Digital Twins for Renovation in Underserved Communities: A Sustainable and Adaptive Framework

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Abstract

A growing housing shortage exists alongside increasing building deterioration, leaving many units vacant or unsafe, while financing stalls due to uncertain conditions. This paper introduces a digital twin (DT) framework that addresses the main barrier to restoring homes: uncertainty about structural integrity, scope, and post-retrofit performance. The approach operates under partial observability. The framework is structured as a clear six-stage process: Capture, Assemble, Analyze, Decide, Deliver, and Verify/Operate. A digital twin is developed using exterior/safe-zone capture and typical envelope values, then refined with on-site evidence, and includes screening checks such as structural assessments, moisture analysis, and a brief life-cycle assessment to compare rehabilitation options. For inaccessible spaces, the model incorporates evidence-based estimations like roofline deviation, out-of-plane drift, crack patterns, damp/thermal anomalies, and construction era, each marked with uncertainty and a plan for ongoing verification.

Analyses remain decision-focused and easy to interpret. We start with structural stability screening based on geometric change detection and simple rules applied at spans, bearings, and openings. Next, we estimate building performance to project energy use intensity (EUI) and comfort hours. The model begins with standard envelope values of walls, roof, windows, and infiltration, derived from similar buildings from the same period and refined with on-site evidence. Finally, a life-cycle assessment compares retain versus replace options for the structure and envelope, highlighting embodied carbon impacts alongside operational effects. Alternative renovation pathways, such as stabilize-and-occupy, targeted retrofit, or deeper adaptive reuse, are compared with clear ranges to ensure transparency in trade-offs.

Results are presented as a concise set of decision artifacts that turn uncertainties into quantifiable, testable assumptions; a scope-of-work map indicating what to keep, fix, or replace; and a risk-to-contingency summary revealing where and why allowances are necessary. Additionally, a plain-language Key Performance Indicator (KPI) scorecard is used for approval and funding decisions. KPIs focus on housing outcomes, for units to be restored to safe occupancy, expected cost range, projected timeframe, predicted EUI and comfort, material reuse/waste diversion, and embodied carbon savings from retention. By converting uncertainty into bounded, testable inputs, this framework aims to facilitate renovation decisions, accurately size contingencies, and speed up the return of safe, energy-efficient housing in underserved communities while lowering energy costs and carbon footprint.

Keywords: Digital Twin, adaptive reuse, embodied carbon, lifecycle assessment, photogrammetry, XR/AR, building performance, residential retrofit.

1. Introduction

The United States faces a major housing shortage and an aging housing stock, with many older homes experiencing poor energy performance, deferred maintenance, and elevated health and safety risks [1, 2, 3, 7, 8, 9]. These issues are particularly severe in legacy cities like Baltimore, where older construction and high vacancy rates in historically disinvested neighborhoods increase rehabilitation needs alongside Maryland's growing long-term housing demand [4, 5, 6]. Renovation efforts in underserved communities are further constrained by uncertainty about structural condition, moisture damage, and post-retrofit outcomes, making it essential to prioritize projects with clearer evidence, especially as policy programs expand retrofit funding [10, 11, 12, 13]. Although digital twins can reduce uncertainty through modeling and scenario testing, most DT retrofit approaches assume stable access, strong documentation, and resource-intensive sensing and workflows, limiting their applicability to distressed housing [14, 15, 16]. Unlike conventional digital twin retrofit studies that often assume complete building access, reliable documentation, and advanced sensing infrastructure, this study positions uncertainty as the central design condition. The novelty of the proposed Adaptive Digital Twin Framework lies in its ability to support renovation decisions before perfect information is available. It converts incomplete field evidence into bounded assumptions, links each assumption to a verification pathway, and translates technical analysis into decision artifacts that can be used by funders, community organizations, homeowners, and contractors. This underserved-first orientation distinguishes the framework from high-resource digital twin models and makes it more applicable to distressed housing rehabilitation.

This paper, therefore, proposes an underserved-first, partial-observability DT framework that replaces "missing data" with bounded, testable assumptions and verification plans, and delivers practical decision artifacts (scope, contingencies, KPI scorecard) to support low-cost, transparent renovation planning and faster returns to safe, energy-efficient occupancy [18, 19, 20, 21, 22, 23, 24, 25].

1.2 Research Gap

Although digital twins are increasingly used for building performance analysis, retrofit planning, and energy optimization, most existing approaches assume that the project team has reliable as-built documentation, stable building access, high-quality baseline data, continuous sensing, and sufficient technical resources. These assumptions are often unrealistic in underserved housing contexts, where buildings may be vacant, deteriorated, unsafe to enter, poorly documented, or affected by long-term deferred maintenance. As a result, current digital twin workflows remain difficult to apply to the exact housing stock where renovation support is most urgently needed.

A second gap concerns decision translation. Many digital twin studies emphasize model development, simulation accuracy, or technical integration, but fewer studies show how uncertain model outputs can be converted into practical renovation decisions for funders, community organizations, homeowners, contractors, and public agencies. In low-resource housing rehabilitation, the central challenge is not only to model the building, but also to decide what to keep, repair, replace, verify, or defer under uncertain conditions. Therefore, there is a need for a digital twin framework that is affordable, scalable, transparent, and capable of functioning under partial observability.

