle to translate design intent into operational outcomes because of poor as-built information, BIM–building energy modelling interoperability issues, weak commissioning-to-operations handover, and fragmented building management system data. Operational digital twins (DTs) are increasingly promoted as a means to connect design and operation by linking information models to real-time data, analytics, and feedback loops. This study develops an expert-validated Sri Lanka-specific framework for integrating BIM 6D/7D with operational DTs to reduce the EPG in tropical buildings. An exploratory sequential mixed-methods design was used. Phase 1 combined policy review and semi-structured interviews with 20 Sri Lankan building lifecycle experts. Phase 2 used a two-round Delphi study with 48 panellists to validate and prioritize 20 statements on barriers and critical success factors, analysed using consensus statistics and the Relative Importance Index. The main barriers are unverified as-built BIM/asset data, BIM–BEM interoperability problems, and insufficient commissioning and controls tuning. The top success factors are capturing control sequences and commissioning evidence, publishing energy-focused digital information requirements for BIM-to-operations continuity, and standardizing asset tagging and FM handover templates. The paper proposes a lifecycle digital thread-to-twin framework and implementation roadmap tailored to tropical buildings and developing-country delivery contexts.

Keywords: *Building Energy Performance Gap; Building Information Modelling (BIM); Operational Digital Twins; Sri Lanka; Tropical Buildings.*

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1. INTRODUCTION

The building and construction sector is central to global energy and climate outcomes, accounting for around 34% of final energy demand and 37% of energy-related CO_2 emissions in 2023 (Ozcan-Deniz & Rodovalho, 2024). Improving operational building performance is therefore a core lever for decarbonisation and energy security. A persistent obstacle is the energy performance gap (EPG), the difference between predicted performance (from compliance calculations or simulations) and measured operational use (Forth & Borrmann, 2024). The EPG undermines confidence in modelling, reduces realised policy and investment benefits, increases operating costs, and, in developing countries with supply constraints and rising cooling demand, contributes to grid stress (Cheng & Das, 2014). Recent work frames the EPG as a lifecycle socio-technical problem arising from modelling assumptions, delivery and installation defects, commissioning and controls practices, maintenance, and occupant-organisation behaviour (Sha & Zhang, 2024), with even well-designed systems drifting into inefficiency over time.

Building Information Modelling (BIM) has expanded beyond geometry to include sustainability and lifecycle information. BIM 6D supports design-stage energy analysis, while BIM 7D targets facilities management (FM), asset registers, and lifecycle O&M. However, BIM 6D/7D outputs often fail to influence operations: simulations are done for approvals and then archived; as-built info is incomplete or late; FM teams revert to spreadsheets; and interoperability issues and poor workflow alignment persist (Kurniawan et al., 2023; Rashwan et al., 2023). Operational digital twins (DTs) are promoted as a bridge between design and operation by linking BIM models with live building management system (BMS)/Internet of Things (IoT) data for monitoring, fault detection and diagnostics (FDD), commissioning, and feedback (Altaf et al., 2024; Choi & Lee, 2023). In this study, an operational DT is more than a BIM-linked dashboard: live data must update the model and support diagnosis, learning, and corrective action; otherwise, it remains a visualisation rather than an operational tool.

This study focuses on Sri Lanka because tropical, cooling-dominated buildings are especially sensitive to heating, ventilation, and air-conditioning (HVAC) operation, humidity control, commissioning quality, and maintenance drift, all of which directly affect the EPG. Although the 2020 Energy Efficiency Building Code addresses large buildings and emphasizes HVAC and controls, lifecycle digitalisation remains uneven because O&M budgets are limited, digital requirements are fragmented, post-occupancy verification is sparse, and analytics capability is patchy. There is no consensus-based, expert-validated framework for operationalising BIM 6D/7D with DTs in tropical, developing-country contexts. Accordingly, the study aims to develop an expert-validated framework for integrating BIM 6D/7D with operational DTs to reduce the EPG in Sri Lankan tropical buildings. The study addresses five research questions: (1) policy and institutional factors for energy efficiency and digitalisation; (2) current BIM 6D/7D practices and their limitations; (3) barriers and enablers to BIM 6D/7D–DT integration across the lifecycle; (4) critical success factors and governance needed to reduce EPG using BIM-enabled DTs; and (5) which factors achieve expert consensus and priority via Delphi. The remainder of the paper reviews the literature, explains the mixed-methods design, presents the qualitative and Delphi findings, discusses Sri Lanka-specific and transferable implications, and concludes with the framework, limitations, and future research.

2. LITERATURE REVIEW AND CONCEPTUAL FRAMING

2.1 EPG AS A LIFECYCLE PROBLEM

The EPG is commonly defined as the difference between predicted energy use or intensity (e.g., kWh/m²·year) and measured operational energy use. It can be expressed as an absolute difference or ratio:

$$EPG\ ratio = \frac{E\ actual}{E\ predicted}$$

$$EPG\ diff = E\ actual - E\ predicted$$

Recent reviews indicate the EPG is caused by multiple, lifecycle-driven factors, including modelling assumptions (weather, loads, schedules, control strategies, calibration); delivery issues (tolerances, substitutions, installation defects); commissioning and controls (incomplete testing, poorly tuned setpoints/sequences, weak trend checks); operations (maintenance deferral, sensor drift, overrides, organisational practices); and occupant or organisational changes diverging from modelled schedules (Al-Rudainy & Mahjoob, 2024; Qi, 2024). These factors interact: poor commissioning can push systems outside control bounds and increase modelling uncertainty, while strong, ongoing commissioning can limit drift and reduce the EPG even with imperfect models.

