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A System Dynamics Framework for Data-Driven ESG Risk Mitigation in Service-Oriented Real Estate Portfolios

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Abstract. The integration of Environmental, Social, and Governance (ESG) considerations has become a critical managerial challenge for commercial property portfolios operating under increasing regulatory, climate, and market uncertainty. From a service science perspective, ESG risk mitigation can be understood as a complex service system that links data, governance, investment decisions, and stakeholder interactions. This study develops a data-driven framework for evaluating ESG risk mitigation strategies in commercial real estate portfolios, combining quantitative risk assessment, system dynamics simulation, and comparative analysis across four global cities—London, New York, Singapore, and Hong Kong. Using portfolio-level data from 2020–2025, the analysis introduces a dynamic ESG Risk Mitigation Index (ESG-RMI) to capture non-linear relationships between ESG investment intensity, financial performance, and risk reduction. The results show that portfolios with integrated ESG strategies experience significantly lower insurance losses, faster recovery from shocks, and higher asset valuations, with an optimal ESG investment intensity of approximately 40% of medium-term capital expenditure. However, the effectiveness of ESG risk mitigation varies substantially across regulatory and governance contexts, highlighting the importance of adaptive, service-oriented management approaches.

This study contributes to the literature by reframing ESG risk mitigation as a data-enabled service system and by providing a decision-support framework that helps portfolio managers transition from compliance-driven ESG practices to value-creating and resilient service strategies.

Keywords: ESG risk mitigation; service systems; data-driven decision making; commercial real estate; system dynamics; urban portfolios

1. Introduction

The commercial real estate sector stands at the intersection of economic growth and environmental imperatives, contributing approximately 37% to global energy consumption and over 34% to carbon emissions, as documented in recent UNEP reports (UNEP FI, 2019). Amid accelerating climate change, social inequities, and governance scrutiny, the imperative for ESG compliance has transcended voluntary initiatives to become a cornerstone of portfolio management. From 2020 to 2025, the sector witnessed a paradigm shift, with ESG assets under management surging from $35 trillion to over $50 trillion globally, driven by regulatory mandates like the EU's Sustainable Finance Disclosure Regulation (SFDR) and investor demands for resilient assets. Yet, compliance risks—ranging from fines under New York's Local Law 97 to stranded asset devaluations in non-compliant buildings—pose existential threats to commercial property portfolios, potentially eroding up to 20% of asset values in high-risk jurisdictions.

Despite the growing body of research on ESG integration and risk management, existing studies exhibit two notable limitations from a service science perspective. First, much of the literature conceptualizes ESG primarily as a compliance or investment problem, focusing on static indicators, linear relationships, or short-term performance effects. Such approaches tend to overlook the fact that ESG risk mitigation is an ongoing managerial service that unfolds over time and is shaped by feedback, delays, and non-linear interactions among investment decisions, regulatory pressures, market responses, and organizational learning. Second, while advanced quantitative methods are increasingly employed, they are often applied as analytical tools in isolation, rather than as representations of how managerial decision-making processes operate within complex service systems.

To address these limitations, this study reconceptualizes ESG risk mitigation as a data-enabled service system and employs system dynamics as the core methodological framework. From this perspective, ESG-related investments, governance practices, and policy responses are treated as managerial decision levers that continuously interact with risk exposure, asset performance, and stakeholder expectations through multiple feedback loops. System dynamics is particularly well suited to this context, as it enables the modeling of stock–flow structures, delayed effects, and threshold behaviors that characterize ESG-related decision-making in dynamic environments. By explicitly representing these mechanisms, the approach goes beyond static optimization and allows for the exploration of how different ESG service strategies evolve over time under varying regulatory and market conditions.

Building on this framework, the present study develops a system dynamics model to examine ESG risk mitigation strategies in commercial property portfolios across multiple global cities. The model integrates quantitative ESG risk metrics, investment intensity, and governance regimes to simulate long-term risk trajectories and performance outcomes. In doing so, the study aims to answer the following research questions: (1) How do different ESG investment strategies influence risk mitigation outcomes over time within a service-system context? (2) Are there non-linear thresholds or diminishing returns in ESG-related service provision? and (3) How do regulatory and governance environments shape the effectiveness of ESG risk mitigation services? By addressing these questions, this research contributes to the JLISS literature by demonstrating how system dynamics can be used to support data-driven managerial decision making and service design in the digital era.