This study addresses that gap by proposing an Adaptive Digital Twin Framework (ADTF) that treats missing building information as bounded and testable assumptions. Rather than waiting for perfect data, the framework enables early-stage decision-making while requiring each uncertain input to be tagged with a confidence level and a verification plan. This makes the framework suitable for underserved housing renovation, where the goal is to reduce uncertainty enough to support safe, fundable, and performance-oriented rehabilitation decisions.

1.3 Research Objectives

To tackle the above problem, this paper is guided by four main research objectives and three corresponding research questions, which are to:

1. Develop a structured digital twin framework (in six stages from data capture to verification) that is adapted for low-resource residential renovations.
2. Integrate affordable data sources and tools (e.g., smartphone scans, BIM modeling, energy simulation, spreadsheets, and rule-based decision templates) into a unified workflow for evaluating a building's current state and potential retrofit options.
3. Define and calculate a set of key performance metrics – including energy efficiency, maintenance condition, technology integration, sustainability, and financial payback – that collectively inform renovation decisions in an intuitive "report card" format.
4. Demonstrate the framework with a pilot case study house in an underserved community and assess its feasibility, decision value, and potential for future validation.

From these objectives, we investigate the following Research Questions (RQs):

1. How can digital twin technology be designed or modified to support renovation decision-making for aging housing in underserved communities, keeping the solution affordable and scalable?
2. What data inputs (e.g. building geometry, material conditions, utility data) and tools are required to construct a useful digital twin of a residential building under partial observability, and how can these be obtained at low cost?
3. What improvements in performance (energy savings, reduced maintenance needs, improved sustainability) and financial returns (ROI, payback period, NPV) can be achieved through the digital twin-informed renovation, and how do these compare to the baseline (no renovation) scenario for the case study house?

Answering these questions will help evaluate whether the proposed framework meets its intended goals and where it offers advantages over conventional approaches. The case study application (Objective 4) provides a concrete basis to answer RQ3, while the framework development process addresses RQ1 and RQ2.

1.4 Contribution To Knowledge

This paper makes four main contributions to digital twin research and sustainable housing renovation.

1. It introduces a partial-observability digital twin approach for distressed residential buildings, where full access, accurate drawings, and continuous sensing may not be available during early decision-making.
2. It presents a six-stage Adaptive Digital Twin Framework: Capture, Assemble, Analyze, Decide, Deliver, and Verify/Operate. This workflow translates fragmented building evidence into renovation decisions while allowing the model to improve as new data becomes available.
3. It develops a practical set of decision artifacts for underserved housing rehabilitation, including an assumption and uncertainty register, a scope-of-work map, a risk-to-contingency summary, and a plain-language KPI scorecard.
4. It demonstrates how digital twin-informed renovation can support integrated decisions across energy performance, comfort, structural risk, moisture control, cost, payback, embodied carbon, operational carbon, and long-term maintenance. This expands digital twin retrofit research beyond energy-only optimization toward a broader sustainability and equity-centered renovation model.

2. Literature Review

2.1 Digital twins for renovation and retrofit decision support

Digital twins (DTs) are increasingly applied in retrofits as decision-support systems that combine building geometry, condition/performance evidence, and simulation or prediction models to compare intervention options before spending money [12, 13, 14]. In existing-building workflows, this typically starts with scan-based capture or Building Information Modeling (BIM), followed by energy/carbon simulation, calibration, and scenario testing [12, 13, 14]. DanRETwin illustrates the current direction by using sensing and analytics for stock-level retrofit selection and decarbonization planning, but research notes that legacy buildings often lack reliable as-builts, instrumentation, and consistent operational data needed for continuous updating [12, 13]. Figure 1 summarizes the DanRETwin-style pipeline and highlights its underlying assumptions, stable access, robust metering/sensing, and technical resources, conditions that are often missing in underserved and distressed housing, motivating a partial-observability, low-cost, verification-driven framework.

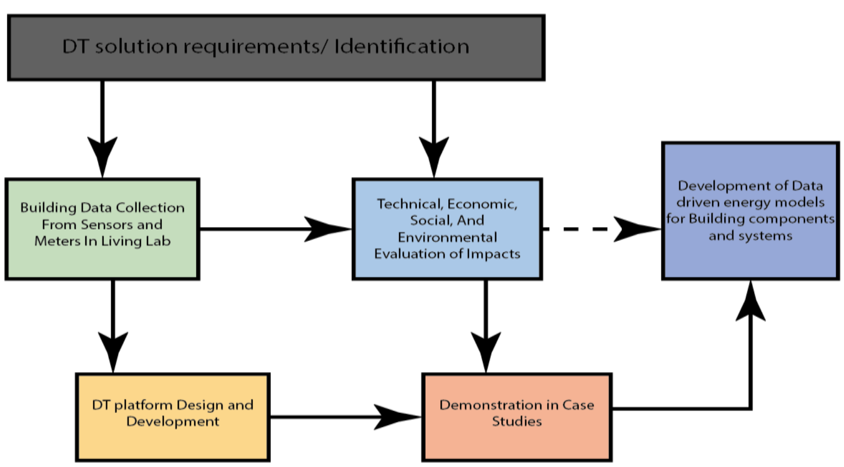

Figure 1. DanRETwin-style digital twin retrofit framework (adapted from Jradi et al., 2023).