2.2 BIM 6D AND ENERGY ANALYSIS

BIM-based energy workflows enable early evaluation of design concepts, support performance-informed decisions, and reduce late changes. However, interoperability barriers persist due to geometry translation errors, inconsistent definitions, incomplete metadata, and divergent modelling paradigms between BIM and simulation tools. Exchange requirements are often implicit and lack quality assurance, leading to manual corrections and limited scalability (Sadeghifam et al., 2016). This drives a shift from "export-and-fix" approaches to managed interoperability with contractual rules, test cases, and quality checks at specific stages.

2.3 BIM 7D AND FACILITIES MANAGEMENT

The operations phase, the longest lifecycle stage, accounts for the majority of costs and emissions. BIM 7D supports FM by integrating asset data with maintenance workflows. Adoption barriers include incomplete models, limited FM tools and skills, and misaligned BIM and FM/BMS workflows (Ghoneim et al., 2025). The handover issue involves incentives and information: contractors may not invest in high-quality data without contractual and verification requirements, and owners may lack the resources or capabilities to maintain digital assets, leading to "information waste" when BIM models remain unused.

2.4 DIGITAL TWINS AND OPERATIONAL ENERGY

Digital twins (DTs) now extend from manufacturing to buildings, serving as virtual counterparts of physical assets through sensing, data integration, and analytics. Built-environment DTs consist of: (i) a physical layer with assets and sensors; (ii) a data layer with BMS/IoT interfaces and databases; (iii) a semantic/modelling layer from BIM models; and (iv) an analytics layer for FDD, optimization, and prediction (Abouelkhier et al., 2025). Energy-focused DTs enable real-time monitoring, fault detection, commissioning, retrofit simulations, and control optimization. DT value relies on data availability and governance: asset identities, sensing accuracy, and actionable workflows. Without these, DTs risk becoming static visualizations with limited energy impact.

2.5 FROM DIGITAL TWIN TO OPERATIONAL DIGITAL TWIN: CLOSING LOOPS

Not all digital twin implementations are the same. Static BIM provides geometry and structured asset information but no live operational feedback. BIM-linked dashboards display live data against spaces or assets, but they do not necessarily diagnose faults or trigger action. In this study, an operational DT closes three loops: a sensing loop that updates the model with time-series data; an inference loop that diagnoses faults or predicts performance; and an action loop that supports or triggers corrective intervention. Closing these loops requires both technical integration and organisational readiness, which is why data quality, governance, and staged maturity are central to the framework.

2.6 DIGITAL THREAD, INTEROPERABILITY, AND GOVERNANCE

BIM–DT integration is seen as creating a “digital thread”: a traceable info chain linking design, delivery, and operation, allowing data to connect to models of spaces, systems, and assets. ISO 19650 principles guide lifecycle info management, including operations and maintenance (Al-Rudainy & Mahjoob, 2024). ISO-aligned processes (requirements, data environments, roles, approvals) help ensure energy data is retained at handover. Integration demands semantic interoperability: operational systems use point tags and vendor names, whereas BIM models represent hierarchies and spatial relationships. Successful scaling depends on mapping strategies and governance that withstand changes in tools and vendor boundaries.

2.7 TROPICAL OPERATIONAL CONTEXT

Tropical buildings focus on cooling in high-humidity environments, increasing latent cooling requirements. Control settings such as setpoints, ventilation, and dehumidification affect energy use. Sri Lanka’s building code covers HVAC, insulation, and controls, including measures to prevent condensation in chilled water and ducts (Perera et al., 2022). In tropical buildings, however, the EPG is often amplified by latent loads, sensor drift, ventilation imbalance, unstable chilled-water temperatures, poor dehumidification control, and control overrides after handover. These conditions make commissioning continuity and post-occupancy tuning especially important in hotels, hospitals, universities, and other variable-occupancy buildings. In developing-country settings, these risks are compounded by incomplete asset data, fragmented digital requirements, limited analytics capability, and weak governance, which helps explain why many BIM/DT initiatives fail to close the EPG in practice.

2.8 CONCEPTUAL PROPOSITION

Drawing on this literature, the study proposes that EPG reduction in tropical buildings depends on linking BIM 6D energy intent, BIM 7D operational information, and operational DT feedback loops through four conditions: verified asset and as-built data, BIM–BEM interoperability, commissioning-to-operations continuity, and lifecycle governance. Figure 1 later operationalises this conceptual grounding into the Tropical Digital Thread-to-Twin Energy Governance framework.

3. METHODOLOGY

3.1 RESEARCH DESIGN

An exploratory sequential mixed-methods design was used because the topic is complex, under-standardized, and strongly shaped by context and professional practice. Qualitative exploration was first conducted to identify locally relevant barriers and enablers, after which Delphi was used to test expert consensus, prioritize factors, and refine the framework transparently.

3.2 PHASE 1: DOCUMENT ANALYSIS

Documents selected to reflect national policies on building energy performance and lifecycle info include (i) Sri Lanka's Energy Efficiency Building Code (2020); (ii) the Sri Lanka Sustainable Energy Authority Act (2007); and (iii) energy policy and guidance emphasizing efficiency and conservation. They were coded for focus on design-stage versus operational verification, accountability mechanisms, and digital requirements or gaps for FM and energy monitoring.

3.3 PHASE 1: SEMI-STRUCTURED INTERVIEWS

3.3.1 Sampling and Participants

Purposive sampling involved 20 experts across the building lifecycle, including BIM managers/consultants (5), policymakers/regulators (4), facility managers (3), architects (2), MEP/energy engineers (1), energy auditors/ESCOs (2), technology integrators (2), and academics/researchers (1), averaging 14.1 years of experience (Table 1).

3.3.2 Data Collection

Interviews followed a semi-structured protocol on EPG manifestations in Sri Lanka's tropical buildings, BIM 6D practices, BIM–BEM workflows, BIM 7D/FM handover, DT awareness and readiness, governance, procurement, and skills. All were anonymized and de-identified, with participants giving informed consent.