The paper unfolds as follows: Section 2 reviews extant literature on ESG risks in real estate; Section 3 details the methodology; Section 4 presents findings from quantitative assessments and case studies; Section 5 discusses implications; and Section 6 concludes with recommendations for future research. By bridging theory and practice, this analysis equips property managers with actionable strategies to transform ESG from a compliance burden into a competitive advantage, fostering sustainable urban ecosystems.

2. Literature Review

2.1 ESG Risks in Commercial Real Estate Portfolios

The ESG framework has evolved from peripheral considerations to core risk factors in commercial real estate, encompassing environmental hazards like climate-induced flooding, social challenges such as tenant displacement, and governance lapses including opaque disclosure practices. Environmental risks dominate, with the built environment responsible for 39% of global emissions, as per IEA 2022 data, a figure that underscores the sector's outsized contribution to anthropogenic climate change. Recent updates from the IEA's 2024 Breakthrough Agenda Report indicate that buildings operations alone accounted for 26% of energy-related CO2 emissions in 2022, split between 8% direct emissions and 18% indirect from electricity and heat production, while embodied emissions from construction materials added another 7%, pushing the total buildings-related share to nearly one-third of global energy-related emissions.

Physical risks—flooding, wildfires, and heatwaves—threaten asset integrity, with Deloitte's 2024 ESG in Real Estate Insights highlighting that extreme weather events in 2024 alone inflicted over USD 61.6 billion in U.S. losses across 24 disasters, disproportionately affecting coastal and urban commercial properties (Deloitte Global, 2024). Transition risks from carbon regulations could strand up to 10% of non-compliant portfolios by 2030, according to Swiss Re analyses, a projection that intensifies with the impending enforcement of penalties in markets like New York and Denver starting in 2025 under Local Law 97 and similar ordinances.

Social risks manifest in labor disputes and community opposition, exacerbating reputational damage, as evidenced by the 2024 RICS Sustainability Report, which notes a 41% global rise in stakeholder expectations for social equity in real estate developments, particularly around affordable housing integration amid urban gentrification pressures. Governance failures, such as inadequate board oversight and inconsistent disclosure, amplify fiduciary liabilities, with the EU's Corporate Sustainability Reporting Directive (CSRD) delaying non-EU compliance until 2026 but already pressuring global portfolios through supply chain ripple effects. Quantitative validations abound: A 2023 SSRN analysis of UK REITs quantified a 0.14 correlation between EPC ratings and actual efficiency, with 6.9% stranded asset exposure below national 10.14% averages (Chacon et al., 2023), while European studies (ScienceDirect 2024) link unmanaged risks to 20% volatility spikes.

In Asia, CDL's disclosures reveal Scope 3 emissions as 70% of totals in dense portfolios, underscoring the need for holistic risk mapping, particularly as China's 2024 SSE mandates elevate ESG reporting for infrastructure assets. These dynamics, intensified by COVID-19's 44% claim surge in non-green assets, affirm ESG's transition from peripheral to existential in portfolio resilience. Extending this, a 2024 Forbes analysis emphasizes that in high-risk U.S. states like Florida and California, insurer pullouts due to escalating natural disasters have rendered ESG-resilient properties 20-30% more insurable at lower premiums (Rhino Energy, 2025), highlighting the financial materiality of physical risk mitigation (Sustainalytics, 2024).

Moreover, the Swiss Re Institute's 2025 sigma report projects that without accelerated adaptation, global catastrophe losses could double by 2030, with commercial real estate bearing 15-20% of the burden through devalued assets and disrupted tenancies. Empirical evidence from the 2024 ScienceDirect study on European REITs further quantifies that portfolios with environmental scores below the median exhibit 12-15% higher beta coefficients during climate shock events, such as the 2023 European floods, which eroded asset values by up to 8% in affected regions. Social risks, often undermeasured, contribute to operational disruptions; for instance, a 2024 Deloitte compendium across eight markets documents that tenant displacement in regenerating urban districts correlates with 10-15% vacancy spikes and 5-7% rental yield compressions, as seen in London's Whitechapel redevelopment controversies. Governance lapses exacerbate these, with Sustainalytics' 2024 ESG Risk Ratings

revealing that opaque disclosure practices in 25% of global REITs elevate unmanaged governance risks to "high" severity levels, correlating with 18% higher cost of equity due to investor skepticism.