Secondly, the scan-to-BIM DT evaluation approaches for existing residential buildings show how point clouds can be translated into a BIM representation and used to test packages of retrofit measures (envelope, systems, renewables) under different performance and carbon objectives [14]. Together, these works demonstrate technical feasibility, but they also highlight a key translation issue for underserved housing: many published demonstrations assume stable access, higher-quality baseline data, and more resources than are typical for distressed or vacant homes.

2.2 The SDTF Framework

The Scalable Digital Twin Framework (SDTF) begins with simple two-dimensional (2D) project inputs. It develops them into richer three-dimensional (3D) models that carry embedded metadata, such as material properties, safety/condition indicators, and planned maintenance intervals. As shown in Figure 2 below, 3D models can be explored either through a desktop interface or via virtual reality (VR) environments, and they are connected to a lifecycle repository that stores inspection outcomes, maintenance histories, and relevant project or contract documentation. With this setup, the digital twin can be updated over time as new evidence becomes available, while also linking technical information (for example, sensor readings and geometric updates) to operational workflows like maintenance planning and renovation decision-making [28].

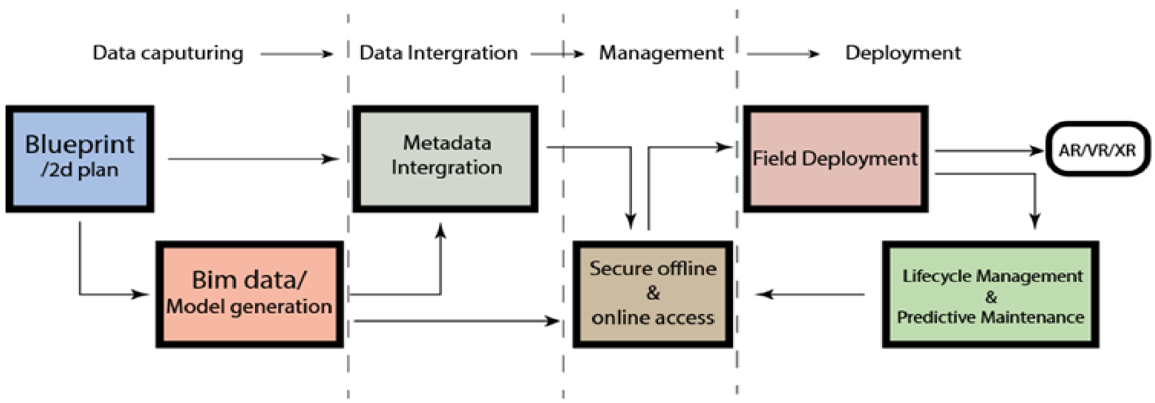

Figure 2. Scalable Digital Twin Framework (SDTF) Pipeline for Residential Projects (adapted from Banjo et al., 2025).

In this study, the SDTF is structured as a practical, repeatable process that combines lightweight modeling tools, Internet of Things (IoT) data capture, immersive visualization, and lifecycle asset management into a single, integrated workflow. Figure 2 illustrates the conceptual pipeline, demonstrating how information flows across the key layers of the digital twin environment.

2.3 Equity and implementation gap

Despite strong technical progress, a consistent gap remains between what DT retrofit research demonstrates under controlled or well-resourced conditions and what is deployable in underserved contexts. Systematic reviews of built-environment DT research show that the field is expanding rapidly and is dominated by countries with strong research infrastructure, while implementation barriers persist in data-scarce and resource-limited settings [26]. When applied to underserved renovation pipelines, this gap appears as: lack of records and instrumentation, access constraints and safety risks, limited budgets for sensing, scanning, and proprietary software ecosystems, and the need to communicate decisions in plain language for non-expert stakeholders.

Building on these findings, the present study extends DT retrofit thinking into an underserved-first renovation workflow by emphasizing:

1. operation under partial observability,

2. progressive refinement of uncertain parameters,

3. lightweight decision-grade screening (structural, moisture, and performance), and

4. decision artifacts (scope-of-work, risk-to-contingency, KPI scorecard) that translate technical outputs into fundable actions.

The approach remains aligned with prior DT retrofit pipelines (Scan/model → Analyze → Evaluate) [13, 14] but differs by explicitly designing for constrained access, missing data, and low-cost deployment, conditions that are typical in vacant and distressed housing restoration.

3. Conceptual and Theoretical Framework

This study presents a sustainable, adaptive digital twin (ADT) framework to support housing renovation in underserved communities, where budgets are tight, and building information is often incomplete. The framework is designed for practical deployment in low-resource settings and follows a clear six-stage workflow: Capture (safe-zone/exterior) → Assemble (DT baseline + typology priors) → Analyze (structural + moisture + performance) → Decide (pathways + ranges) → Deliver (scope map + contingencies) → Verify/Operate (update assumptions with evidence)