3.3.3 Qualitative Analysis

Interview transcripts were analysed using thematic analysis through familiarisation, coding, theme development, review, and refinement, and were triangulated with the findings from document analysis. Coding proceeded iteratively until successive interviews yielded no materially new themes and the coding frame stabilized. The resulting themes were then consolidated into lifecycle barriers, enablers, and candidate Delphi statements grouped under technical, process, governance, capability, and financial dimensions.

3.4 PHASE 2: DELPHI STUDY

3.4.1 Panel Recruitment and Composition

A two-round Delphi study involved 48 panellists with diverse lifecycle roles and experience ranging from 0–5 to 16+ years, spanning early career to senior expertise (Table 2).

3.4.2 Delphi Instrument and Rounds

Twenty statements (10 barriers B01–B10 and 10 CSFs CSF01–CSF10) were rated on a 5-point scale (1 = Not important, 5 = Very important). Round 1 collected initial importance ratings. Round 2 provided feedback (group medians and dispersion) and invited panellists to reconsider ratings, supporting convergence without forcing consensus.

3.4.3 Analysis and Consensus Criteria

For each statement and round, medians and interquartile ranges (IQR) were summarized to describe the central tendency and dispersion. Agreement was assessed via top-two-box percentages (ratings 4-5) and Relative Importance Index (RII) rankings. Round 2 consensus was IQR ≤ 1 and $\geq 70\%$ ratings in 4–5. Stability across rounds was assessed using median comparisons and Wilcoxon signed-rank tests for responses. Overall concordance was assessed using Kendall's coefficient of concordance (W). Descriptive statistics, Wilcoxon signed-rank tests, Kendall's W, and RII calculations were performed using SPSS and R.

3.5 TRUSTWORTHINESS AND ETHICS

Qualitative trustworthiness was enhanced through triangulation of documents and stakeholder perspectives, along with an audit trail of coding decisions. Delphi validity was supported by a diverse panel, controlled feedback, and stability checks. The study adhered to ethical standards with informed consent, anonymization, and secure data management. The findings support analytical rather than statistical generalization and do not constitute direct empirical validation of energy savings in operating buildings. Tables 1 and 2 summarize interview participants by role and Delphi panel composition.

Table 1: Interview participant profile (n=20)

Role category	n	%
BIM Manager/Consultant	5	25.0
Policy/Regulator	4	20.0
Facility Manager/Operator	3	15.0
Architect	2	10.0
Energy Auditor/ESCO	2	10.0
Tech Integrator	2	10.0
Academic/Research	1	5.0
MEP/Energy Engineer	1	5.0

Table 2: Delphi panel profile (n=48)

Role group	n	%
Energy Auditor/ESCO	13	27.1
BIM Manager/Consultant	7	14.6
Architect	7	14.6
MEP/Energy Engineer	6	12.5
Facility Manager/Operator	5	10.4

Role group	n	%
Policy/Regulator	4	8.3
Academic/Research	4	8.3
Tech Integrator	2	4.2

4. RESULTS

4.1 DOCUMENT ANALYSIS: POLICY AND REGULATORY SIGNALS FOR LIFECYCLE ENERGY PERFORMANCE

Sri Lanka's policy views energy efficiency as a national priority, providing a technical basis for design standards. The 2020 Energy Efficiency Building Code covers the building envelope, HVAC, lighting, water heating, and related services, focusing on design compliance, including enforcement and calculations such as ETTV/RTTV for large buildings. However, it emphasizes design and installation over operational verification and performance tracking. Operational energy practices lack strong institutional support, creating gaps that lifecycle digital tools such as BIM 7D, operational digital twins, and continuous commissioning could help fill. National policies also recognize energy efficiency and conservation as strategic, with buildings as a major sector. While aligned with priorities, delivery mechanisms and data governance remain fragmented.

4.2 INTERVIEW FINDINGS: SOCIO-TECHNICAL THEMES AFFECTING BIM–DT ADOPTION FOR EPG CLOSURE

Table 3 summarises the five socio-technical themes most frequently identified across the interviews, which are then discussed in turn. The most cited were as-built model quality (40%), skills/training needs (35%), and commissioning, controls tuning, sensor readiness, data governance, and BMS vendor silos (each 30%). This shows EPG closure is limited by information continuity and operational capability.

Theme 1: Commissioning and controls are central EPG drivers in tropical buildings.

Participants noted that operational setpoints, schedules, and control sequences often differ from design assumptions after handover. Small deviations in control logic, such as simultaneous heating/cooling, high outside-air rates, or supply-air temperature resets, can cause significant energy penalties in cooling-dominated buildings. A common comment was: "Our biggest energy wastage is after handover controls are not tuned, sensors drift, and nobody owns continuous commissioning."

Theme 2: As-built information and asset data are unreliable, limiting DT feasibility.

As-built BIM models are often incomplete or outdated, affecting digital twin (DT) efforts that rely on accurate asset data. A common view was: "As-built BIM is delivered but rarely verified or updated; FM teams can't rely on it."

Theme 3: Data fragmentation and vendor silos limit operational integration.

Participants highlighted that BMS data are often locked in proprietary vendor systems, and sensor/meter data are inconsistent across buildings. This makes each integration a custom project and constrains scalability: "BMS data is in vendor silos; integrating it with BIM and FM systems is still a custom project every time."

Theme 4: Skills and organizational capability gaps constrain lifecycle digitalization.

Even where BIM models exist, FM teams may lack tools, training, or mandates to maintain model fidelity. Respondents highlighted the need for cross-disciplinary skills: BIM, data management, controls/commissioning, and analytics literacy.

Theme 5: Governance and procurement are missing backbones.

Interviewees said procurement docs rarely specify energy-related digital deliverables, data ownership, or responsibilities for the "single source of truth." A tech integrator summarized: "Digital twin projects fail without clear governance, who owns the data, maintains the model, and acts on analytics?"