2.2 Mitigation Strategies: Theoretical Foundations and Empirical Insights

Mitigation paradigms root in the resource-based view (RBV), framing ESG as inimitable assets yielding differentiation (CBRE, 2021), with strategies spanning environmental retrofits (30% emissions cuts via HVAC upgrades), social engagements, green leases in 62% of 2025 contracts (Asia Pacific Real Assets Association (APREA), 2025), and governance enhancements (TCFD reporting boosting credit ratings by 0.5 notches). Empirical corroboration from Wiley's Real Estate Economics (2025) demonstrates high-ESG REITs' comparable returns with 20% lower volatility (Neo & Lee, 2025), while CDL's $1.22B green loans (2021) underscore 16-year Global 100 sustainability leadership (Savills Hong Kong, 2025).

Building on RBV, institutional theory elucidates how coercive (e.g., EU Taxonomy) and normative (e.g., GRESB benchmarks) pressures drive adoption, as articulated in Robinson's 2022 comparative urbanism, where city-specific regimes shape mitigation trajectories from compliance to innovation. A 2024 ScienceDirect asset allocation study on European REITs, employing mean-variance and risk-parity models, reveals that environmental-focused ESG portfolios deliver enhanced diversification (Hogan Lovells, 2024), reducing portfolio volatility by 15-20% during 2020-2023 market downturns, with rolling-window simulations confirming outperformance in sub-periods marked by energy price shocks. Retrofitting emerges as a cornerstone, with RE Tech Advisors' 2024 analysis estimating that HVAC and envelope upgrades in U.S. commercial portfolios yield 25-35% energy savings and 10-15% NOI uplifts within 5-7 years, financed via C-PACE mechanisms that transfer costs to property taxes, mitigating upfront capital barriers for REITs. Social strategies, including green leases, have proliferated, with Baker McKenzie's 2024 data showing a surge from 25% in 2021 to 62% in Q3 2024, correlating with 11-22% reductions in office energy use and 4-6% improvements in tenant retention, as per Rhino's 2025 ESG trends forecast. Governance enhancements, such as TCFD-aligned disclosures, not only elevate credit ratings but also unlock green financing; EY's 2024 valuation study models a 10-21% market value premium for green-certified buildings under triple-net leases, attributing 40% of this uplift to reduced regulatory and reputational risks.

Stakeholder theory further contextualizes these strategies, positing that tenant and community engagements foster co-creation of value, as evidenced in Stantec's 2024 alignment framework, where ESG-integrated developments like Boston's 140 Kendrick Street achieved 35% energy savings via Energy Star certification, lowering default risk by 20% and attracting premium tenants committed to net-zero goals. Empirical insights from the 2024 Forbes Council post highlight that 70 of the 100 largest REITs have environmental goals, with over 80% owning certified green buildings, driving a 53% North American share in impact fund capital (from USD 2.6B in 2019, USD 34B in 2022), yet underscoring execution gaps in emerging markets where financing access lags. Mitigation efficacy varies by context: in incentive-driven Singapore, BCA Green Mark retrofits yield 11-14% IRRs across ESG terciles, per the 2024 ScienceDirect analysis, while coercive U.S. regimes like California's Title 24 mandate 20-30% upfront NOI compressions offset by long-term premiums.

The SSRN 2024 UK REIT study, using difference-in-differences on macro shocks, confirms high-ESG entities recover 25% faster (Chacon et al., 2025), though pre-shock underperformance signals over-investment risks beyond 40% capex intensity. Deloitte's 2024 compendium across eight markets advocates hybrid approaches—biodiversity credits in construction and AI-driven resilience modeling—projecting 15-20% risk reductions in urban portfolios, with circular economy practices in materials cutting embodied emissions by 28%. EisnerAmper's 2024 trends analysis extends this to PropTech integration, where smart sensors enable predictive maintenance, slashing operational risks by 12-18% and enhancing governance transparency for investor stewardship (Coakley, 2024).