Capture focuses on efficient data collection from aging buildings with limited documentation. Assemble integrates field evidence into a coherent DT model, such as generating a Building Information Model (BIM) from scans and inspections. Analyze evaluates current conditions and retrofit options using simplified but decision-grade assessments (energy, structural, moisture, and related checks), even when inputs are uncertain. Decide uses Key Performance Indicators (KPIs) and multi-criteria reasoning to select a renovation scope under budget constraints through a transparent scorecard. Deliver translates ADTF outputs into actionable construction planning, quality control, and safety-focused execution. Verify/Operate, then commission and monitor the renovated building to confirm performance targets and enable ongoing adaptive management. The framework is grounded in three complementary ideas: digital twin lifecycle thinking, partial observability, and KPI-based decision support. First, digital twin lifecycle thinking frames the model as an evolving representation of the building rather than a one-time geometric product. Second, partial observability explains how the framework treats missing or inaccessible building information as bounded assumptions with confidence ratings and verification plans. Third, KPI-based decision support connects the technical model to practical renovation decisions by evaluating energy, comfort, cost, carbon, moisture, structural risk, and payback indicators. The framework's key contribution is its partial-observability strategy: it treats missing information as bounded assumptions based on building age and typology, then progressively reduces uncertainty through targeted tests and low-cost sensing while updating the digital twin over time. It also expands beyond energy-only retrofits by integrating structural screening, moisture risk checks, and life-cycle carbon considerations, and the paper demonstrates the approach through a case study before discussing scalability, limitations, and future work.

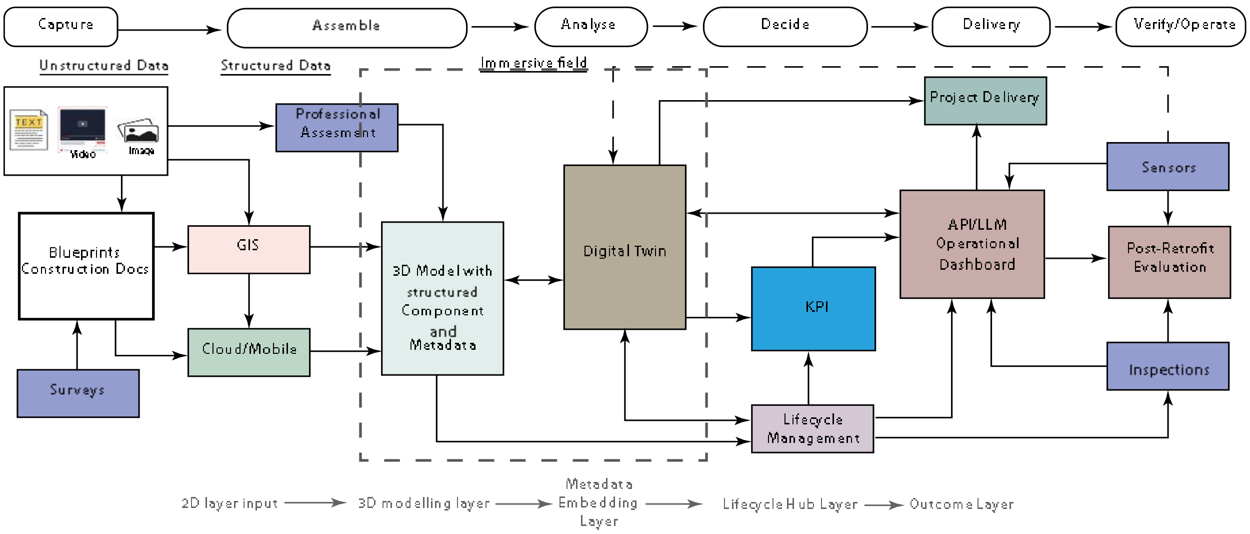

Figure 3. Conceptual framework of the Adaptive Digital Twin Framework (ADTF).

Figure 3 illustrates the overall ADTF workflow, beginning with initial data capture and ending with verification, operation, and feedback loops. Each stage is described in its own subsection below, including objectives, methods, tools, and assumptions. Table 1 summarizes the key activities and outputs of each stage for clarity.

While Figure 3 presents the overall structure of the Adaptive Digital Twin Framework (ADTF), Figure 4 explains the internal decision logic that makes the framework useful under partial observability. The central argument is that missing or incomplete building information should not be treated as a project barrier. Instead, uncertainty is converted into bounded assumptions, assigned confidence ratings, linked to verification tasks, and translated into risk-to-contingency decisions. This process allows the digital twin to evolve as more evidence becomes available and supports practical outputs such as an updated digital twin, a scope-of-work map, a KPI scorecard, and a fundable renovation pathway.