4.3 DELPHI RESULTS: VALIDATED AND PRIORITIZED FACTORS

Table 4 presents the highest-ranked Round 2 barriers and CSFs that informed the framework design principles; overall ratings were high (median = 4), with 8 of 20 statements meeting consensus thresholds (IQR ≤ 1, ≥ 70% top-two-box). Kendall's W showed modest but significant agreement (Round 1 $W \approx 0.176$; Round 2 $W \approx 0.170$; $p < 0.001$), reflecting typical Delphi study patterns where item-level consensus is more informative than full convergence.

4.3.1 Top-Ranked Barriers

The top barrier was the lack of verified as-built BIM and asset data (B02; median=5, IQR=1; RII=0.93). Next were interoperability issues between BIM and BEM tools (B01; median=4, IQR=1; 97.9% top-two-box; RII=0.89). The third was insufficient commissioning and controls tuning (B03; median=4, IQR=1; RII=0.87). These align with qualitative themes.

4.3.2 Top-Ranked Critical Success Factors

The key success factors included capturing control sequences and commissioning evidence in operations, publishing energy digital information requirements, standardizing asset tagging and FM handover templates, and using DT pilots and quick wins to drive implementation. These factors received high rankings (medians around 4-5, RII~0.86-0.89).

4.3.3 Stability Across Rounds

Several items, such as policy incentives for verification (CSF10) and BIM 7D integration with FM (CSF09), showed greater central tendency after controlled feedback, indicating improved recognition of governance and systems integration. Overall, top items remained stable, aligning with Phase 1 findings.

Table 3: Frequency of interview themes (n=20; top themes shown)

Theme	Count	% of interviews
As-built model quality	8	40.0
Skills/training needed	7	35.0
Sensor readiness	6	30.0
Commissioning/controls tuning	6	30.0
Data governance & ownership	6	30.0

Theme	Count	% of interviews
BMS vendor silos	6	30.0
Tropical cooling loads	5	25.0
Procurement specs	5	25.0
Post-occupancy verification	4	20.0
BIM–BEM interoperability	4	20.0

Table 4: Delphi round 2 top-ranked barriers and CSFs (importance)

Type	Code	Statement (abridged)	Median	IQR	RII
Barrier	B02	As-built BIM models are not updated/verified, limiting operational energy use.	5.0	1.0	0.93
Barrier	B01	BIM-to-BEM interoperability issues reduce confidence in energy predictions.	4.0	1.0	0.89
Barrier	B03	Insufficient commissioning and controls tuning drive the energy performance gap.	4.0	1.0	0.87
Barrier	B10	Cybersecurity and privacy concerns hinder the operation of connected systems.	4.0	2.0	0.76
Barrier	B06	Procurement rarely specifies energy-focused BIM deliverables and handover needs.	4.0	1.0	0.72
CSF	CSF03	Capture and transfer control sequences and commissioning evidence at handover.	5.0	1.0	0.89
CSF	CSF01	Publish energy digital information requirements for BIM 6D/7D deliverables.	4.5	1.0	0.89
CSF	CSF02	Standardize asset tagging and FM handover templates for BIM 7D.	4.0	1.0	0.86
CSF	CSF04	Start with DT quick wins (fault detection, scheduling, chiller optimization).	4.0	1.0	0.86
CSF	CSF06	Define data ownership, access, and update responsibility across the lifecycle.	4.0	1.0	0.78

4.4 INTERPRETING THE DELPHI PRIORITIES AS AN IMPLEMENTATION LOGIC

The ranked items suggest a multi-stage implementation logic. The highest-priority barriers, built-in data quality, BIM–BEM interoperability, and commissioning/controls form the foundation of any operational DT, as they determine if operational data can be reliably mapped to assets and deviations interpreted against an agreed baseline. Mid-ranked barriers, procurement, finance, culture, and data integration indicate that scaling beyond pilots requires contractual and organizational change once initial data trust and value are established. Lower-ranked factors, such as cybersecurity and privacy, are necessary design considerations but not immediate bottlenecks, aligning with a staged approach where early pilots focus on proving value while embedding security and governance from the start.

4.5 DELPHI-VALIDATED FRAMEWORK: FROM BIM 6D/7D TO AN OPERATIONAL DIGITAL TWIN FOR EPG CLOSURE

This study presents the Tropical Digital Thread-to-Twin Energy Governance framework (TDT2-EG), based on Phase 1 themes and Phase 2 Delphi priorities. It operationalizes BIM 6D/7D info via an operational DT, reducing EPG by linking design intent with operational reality. The lifecycle model has three layers: (L1) Governance and info management, covering roles, data ownership, cybersecurity, and ISO 19650 processes; (L2) Digital thread deliverables, key digital artifacts from design to operations; (L3) Operational twin services, including data pipelines, analytics, and decision workflows for monitoring, fault detection, and optimization. Figure 1 shows the framework across four lifecycle stages: Design (BIM 6D), Delivery (verification), Commissioning & soft landings, and Operations (BIM 7D + operational DT).

4.5.1 Core Design Principles Derived from Delphi Priorities

The framework includes Delphi-based design principles:

P1. Use as-built verification as a data quality gate before DT analytics (B02).
P2. Ensure BIM–BEM interoperability through agreed formats and validation (B01).
P3. Digitally capture commissioning and control knowledge (B03; CSF03).
P4. Formalize energy data requirements (E-DIR) for datasets, responsibilities, and updates (B06; CSF01; CSF06).
P5. Standardize asset-tagging and handover templates for operations (B02; CSF02).
P6. Focus on quick DT wins such as fault detection and scheduling to justify investment and build capability (CSF04).

