Digital Twins for Development in Brazilian Public Housing: A Conceptual Framework for Scenario Planning, Energy Efficiency, Predictive Maintenance, Structural Durability, and Mixed-Use Economic Feasibility

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Abstract— *Digital Twins (DTs) are evolving from isolated pilots into decision infrastructures for the built environment. This paper proposes DT4D (Digital Twins for Development), a conceptual framework tailored to Brazilian public housing estates. DT4D integrates multi-scale scenario planning for retrofit and land use reconfiguration, DT-driven energy optimisation, predictive maintenance for critical building systems, hybrid physics and machine learning models for structural durability, and economic appraisal of mixed-use redevelopment (housing plus retail and services) to improve neighbourhood integration and urban quality. The paper contributes a consolidated architecture linking operational building data to discounted cash flow simulation, value capture instruments, and performance-based finance, plus five testable hypotheses, a measurement model, a validation blueprint, and an implementation roadmap.*

Keywords— *digital twins; public housing; mixed-use development; energy efficiency; predictive maintenance; structural durability; urban economics; value capture.*

I. INTRODUCTION

Brazilian public housing estates frequently face reactive maintenance, premature deterioration, inefficient energy use, and limited integration with surrounding services and commerce. Conventional retrofit practices often optimise isolated subsystems and rarely connect technical decisions to financial feasibility and neighbourhood outcomes. Digital Twins, defined here as continuously synchronised cyber-physical replicas combining sensing, BIM or IFC representations, and analytics, can support lifecycle management and intervention planning.

The feasibility of high-resolution digital representation in Brazil has been demonstrated using UAV-based workflows in complex settlements [2]. DT value for infrastructure operations has been illustrated in Brazilian sanitation modernisation initiatives [10]. Urban DT literature supports planning use cases with geospatial integration and multi-stakeholder decision support [4]. However, research remains fragmented when linking DT operational analytics (energy, reliability, durability) to development feasibility, particularly mixed-use programming and value capture mechanisms that enable financially sustainable upgrades. DT4D is proposed to bridge this gap.

Contributions of this paper:

(1) A DT-to-development conceptual architecture connecting building performance analytics to economic feasibility, value capture, and performance-based finance.

(2) Five hypotheses with measurable outcomes spanning scenario planning, energy, maintenance, durability, and mixed-use feasibility.

(3) A measurement model and a validation blueprint suitable for empirical studies in Brazilian cities.

(4) A policy and implementation roadmap for scaling.

II. SCOPE, ASSUMPTIONS, AND LIMITATIONS

A. Scope

This is a conceptual and propositional paper. It consolidates a system model, hypotheses, metrics, and evaluation designs. It does not claim empirical impact results.

B. Assumptions

(1) Minimum data layer: at least energy metering and core environmental sensing can be deployed and maintained.

(2) Actionability: the operator can act on insights (dispatch maintenance, adjust schedules, plan retrofits).

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(3) Planning feasibility: governance can permit limited retail or service space (ground floor or perimeter).

(4) Economic observability: rent benchmarks, vacancy signals, and footfall proxies can be obtained from public or private sources.

C. Limitations

(1) Interoperability: legacy municipal datasets may constrain completeness.

(2) Cybersecurity and privacy: expanded sensing increases exposure and requires privacy by design and security controls.

(3) Market volatility: mixed-use feasibility is sensitive to local demand; sensitivity and risk analysis are mandatory.

(4) Equity risk: redevelopment and value uplift can create displacement pressure if safeguards are absent.

III. RELATED WORK

UAV-based modelling demonstrates rapid digitisation workflows applicable to complex Brazilian contexts [2]. The adoption of urban digital twins has been discussed in the broader urban systems literature [4]. DT-driven methods for improving building energy performance include deep learning and simulation coupling [1], and DT integration with energy management tools supports coordinated control of multi-vector energy systems [6]. National and bilateral reports describe the potential of digitalisation to improve energy efficiency in Brazil's building sector [5], [13]. Predictive maintenance is enabled by time-series modelling and anomaly detection, supporting a shift toward condition-based strategies [6]. Structural durability modelling benefits from calibration with inspection and non-destructive testing data, which DTs can systematise [7]. Mixed-use and housing supply economics motivate the use of feasibility analysis under uncertainty and the importance of local market dynamics [14]. Value capture provides instruments to convert part of land value uplift into reinvestment streams for public goals [9].

IV. DT4D CONCEPTUAL MODEL

DT4D links operational digital twin intelligence to development planning and finance.

A. Data Acquisition

Building operations: meters, submeters, equipment logs. Environment and comfort: temperature, humidity, CO2 proxies. Condition monitoring: vibration for pumps and fans, leak detection where feasible. Structural inspections: NDT data, crack mapping, carbonation depth samples [7]. Geospatial context: UAV or LiDAR, cadastral and zoning datasets [2]. Market and urban proxies: rent benchmarks, vacancy signals, footfall estimators [14].