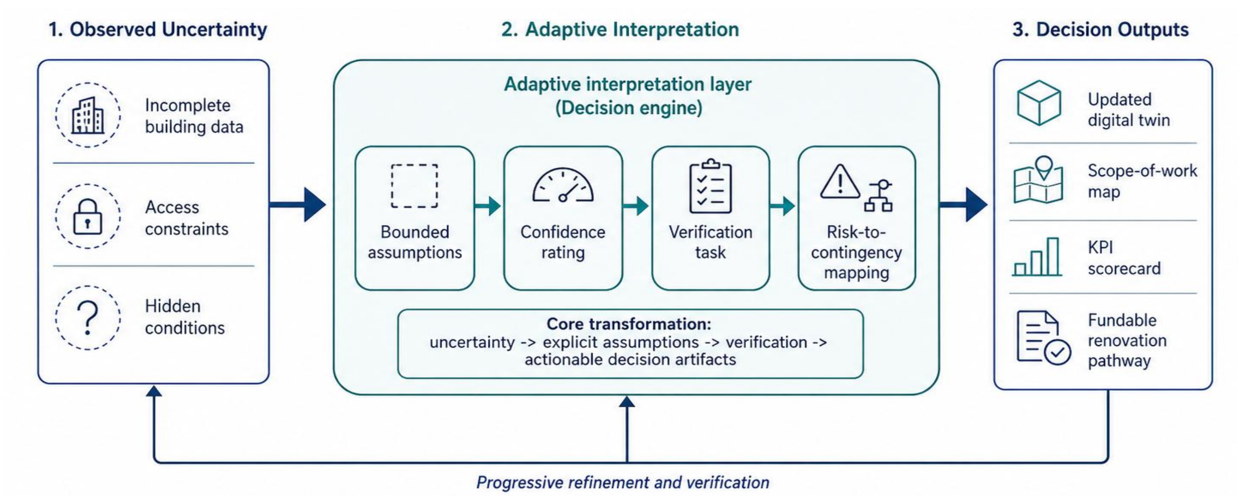

Figure 4. Uncertainty-to-decision logic in the Adaptive Digital Twin Framework (ADTF).

As shown in Figure 4, the ADTF operates as a progressive refinement system. Initial uncertainty may arise from incomplete drawings, limited access, hidden defects, or fragmented field evidence. The framework responds by generating bounded assumptions, assigning confidence levels, and identifying verification tasks needed to reduce uncertainty. The verified evidence then updates the digital twin and informs decision artifacts that can support renovation planning, contingency allocation, and funding justification.

The following methodology section operationalizes this conceptual logic by describing each ADTF stage, the required data inputs, and the decision artifacts generated from the pilot case.

4. Methodology

Renovating underserved housing often happens under partial observability, where early decisions must be made without full access, reliable records, or visibility of hidden issues, so teams rely on rapid screening and progressive refinement guided by established assessment standards [15, 16, 17]. Because retrofit choices balance multiple criteria (cost, energy, comfort, emissions, safety), KPI-based evaluation helps communicate trade-offs clearly and support consistent, verifiable delivery [19, 20, 21].

4.1 Research Design: Implementing Decision-Focused Analyses

4.1.1 Stage 1 - Capture

Capture prioritizes safety and speed. The initial dataset can be collected from the exterior and any safe interior zones using smartphones, cameras, and basic field measurements. When access is limited, the method still collects enough information to build a first-pass geometry and condition profile. Evidence includes facade photos, roof photos from public viewpoints, window and door counts, visible cracking, drainage and grading notes, and basic dimensional checks at openings and spans.

4.1.2 Stage 2 - Assemble

Assemble transforms evidence into a baseline digital twin. Geometry can be developed as a simplified Building Information Model (BIM) or a lightweight mesh. Envelope properties start from typical values for buildings from the same era and construction type (walls, roof, windows, and infiltration), then are refined as on-site evidence becomes available. All inferred inputs are tagged with uncertainty ranges and a planned verification method.

4.1.3 Stage 3 - Analyze

Analyze remains screening-oriented and decision-focused. The goal is not to fully engineer the building at this stage, but to identify stability concerns, likely moisture pathways, and the performance implications of realistic retrofit options. The analysis is organized into four short modules: structural stability screening, moisture screening, building performance estimation (EUI and comfort hours), and a brief life-cycle comparison of retain versus replace options.

4.1.4 Stage 4 - Decide

Decide converts analysis results into a set of renovation pathways and a clear recommendation. Instead of a single-point estimate, the method presents ranges (low, likely, high) for costs, timeline, energy use, and carbon impacts. Risk drivers are explicitly connected to contingency allowances to show where uncertainties remain and what verification actions will reduce them.

4.1.5 Stage 5 - Deliver

Deliver a scope-of-work map and work packages that can be used for procurement, permitting, and site execution. The digital twin supports clash reduction between trades and helps stabilize sequencing, repair envelopes, and upgrade systems. Where teams have access to extended reality (XR) tools, the same model can be viewed in the field to clarify intent and reduce rework.

4.1.6 Stage 6 - Verify/Operate

Verify/Operate closes the loop by comparing predictions with observed outcomes and updating the twin. Verification can include targeted inspections (e.g., attic/roof framing checks once safe access is possible), moisture meter readings, blower-door or simplified infiltration checks where feasible, and post-occupancy feedback. The output is an updated model and a lightweight operations checklist that supports durable performance. Table 1 presents the data categories, tools, purposes, outputs, and limitations used in the Adaptive Digital Twin Framework. The table clarifies how low-cost field evidence is converted into decision-grade digital twin inputs while acknowledging uncertainty in inaccessible or poorly documented building areas.

Table 1. Data inputs, tools, outputs, and limitations in the Adaptive Digital Twin Framework.