4.5.2 Energy Digital Information Requirements (E-DIR)

E-DIR is proposed as the contractual and governance mechanism that specifies the minimum set of energy-relevant digital deliverables throughout the lifecycle. Unlike generic BIM execution plans, E-DIR is energy-outcome oriented: it defines which data are required to enable post-occupancy verification and continuous optimization. Table 5 provides an illustrative E-DIR structure. The E-DIR should be attached to procurement and handover requirements and should define: (i) energy intent assumptions and modelling inputs; (ii) asset metadata, tags, and relationships; (iii) commissioning and controls deliverables; (iv) metering and sensing requirements; and (v) data governance rules.

4.5.3 Digital Thread Deliverables Across the Lifecycle

The digital thread is operationalized through explicit deliverables and quality gates at each lifecycle stage:

Design: Develop an "energy intent model" that details the zoning strategy, schedules, loads, setpoints, and control logic, and documents assumptions in a structured narrative. Define rules for BIM–BEM interoperability exchange.

Delivery: Implement as-built verification and asset tagging to capture equipment identifiers, capacities, and key parameters, and reconcile them with design intent.

Commissioning: Capture testing evidence, logs, calibration certificates, control sequences, and setpoints to turn commissioning knowledge into reusable digital assets.

Operations: Maintain an asset registry linked to CMMS, establish secure data pipelines from BMS/IoT, and use analytics to support continuous commissioning and optimization.

4.5.4 Operational Twin Services for EPG Closure

Once digital thread prerequisites are met, the operational DT supports a closed-loop EPG reduction cycle:

Measure: Ingest and validate time-series data (energy, temperatures, flows, pressures, humidity, occupancy proxies) and map to assets/spaces.

Diagnose: Perform automated FDD and detect performance drift relative to design intent and commissioning baselines.

Decide: Recommend corrective actions (setpoint correction, schedule optimization, maintenance work orders) and prioritize by energy impact and comfort risk.

Act: Implement changes through operators, FM workflows, or supervisory control.

Verify and learn to perform measurement & verification (M&V) of savings and feed learning back to standards, energy models, and future project E-DIR templates.

In tropical buildings, the analytics library should explicitly address cooling and humidity issues, such as AHU overventilation, excessive reheat, chilled-water temperature drift, condenser degradation, valve leaks, sensor bias, and dehumidification problems.

4.5.5 Implementation Maturity Pathway

To support staged adoption in resource-constrained contexts, the framework defines an operational DT maturity pathway:

Level 0 - Disconnected: BIM models and BMS data exist but aren't linked; energy modelling is only for design compliance.

Level 1 - Visibility: Establish metering, sensing, and dashboards linked to assets and zones.

Level 2 - Diagnostics: Implement rules-based and data-driven FDD and continuous commissioning workflows.

Level 3 - Prediction: Develop calibrated models for scenario analysis, maintenance forecasting, and anomaly detection prediction.

Level 4 - Optimization: Implement predictive control and optimization loops with formal M&V and governance.

The Delphi results indicate that Sri Lanka's near-term value peaks when projects focus on Level 1-2 capabilities, visibility, and diagnostics, backed by commissioning continuity and reliable as-built information.

4.5.6 Stakeholder Responsibilities (RACI logic)

A practical framework must allocate responsibilities across stakeholders:

Designers/energy modellers: Accountable for the energy intent model and assumptions, and for defining E-DIR inputs.

Contractors and commissioning agents: Responsible for as-built updates, asset tagging, and evidence-based commissioning deliverables.

Owners/FM teams: Accountable for operational KPIs, data governance decisions, and ongoing model maintenance.

BMS/IoT vendors and integrators: Responsible for secure data pipelines, point mapping, and analytics integration.

Regulators and public clients: Enable adoption through procurement templates and incentives for post-occupancy verification. This allocation of responsibilities directly addresses governance gaps identified in interviews and supports lifecycle continuity.

Figure 1 consolidates the preceding Delphi-derived design principles, digital thread deliverables, maturity pathway, and stakeholder responsibilities into a single lifecycle framework. The framework should be read from left to right across the four lifecycle stages, design, delivery, commissioning and soft landings, and operations. It shows that EPG reduction depends not only on introducing an operational digital twin at the operations stage, but also on creating verified energy-relevant information, control knowledge, and governance rules earlier in the project lifecycle.

To operationalise the framework, Table 5 translates the lifecycle logic in Figure 1 into minimum Energy Digital Information Requirements (E-DIR), verification gates, and primary ownership responsibilities. This prevents the framework from remaining conceptual and clarifies what information must be produced, checked, and transferred before BIM 6D/7D can support operational digital twin services.

Table 5: Illustrative Energy Digital Information Requirements (E-DIR) structure for BIM 6D/7D–DT integration

Lifecycle stage	Minimum digital deliverables (energy-relevant)	Quality gate/verification	Primary owner (RACI: A/R)
Design (6D)	Energy intent model; zoning & schedules; setpoint logic; BEM inputs; interoperability mapping rules; metering & sensing plan.	Model QA/QC; traceability of assumptions; BIM–BEM exchange test case.	Design lead/energy modeller
Construction/delivery	As-built model update; asset tags; equipment metadata; O&M manuals; commissioning plan; sensor installation records.	As-built reconciliation; asset tag audit; spot checks of key capacities and locations.	Main contractor / BIM manager
Commissioning & soft landings	Functional test records; trend logs; calibration certificates; control sequences; setpoint baselines; handover training logs.	Commissioning sign-off; controls sequence verification; baseline acceptance test.	Commissioning agent/controls engineer
Operations (7D + DT)	Asset registry linked to CMMS; point naming and mapping; data pipeline to time-series DB; dashboards; FDD rules; continuous commissioning workflow.	Data quality monitoring; KPI reporting; M&V verification of interventions.	Owner/FM + DT operator