B. Semantic Integration

BIM or IFC representations are linked to sensor and inspection data through semantic mappings so assets, systems, and spaces maintain a consistent hierarchy.

C. Analytics Core

(1) Scenario Planning Engine: compares retrofit and land use alternatives with sensitivity analysis [4].

(2) Energy Optimiser: combines simulation and learning-based control to reduce EUI and peak demand [1], [6].

(3) Predictive Maintenance Module: prognostics and anomaly detection to trigger work orders [6].

(4) Structural Durability Kernel: hybrid physics and ML estimation of residual service life [7].

(5) Economic Feasibility Simulator: DCF plus Monte Carlo, with vacancy, rent growth, tariffs, inflation, cap rate sensitivity, plus value capture modules [9], [14].

(6) Urban Integration Module: service accessibility, footfall effects, perceived safety proxies, satisfaction feedback loops, informed by urban-scale DT practice [12].

D. Decision and Finance Interface

Outputs include technical KPIs (EUI, MTBF, MTTR, residual life index), economic KPIs (NPV, IRR, payback, downside risk), and urban quality indicators (accessibility index, perceived safety).

V. HYPOTHESES

H1 Scenario planning: DT multi-scenario simulation reduces retrofit cost forecast error by at least 25% versus conventional planning [4].

H2 Energy efficiency: DT optimisation reduces EUI by at least 18% and peak demand by at least 12% within 12 months [1], [6].

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H3 Predictive maintenance: DT prognostics reduce MTTR by at least 40% and increase MTBF by at least 30% [6].

H4 Structural durability: hybrid physics and ML modelling improves residual service life estimation accuracy by at least 25% [7].

H5 Mixed-use feasibility: DT-enabled DCF plus Monte Carlo improves NPV and IRR forecasting accuracy by at least 20% and increases blended finance approval likelihood by at least 15% [9], [14].

VI. MEASUREMENT MODEL

Technical: EUI, peak load, comfort deviation hours; MTBF, MTTR, failure rate; RSL and corrosion probability indicators.

Economic: NPV, IRR, payback, OpEx reduction, maintenance cost avoidance; retail revenue, vacancy, churn, volatility bands.

Urban quality: accessibility index, footfall proxy change, perceived safety surveys, resident satisfaction.

VII. VALIDATION BLUEPRINT

Design: longitudinal pilots in multiple climate zones; matched quasi-experiments against control estates; before-after interventions aligned to scenario outputs.

Data: baseline audits; sensor deployment and calibration; periodic NDT and inspections for durability calibration [7]; local market and service mapping for mixed-use feasibility [9], [14].

Analysis: difference-in-differences for energy and reliability; hierarchical modelling for heterogeneity; Monte Carlo DCF stress testing for demand, tariffs, inflation, cap rates [14].

VIII. IMPLEMENTATION ROADMAP

(1) Regulatory sandbox and standardised data sharing agreements.

(2) Procurement templates requiring IFC and interoperability clauses.

(3) Public-private-community partnerships with equity safeguards and reinvestment rules supported by value capture [9].

(4) Capacity building for municipal operators.

(5) Open data where possible plus privacy by design and security controls.

IX. DISCUSSION

DT4D treats the DT as a decision environment that connects asset performance to development feasibility and neighbourhood integration. Mixed-use activation is framed as an urban qualification strategy that can improve service accessibility and local vitality, but it must be coupled with equity safeguards so that benefits are reinvested and displacement risks are reduced [9], [14]. DT4D operationalises this by quantifying energy and maintenance savings that de-risk financing [1], [6], supporting zoning and stakeholder negotiation through scenario evidence [4], and verifying performance for value capture and performance-based finance [9].

X. CONCLUSION AND FUTURE WORK

DT4D provides a coherent foundation for transforming public housing estates by connecting operational analytics, structural risk management, and development economics. The framework consolidates scenario planning, energy optimisation, predictive maintenance, durability modelling, and mixed-use appraisal into one architecture with explicit hypotheses and measurable indicators.

A key implication is that DT4D enables a shift from reactive interventions to a portfolio approach that prioritises upgrades based on quantified trade-offs among cost, performance, safety, and neighbourhood outcomes. Energy and maintenance savings can become bankable cash flows when measured and verified, supporting performance-based contracting and blended finance structures. Durability modelling becomes a continuous risk management layer, improving decisions about when to reinforce, rehabilitate, or replace components. Mixed-use feasibility analysis becomes less speculative because DT4D reduces uncertainty in operating costs, demand assumptions, and performance verification, while value capture can create reinvestment streams that keep benefits local.

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Future work should empirically test H1 to H5 through staged pilots across different climatic regions and typologies, refine the urban integration module with stronger behavioural evidence, and extend the economic simulator to incorporate climate adaptation scenarios and policy instruments. A governance reference model is also needed, including interoperability standards, privacy patterns, and procurement requirements, so DT4D can be replicated across municipalities while avoiding vendor lock-in.

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