Data Category	Tool or Source	Purpose	Output in the Framework	Limitation
Building geometry	Smartphone camera, Polycam or photogrammetry scan, field measurements	Capture visible dimensions and building form	First-pass 3D model or simplified BIM geometry	Limited accuracy in inaccessible or obstructed zones
Existing drawings	Blueprints, floor plans, construction documents where available	Support baseline model development	2D-to-3D model reference	May be outdated or incomplete
Exterior condition	Site photographs, façade inspection, roofline observation	Identify visible cracks, deflection, drainage, envelope deterioration	Condition map and structural/moisture screening notes	Hidden defects may remain unobserved
Interior condition	Safe-zone inspection, room photos, visible dampness, wall/floor observations	Identify comfort, moisture, structural, and maintenance concerns	Interior condition profile	Unsafe areas may be excluded
Envelope assumptions	Building age, typology, typical wall/roof/window values	Estimate thermal performance where material data are missing	Baseline energy model assumptions	Requires verification through later inspection

Energy performance	Utility data where available, EnergyPlus/OpenStudio-style assumptions, spreadsheet calculations	Estimate Energy Use Intensity (EUI), comfort, and retrofit savings	Baseline and retrofit performance comparison	Sensitive to occupant behavior and infiltration uncertainty
Structural screening	Visual inspection, crack patterns, span/bearing checks, floor deflection observations	Identify priority structural risks	Structural risk category and verification plan	Not a substitute for full structural engineering assessment
Moisture risk	Visual dampness, drainage observation, basement humidity indicators, ventilation review	Identify moisture pathways and indoor air quality risks	Moisture risk map and mitigation priority	Requires field testing for confirmation
Cost and payback	Local cost assumptions, contractor estimates, spreadsheet-based payback calculations	Compare retrofit options	Payback, annual savings, and priority score	Costs may vary by market and scope changes
Carbon assessment	Material retention assumptions, operational energy comparison, simplified life-cycle logic	Compare retain-versus-replace impacts	Embodied and operational carbon estimate	Early-stage embodied carbon values are approximate

4.2 Retrofit Measures Selected

Using a KPI scorecard, various measures were evaluated. Table 2 below condenses part of that decision matrix, showing key KPIs for major measures considered:

Table 2. Excerpt from retrofit scorecard for pilot house.

Measure	Energy Savings	Est. Annual $ Savings	Upfront Cost	Payback (yrs)	Carbon Impact (op./embodied)	Other Impacts	Priority Score
Attic: Add R-38 insulation	15% reduction in total energy	$180/year	$1,200	6.7	–0.8 ton CO_2/yr; +0.1 ton (low embodied)	Improves comfort significantly	High (9/10)

(blown cellulose)							
Walls: Add R-10 interior EPS + drywall	20% reduction	$240/year	$3,000	12.5	–1.0 ton CO_2/yr; +0.5 ton (moderate embodied)	Must address moisture; improves comfort	Med (7/10)
Air sealing (caulk, weatherstrip, etc.)	10% reduction	$120/year	$500	4.2	–0.4 ton CO_2/yr; negligible embodied	Reduces drafts, very cost-effective	High (10/10)
High-efficiency Heat Pump (SEER 18, 9 HSPF)	5% reduction (net, due to higher efficiency but fuel switch)	$100/year savings (plus cooling)	$6,000	15.0	–1.5 ton CO_2/yr (operation, due to cleaner grid); +1.0 ton embodied (equipment)	Provides AC, improves IAQ (no gas combustion)	Med (6/10)
Replace windows (double-pane low-e)	5% reduction	$60/year	$8,000	133	–0.2 ton CO_2/yr; +2.0 ton embodied (frames+glass)	Improves comfort, reduces noise	Low (3/10)
Install bathroom exhaust + kitchen range hood (vented)	N/A (energy slight ↑)	-$20/year (energy use)	$800	N/A	slight CO_2 increase (fan electricity)	Greatly reduces moisture buildup, improves IAQ	High (health)
Fix basement water (grading + sump pump)	N/A	prevents damage	$1,500	N/A	minor CO_2 for pump operation	Mitigates mold risk, protects structure	Essential
Repoint and reinforce brick crack	N/A	N/A	$1,000	N/A	negligible carbon	Structural safety ensured	Essential
Sister floor joists (selected areas)	N/A	N/A	$2,000	N/A	embodied carbon small (wood)	Reduces floor bounce, safety margin	High (safety)

Based on the KPI scorecard and stakeholder discussions, the final scope prioritized cost-effective energy and comfort measures (whole-house air sealing, attic insulation to ~R-50) and essential durability work (basement moisture mitigation), alongside targeted upgrades such as carefully detailed interior wall insulation and improved ventilation. The team also selected grant-supported electrification via a high-efficiency heat pump, chose low-carbon window retention with weatherstripping and storm panels instead of full replacement, and included critical structural repairs (crack stabilization and joist sistering) for safety and long-term performance. These decisions were packaged into a work order and schedule, and the digital twin was updated to reflect the planned envelope, mechanical, and structural changes.

4.3 Decision artifacts and KPI scorecard

The framework reports results as a small set of decision artifacts designed for approvals and funding conversations. It supports renovation choices using energy, comfort, cost, carbon, moisture, and structural indicators. These outputs make uncertainties transparent, show what will be done on site, and explain where contingencies are required. The four primary artifacts are: (i) an Assumption and Uncertainty Register, (ii) a Scope-of-Work Map (keep, repair, replace, verify), (iii) a Risk-to-Contingency Summary, and (iv) a plain-language KPI Scorecard.

Table 3. Key performance indicators comparing baseline conditions and post-retrofit target/estimated performance for the pilot house.