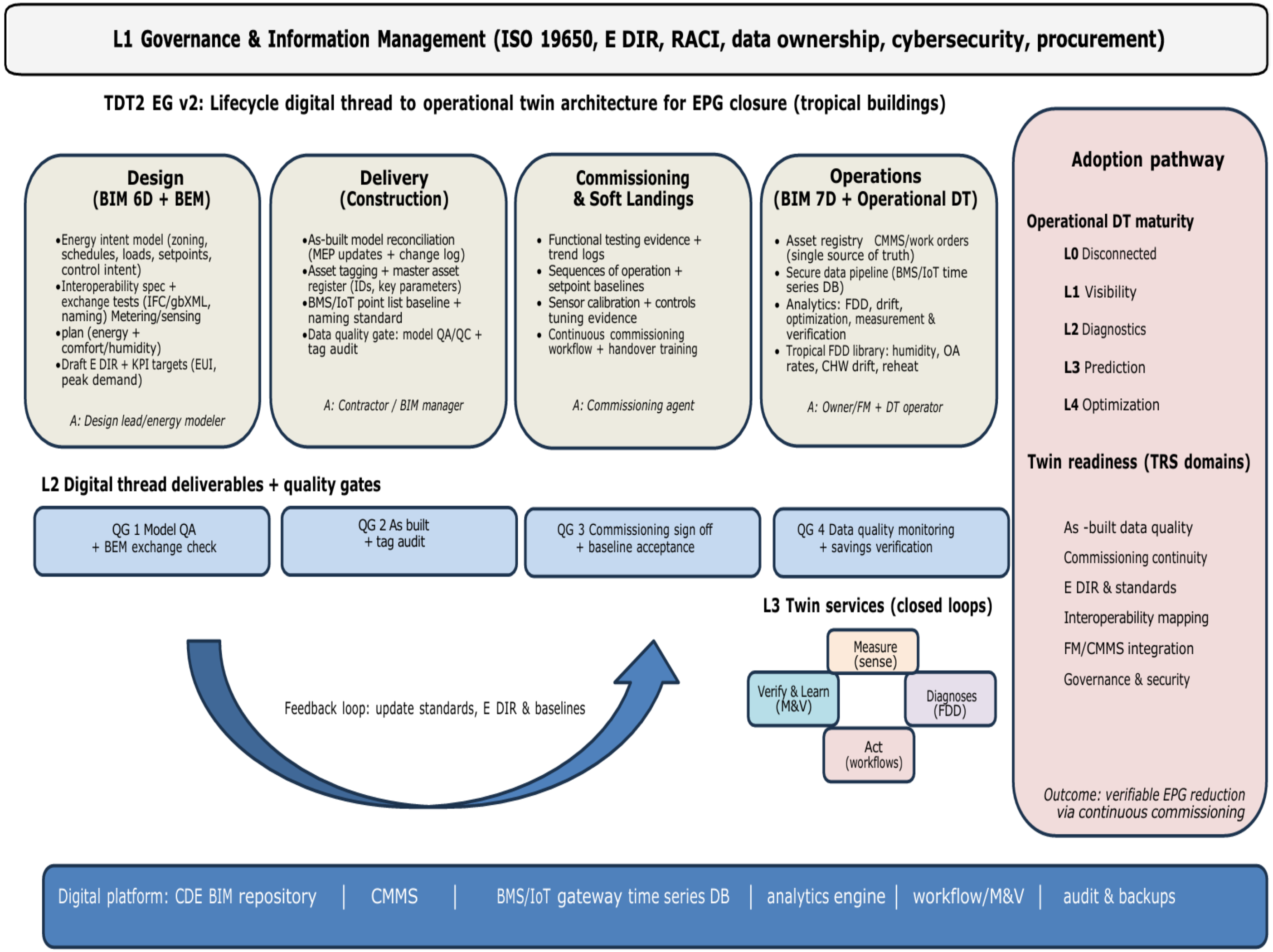

Figure 1: BIM 6D/7D to operational digital twin integration framework (TDT2-EG)

Table 5 shows that the E-DIR functions as the practical bridge between the conceptual framework and implementation. It links each lifecycle stage to specific energy-relevant deliverables and verification activities, thereby addressing the highest-ranked Delphi barriers, unverified as-built data, BIM-BEM interoperability issues, and weak commissioning continuity. By assigning ownership of the design, construction, commissioning, and FM to the actors, the table also clarifies how information accountability should shift from project delivery to operations.

4.5.7 Twin-Readiness Scorecard (TRS)

To support decision-makers, the study proposes a Twin-readiness scorecard (TRS) that assesses whether a project/building is ready to progress from BIM 6D/7D toward an operational DT and identifies which prerequisites should be prioritized. The TRS uses six readiness domains derived from Delphi priorities and assigns weights based on normalized RII values. Each domain is scored on a 1-5 scale (1 = not ready, 5 = fully ready). The overall TRS is calculated as:

$$TRS = \frac{\sum(Wi \times Scorei)}{5} \qquad (01)$$

where Wi are weights summing to 100. The TRS can be interpreted as: <50 ‘not ready’; 50–70 ‘pilot-ready’; 70–85 ‘scale-ready’; and >85 ‘optimization-ready’. Table 6 lists the domains, weights, and diagnostic prompts.

Table 6: Twin-readiness scorecard (TRS) domains and Delphi-derived weights (illustrative)

Readiness domain	Weight (%)	What “ready” looks like (diagnostic prompts)	Evidence artifacts (examples)
Data quality & as-built verification	18.1	Verified as-built model, asset tags reconciled, model QA completed, changes controlled.	As-built QA report; asset tag register; reconciliation log
Commissioning & controls continuity	17.1	Documented control sequences, test records, baselines, trend logs, and calibration certificates are available.	Commissioning report; sequences of operation; trend logs; calibration certificates
Standards & Energy Digital Information Requirements (E-DIR)	17.3	E-DIR agreed contractually; minimum data set defined; update responsibilities and cadence specified.	E-DIR document; BIM execution plan addendum; information delivery schedule
Interoperability & toolchain mapping	16.5	Agreed formats and mapping rules; test case shows data transfer is lossless or acceptable; naming conventions are defined.	Exchange test case; mapping specification; naming/ID standard
Handover & FM system integration	16.0	BIM 7D aligned with CMMS/BMS workflows; work order linkage; operators trained; data maintained post-handover.	COBie/asset export, CMMS integration, training records
Data governance, security & ownership	15.0	Data ownership and access defined; cybersecurity baseline implemented; audit and backup procedures in place.	Data governance charter; access matrix; security baseline checklist

4.5.8 Operational Performance Indicators and Verification

To ensure that a DT contributes to EPG closure rather than merely monitoring, the framework recommends a minimal set of KPIs and a verification cycle. KPIs should be defined at three levels:

i. **Building-level**: energy use intensity (EUI), peak demand, and carbon intensity (if grid emission factors are available).
ii. **System-level**: chiller plant efficiency (kW/ton), cooling tower approach, AHU fan power per airflow, and ventilation rates.
iii. **Zone-level**: temperature and humidity compliance, comfort complaints, and schedule adherence.

Verification should follow a continuous cycle: detect-diagnose-act-verify, with monthly reviews and quarterly retuning, supported by automated FDD alerts and work-order tracking in FM systems. This approach is vital in tropical buildings where humidity and cooling can drift rapidly due to fouling, sensor bias, or control overrides.

5. DISCUSSION

5.1 SYNTHESIS OF FINDINGS

This study advances BIM-DT research by showing that, in Sri Lanka, the EPG is shaped less by the absence of modelling tools than by weak lifecycle continuity between design, delivery, commissioning, and operations. This finding is consistent with Zheng et al. (2024), who argue that the EPG is driven not only by simulation uncertainty but also by poor communication and management of lifecycle information. However, the present study extends this literature by identifying, through Delphi consensus, the specific information failures that matter most in a tropical developing-country context: unverified as-built BIM and asset data, BIM-BEM interoperability limitations, and insufficient commissioning and controls tuning.

The findings also align with Forth and Borrmann (2024), who show that BIM-based energy simulations depend on the availability and enrichment of reliable semantic information. While their work focuses mainly on improving BIM-based energy simulation inputs, the present study shows that semantic and asset-data reliability must continue beyond design-stage modelling into commissioning, handover, and FM. This is why the proposed E-DIR, asset-tagging requirements, and as-built verification gates are positioned as prerequisites for operational DT deployment rather than as optional handover documentation.

The Delphi results further correspond with recent digital twin studies that emphasise operational monitoring, anomaly detection, optimisation, predictive maintenance, and scenario simulation as core building-DT applications (Cespedes-Cubides & Jradi, 2024). Nevertheless, this study adds a more cautious implementation logic for Sri Lanka: most buildings should first target Level 1-2 DT capabilities, namely visibility, metering, dashboards, fault detection, and continuous commissioning, before moving toward predictive optimisation. This differs from technology-led DT narratives by showing that operational value depends on verified data, commissioning evidence, and FM workflow integration before advanced analytics can be trusted.

The emphasis on controls and commissioning also supports recent BIM-DT control literature. Hauer et al. (2024) identify building controls and fault detection as major areas for DT development, while Zech et al. (2025) position commissioning as a critical interface between design intent and operational performance. The present study reinforces these findings in a tropical setting, where control sequences, humidity management, sensor drift, chilled-water temperature control, and post-handover overrides can rapidly widen the EPG. Therefore, the contribution of this study is not simply to confirm that BIM and DTs can improve energy performance, but to show which lifecycle governance conditions must be in place for such improvements to be achievable in Sri Lankan tropical buildings.

5.2 IMPLICATIONS FOR POLICY AND PROCUREMENT

For Sri Lanka, existing design-stage requirements should be supported by operational verification mechanisms. Rather than creating new compliance regimes, it's practical to embed E-DIR and post-occupancy verification in public procurement for large buildings. This aligns with energy efficiency goals and builds market capacity. Procurement should specify as-built verification, asset tagging, commissioning evidence, cybersecurity for connected systems, and post-handover maintenance of the digital thread. These measures address governance and procurement gaps identified by interviewees.

5.3 IMPLICATIONS FOR RESEARCH

The findings point to research opportunities in three areas: (i) semantic interoperability between BIM schemas and operational ontologies to support scalable point mapping; (ii) methods for continuous commissioning and FDD tailored to tropical HVAC and humidity control; and (iii) socio-technical governance models for operational DTs, including cybersecurity, data ownership, and incentives for long-term information maintenance.

6. PRACTICAL IMPLICATIONS AND ROADMAP FOR SRI LANKA

Drawing on the Delphi-ranked CSFs, a practical near-term roadmap for Sri Lanka is to publish an E-DIR template for major buildings; implement 3–5 Level 1–2 pilot projects focused on metering, dashboards, FDD, and soft-landings support; standardize asset tagging and handover templates aligned with computerized maintenance management system (CMMS)/BMS workflows; add procurement clauses for as-built verification, commissioning evidence, and cybersecurity baselines; and progressively embed DT-readiness and post-occupancy verification requirements into major public projects. This staged approach prioritizes capacity building, governance, and early operational value before wider institutionalization.

7. LIMITATIONS AND FUTURE RESEARCH

This study is limited by its Sri Lanka-specific qualitative and Delphi samples and by its reliance on expert judgement rather than measured energy outcomes from implemented digital twins. The findings, therefore, support analytical rather than statistical generalization. Future research should test the framework through longitudinal building case studies, quantify EPG reduction, and examine cost-benefit, semantic interoperability, and data governance issues across different ownership and procurement models.