Indicator	Before Retrofit (Baseline)	Post-Retrofit Target/Estimated Performance	Improvement
Energy Use Intensity (site)	180 kWh/m²/yr	110 kWh/m²/yr	**≈39% reduction**
Heating energy (natural gas)	1200 therms/yr	0 therms/yr (eliminated; now electric)	100% fossil elimination
Electricity use	6000 kWh/yr	8000 kWh/yr (heat pump added)	– (energy source shifted)
Utility cost (annual)	~$2400	~$1700	~30% reduction
Infiltration (ACH50)	18 ACH50	7.5 ACH50	~58% tighter
Attic Insulation	R-11 (poor)	R-50	–
Wall insulation	R-2 (none effectively)	R-10 (moderate)	–
Peak indoor summer temperature	33°C (with 32°C outdoor, no AC in one room)	28°C (with heat pump cooling)	~5°C reduction, plus uniform AC
Winter bedroom night temp	15°C (at coldest night)	19°C	+4°C improvement
Indoor RH (basement)	70-75% RH	50-60% RH	safer range achieved
Mold or damp spots	Several in the basement, bathroom	Target: none visible or measured after verification	Issue resolved
Structural safety	Floor joist deflection felt, crack in wall (risk medium)	Joists reinforced (L/360 met), crack stabilized (risk low)	Structural risks mitigated

Embodied carbon of retrofit	0 (no retrofit yet)	~5.5 tons CO_2 added (materials)	–
Operational carbon (annual)	~8.5 tons CO_2/yr (4 gas, 4.5 elec)	~4.5 tons CO_2/yr (all electric)	~47% reduction
Embodied vs Operational ratio	–	Retrofit embodied = ~1.2 years of baseline emissions	Payback ~1.2 years

5. Results and Findings

The pilot application demonstrates that the Adaptive Digital Twin Framework can transform fragmented building information into a structured renovation decision pathway. The baseline assessment revealed three main categories of uncertainty: physical condition uncertainty, performance uncertainty, and financial uncertainty. Physical condition uncertainty involved unclear structural integrity, possible moisture intrusion, envelope deterioration, and incomplete documentation. Performance uncertainty involved unknown infiltration levels, weak envelope thermal performance, indoor comfort concerns, and uncertain energy use intensity. Financial uncertainty involved an unknown repair scope, potential hidden defects, and difficulty estimating contingency allowances before verification.

The framework addressed these uncertainties by separating known evidence from assumed inputs. Known evidence included visible building geometry, photographs, available drawings, field observations, and visible signs of deterioration. Assumed inputs included envelope thermal values, infiltration estimates, material condition in inaccessible zones, and likely mechanical performance. Each assumption was assigned a verification pathway so that the digital twin could be progressively improved instead of treated as a fixed model. However, it should be noted that a DT is not a one-time model but an evolving representation updated through capture, analysis, delivery, and operation.

The retrofit scorecard showed that not all measures produced equal decision value. Air sealing, attic insulation, basement moisture mitigation, ventilation upgrades, crack stabilization, and selected joist repairs emerged as high-priority interventions because they combined relatively strong performance benefits with safety, comfort, durability, or health benefits. In contrast, full window replacement produced a weak payback result despite comfort and noise benefits, making window retention with weatherstripping and storm panels a more balanced low-carbon strategy.

The KPI comparison showed meaningful improvement between the baseline and retrofit-informed scenario. Energy Use Intensity was reduced from 180 kWh/m²/year to 110 kWh/m²/year, representing an estimated 39% reduction. Annual utility cost declined from approximately $2,400 to $1,700, representing about 30% savings. Infiltration improved from 18 ACH50 to 7.5 ACH50, indicating a substantially tighter envelope. Indoor comfort also improved, with peak summer indoor temperature reduced by approximately 5°C and winter bedroom temperature improved by approximately 4°C. Moisture conditions improved from 70–75% relative humidity in the basement to a safer 50–60% range. Operational carbon was reduced from approximately 8.5 tons CO_2/year to 4.5 tons CO_2/year, representing about 47% reduction.

These findings show that the digital twin did not function merely as a visualization model. It served as a decision-support system that linked building condition, retrofit scope, energy performance, comfort, carbon, cost, and verification needs. The most important result is that the framework made uncertainty visible and actionable. Instead of treating unknowns as barriers to renovation, the framework converted them into assumption registers, verification tasks, and contingency logic.

6. Discussion

The findings suggest that digital twins can be more useful in underserved housing renovation when they are designed as adaptive decision-support systems rather than high-cost, fully instrumented replicas of buildings. In distressed housing contexts, the first need is not always a perfectly detailed model. The first need is a reliable decision pathway that helps stakeholders determine whether a property can be stabilized, what interventions should be prioritized, what risks remain uncertain, and how funding should be allocated.

For RQ1, the study shows that digital twin technology can be modified for underserved renovation by reducing dependence on expensive sensing and emphasizing staged data capture, progressive verification, and plain-language decision artifacts. The six-stage ADTF workflow allows the project team to begin with available evidence and improve the model over time.

For RQ2, the study identifies a practical minimum dataset for low-cost digital twin development. This includes photographs, basic measurements, available drawings, building age, visible condition indicators, envelope assumptions, utility data where available, and targeted field checks. These inputs are not perfect, but they are sufficient to create a decision-grade model when uncertainty is clearly labeled and verification steps are defined.