8. CONCLUSIONS

This paper presents an expert-validated Sri Lanka-specific framework for integrating BIM 6D/7D with operational digital twins to reduce the EPG in tropical buildings. Using interviews (n = 20) and a two-round Delphi study (n = 48), it identifies unreliable as-built data, BIM–BEM interoperability issues, and weak commissioning continuity as the main barriers, and highlights control-sequence capture, energy digital information requirements, asset tagging, and workflow alignment as the priority enablers. The study contributes a lifecycle Tropical Digital Thread-to-Twin Energy Governance framework, an E-DIR mechanism, and a twin-readiness scorecard to guide staged adoption. While developed for Sri Lanka, the framework offers analytical lessons for other tropical, developing-country contexts where data quality, commissioning, and lifecycle governance constrain operational performance.

9. REFERENCES

Abouelkhier, N., Rauf, A., Luyten, L., & Shafiq, M. T. (2025). Mitigating early-phase miscommunication between architects and structural engineers: A systematic review and framework linking BIM/VR strategies to communication barriers. *Architectural Engineering and Design Management*, 1–23. https://doi.org/10.1080/17452007.2025.2586665

Al-Rudainy, A. S. A., & Mahjoob, A. M. R. (2024). Using building information modelling to optimise design quality of natural lighting in Iraqi school buildings. *Organization, Technology and Management in Construction*, *16*(1), 52-62. https://doi.org/10.2478/otmcj-2024-0004

Altaf, M., Alalaoul, W. S., Musarat, M. A., Abdelaziz, A. A., & Thaheem, M. J. (2024). Optimization of energy and life cycle costs via building envelope: a BIM approach. *Environment, Development and Sustainability*, *26*(3), 7105-7128.

Cespedes-Cubides, A. S., & Jradi, M. (2024). A review of building digital twins to improve energy efficiency in the building operational stage. *Energy Informatics, 7*, Article 11. https://doi.org/10.1186/s42162-024-00313-7

Cheng, J. C. P., & Das, M. (2014). A BIM-based web service framework for green building energy simulation and code checking. *Journal of Information Technology in Construction, 19*, 150–168. http://www.itcon.org/2014/8

Choi, J., & Lee, S. (2023). A Suggestion of the Alternatives Evaluation Method through IFC-Based Building Energy Performance Analysis. *Sustainability*, *15*(3), 1797. https://doi.org/10.3390/su15031797

Forth, K., & Borrmann, A. (2024). Semantic enrichment for BIM-based building energy performance simulations using semantic textual similarity and fine-tuning multilingual LLM. *Journal Of Building Engineering*, *95*. https://doi.org/10.1016/j.jobe.2024.110312

Ghoneim, M. M., Halabya, A., Moussa, O. M., & Hassan, A. A. (2025). An empirical assessment of material waste drivers and sustainability strategies in Egypt's construction sector. *Discover Sustainability*, *6*(1), 30, Article 1154. https://doi.org/10.1007/s43621-025-01976-2

Hauer, M., Hammes, S., Zech, P., Geisler-Moroder, D., Plörer, D., Miller, J., van Karsbergen, V., & Pfluger, R. (2024). Integrating digital twins with BIM for enhanced building control strategies: A systematic literature review focusing on daylight and artificial lighting systems. *Buildings, 14*(3), 805. https://doi.org/10.3390/buildings14030805

Kurniawan, T. B., Dewi, D. A., Usman, F., & Fadly, F. (2023). Towards Energy Analysis and Efficiency for Sustainable Buildings. *Emerging Science Journal*, *7*(6), 2226-2238. https://doi.org/10.28991/ESJ-2023-07-06-022

Ozcan-Deniz, G., & Rodovalho, S. (2024). Towards carbon-neutral construction: Integrating BIM and energy analysis for sustainable design decision-making. *International Journal of Architectural Computing*. https://doi.org/10.1177/14780771241310213

Perera, U. D. S., Kulatunga, U., Abdeen, F. N., Sepasgozar, S. M. E., & Tennakoon, M. (2022). Application of building information modelling for fire hazard management in high-rise buildings: An investigation in Sri Lanka. *Intelligent Buildings International*, 14(2), 207–221. https://doi.org/10.1080/17508975.2021.1874858

Qi, C. (2024). Simulation of indoor thermal energy cycle in green building VR design based on BIM and computer virtual vision. *International Journal of Advanced Manufacturing Technology*. https://doi.org/10.1007/s00170-024-14826-8

Rashwan, Y. G. M., & Mostafa, A. O. M. S. (2023). Top trends and challenges of building information modeling (BIM) to enhance the performance of building designs' energy consumption, and the reality of its practice in the Saudi local market - Riyadh city as a model. *Journal of Architecture and Planning – King Saud University*, 35(1), 1–41. https://doi.org/10.33948/JAP-KSU-35-1-1

Sadeghifam, A. N., Marsono, A. K., Kiani, I., Isikdag, U., Bavafa, A. A., & Tabatabaee, S. (2016). Energy analysis of wall materials using building information modeling (BIM) of public buildings in tropical climate countries. *Jurnal Teknologi*, *78*(10), 35-41. https://doi.org/10.11113/jt.v78.7591

Sha, X., & Zhang, X. (2024). High-rise building steel structure monitoring and energy efficiency optimization based on BIM and strain sensor vibration signal processing. *EAI Endorsed Transactions on Energy Web*, *11*, 1-10. https://doi.org/10.4108/EW.6560

Zech, P., Hammes, S., Goldin, E., Geisler-Moroder, D., Breu, R., & Pfluger, R. (2025). From BIM to digital twin: A transformation process through advanced control modeling and automated commissioning using daylight and artificial lighting as examples. Energy and Buildings, 329, 115184. https://doi.org/10.1016/j.enbuild.2024.115184

Zheng, Z., Zhou, J., Zhu, J., Yang, Y., Xu, F., & Liu, H. (2024). Review of the building energy performance gap from simulation and building lifecycle perspectives: Magnitude, causes and solutions. *Developments in the Built Environment, 17*, 100345. https://doi.org/10.1016/j.dibe.2024.100345