For RQ3, the pilot application suggests that digital twin-informed renovation can produce measurable benefits across energy, comfort, cost, carbon, and safety indicators. The results indicate that high-impact, lower-cost measures such as air sealing, attic insulation, moisture mitigation, and targeted structural repair can produce stronger decision value than expensive measures with long payback periods. This finding is important for underserved communities, where funding is limited, and renovation decisions must balance safety, affordability, sustainability, and long-term performance.

Compared with conventional renovation planning, the ADTF approach offers three advantages. First, it improves transparency by separating observed evidence from assumed values. Second, it supports better contingency planning by connecting uncertainty to specific risk drivers. Third, it improves communication by translating technical outputs into a scope map, scorecard, and verification plan that non-expert stakeholders can understand. The main strength of this approach is that it treats uncertainty as something that can be managed, not ignored. By making assumptions explicit and testable, stakeholders can move forward with bounded risk, better-sized contingencies, and a clearer path to verification. The method also supports sustainability outcomes by comparing retain-versus-replace options and highlighting embodied carbon savings from structural and envelope retention.

7. Practical Implications

The framework has practical implications for public agencies, nonprofit housing organizations, universities, contractors, and community development partners. For public agencies, the framework can support screening and prioritization of aging housing units before allocating rehabilitation funds. For nonprofit organizations, it provides a transparent way to document building needs and justify grant-supported interventions. For contractors, it helps clarify scope, sequencing, and risk allowances before construction begins. For homeowners, it provides a plain-language explanation of what is wrong, what should be repaired, what can be retained, and what performance benefits may result. For universities and research laboratories, it offers a scalable model for combining digital twin research with community-engaged housing restoration.

The framework is also relevant to environmental justice because it helps underserved communities access the same quality of technical decision support that is often available in better-funded renovation projects. By relying on low-cost capture tools, structured assumptions, and progressive verification, the method lowers the technical barrier to digital twin adoption while still supporting energy efficiency, carbon reduction, comfort improvement, and safer housing outcomes.

8. Scalability and Implementation Considerations

The framework is designed to be scalable for many small projects by keeping tools modular and costs low. From the scalable digital twin literature for residential projects, practical adoption improves when workflows rely on commonly available modelling tools (BIM and lightweight 3D), simple databases for component tracking, and optional low-cost sensing rather than expensive always-on platforms. In practice, communities can start with smartphones and open or low-cost software, then grow capability over time (e.g., adding structured asset inventories, maintenance schedules, and periodic inspections).

For institutions such as universities, city programs, and community development organizations, the same workflow can be packaged as a repeatable kit: templates for capture logs, envelope default libraries by era, short screening checklists, and a standard set of decision artifacts. This reduces dependence on expert-only knowledge and helps scale renovation planning across multiple properties.

9. Limitations and Future work

This study has several limitations. First, the framework is demonstrated using a pilot case, so the findings should be interpreted as proof-of-concept rather than universal performance evidence. Additional case studies across different housing types, ages, occupancy conditions, and neighborhood contexts are needed to validate the framework.

Second, early-stage digital twin development under partial observability depends on proxy indicators and typology-based assumptions. These assumptions are useful for preliminary decision-making, but they may not fully capture hidden defects such as concealed moisture damage, structural decay, unsafe electrical conditions, or undocumented modifications. For this reason, the framework should not replace professional structural, mechanical, or code inspections. Instead, it should guide where those inspections are most needed.

Third, energy and comfort estimates are sensitive to uncertain variables such as occupant behavior, infiltration, thermostat settings, equipment efficiency, and weather normalization. Future work should improve calibration using utility bills, blower-door testing, thermal imaging, and post-retrofit monitoring where feasible.

Fourth, cost and payback values may vary by location, contractor pricing, material availability, labor conditions, and funding program requirements. Future versions of the framework should include localized cost libraries and uncertainty ranges for different renovation markets.

10. Conclusion

This paper presented an Adaptive Digital Twin Framework for renovation decision-making in underserved housing contexts where full information is often unavailable at the beginning of a project. The framework responds to a critical problem in housing rehabilitation: many aging and vacant homes remain difficult to restore because stakeholders lack reliable information about structural condition, moisture risk, retrofit scope, cost exposure, and post-renovation performance.

The proposed six-stage workflow — Capture, Assemble, Analyze, Decide, Deliver, and Verify/Operate — provides a practical method for converting incomplete building evidence into structured renovation decisions. Rather than treating missing data as a reason to delay action, the framework converts uncertainty into bounded assumptions, verification tasks, scope decisions, and contingency logic. The pilot application demonstrated how the framework can support decisions across energy performance, comfort, moisture control, structural safety, utility cost, embodied carbon, operational carbon, and payback.

The main contribution of this study is an underserved-first digital twin model that is affordable, adaptive, and decision-focused. It does not require a fully instrumented building or perfect documentation before useful decisions can be made. Instead, it enables progressive improvement as more evidence becomes available. This makes the framework especially relevant for distressed housing, community development programs, nonprofit rehabilitation work, and public-sector housing initiatives.

Overall, the study shows that digital twins can move beyond visualization and technical simulation to become practical tools for equitable housing restoration. By making uncertainty visible, testable, and communicable, the ADTF can help accelerate safe, energy-efficient, and sustainable renovation in communities that need it most.

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