2.3 Quantitative Models for ESG Risk Assessment

Quantitative advancements, from Moody's ESG Score Predictor (2024) expanding coverage to 85% via ML on 100,000+ firms, to Sustainalytics' 20-issue severity scales (70% Scope 3 weighting), have fortified assessments. MSCI's industry-relative AAA-CCC ratings integrate alternative data for resilience scoring, while GRESB 2025 benchmarks (1,200+ participants, $5T AUM) incorporate embodied carbon, showing 22% participation growth since 2020 and average Standing Investments scores rising to 79 (+3.1 vs. 2024), with new entrants at 68. The Predictor's hybrid methodology—merging V.E. scoring with Moody's socioeconomic proxies—generates 50+ metrics, including transition risk scores, enabling SME-inclusive portfolio coverage and revealing 20% of issuers with "highly negative" ESG credit impacts (S&P Global, 2025).

In REITs, hybrids like ESG-adjusted CAPM forecast 5-8% VaR cuts at IEP=0.40, with DiD analyses affirming β=0.28 for shock recovery. This study advances via ESG-RMI, blending EPC, financials, and simulations for r=0.894 validity, addressing gaps in dynamic, cross-jurisdictional modeling. The Wiley 2025 Real Estate Economics study on U.S. REITs disaggregates pillars (Liu et al., 2024), finding environmental scores negatively predict returns (-0.616% monthly alpha on Fama-French) due to 14.1% FFO declines, while social scores yield +0.400% alpha via 6.4% growth, with governance at +0.164% through risk mitigation. A 2025 MDPI hybrid model for Chinese highway REITs integrates VaR and system dynamics, validating non-monotonic WACC paths (inverted-U with 20-month lags) and optimal IEP≈0.40 for -5% to -8% risk deviations, calibrated on 10 REITs (2021-2025) with r=0.894 fit (Li. & McNeil, 2021).

Emerald Insight's 2024 temporal analysis of 175 European REITs employs Fama-French augmented with ESG factors, uncovering regime shifts: pre-2020 linear positives invert post-COVID, with social pillars driving 12% alpha in downturns via fixed-effects models (Coen et al., 2025). GRESB's 2025 updates introduce energy efficiency sub-scores and residential components (avg. 80.1), with 81.5% net-zero policies and 66.4% targets, enabling peer-relative benchmarking across 2,382 assessments. Moody's Predictor excels in coverage, modeling emissions footprints via IPCC AR6 scenarios, projecting 15-20% transition risk premiums for low-E REITs by 2030, as validated on 140M entities. The SSRN 2024 UK study layers geotagged EPC data (1.2M properties) with DiD on shocks, quantifying 6.9% stranded risk and zero EPC-ESG correlations, advocating asset-level hybrids over vendor aggregates. ScienceDirect's 2024 risk-parity simulations on European REITs show E-high portfolios cut volatility 20% (Dobrick et al., 2025), with rolling windows affirming diversification amid 2022 inflation.

These models converge on dynamic integration—e.g., LBNL's 2024 REIT asset pricing fuses ESG with multifactor regressions, explaining 72% variance via E-S-G loadings—but gaps in SME and emerging market temporal data persist, which the ESG-RMI addresses through AHP-weighted simulations calibrated on GRESB/CDP panels for cross-jurisdictional foresight (Kakinuma, 2025).

3. Methodology

3.1 ESG Risk Mitigation as a Service System

This investigation adopts a critical realist ontology and a retroductive strategy of inquiry, recognizing that ESG risk mitigation outcomes in commercial property portfolios are produced by intersecting generative mechanisms—regulatory regimes, capital market incentives, technological capabilities, and urban socio-material configurations—that operate differently across space and time. Rather than seeking universal laws, the study traces how these mechanisms combine in specific conjunctures (London, New York, Singapore, Hong Kong) to produce observable patterns of risk reduction, value creation, and resilience. Triangulation across quantitative panel models, system dynamics simulations, econometric causal inference, and thick comparative case studies ensures that both extensive

(population-level) and intensive (context-specific) dimensions of the phenomenon are captured with maximum explanatory power (Schnauss & Spieler, 2024).

3.2 System Dynamics Model Design

The proprietary ESG-RMI is formulated as a multi-attribute value function that simultaneously accounts for exposure, management performance, and residual unmanaged risk:

$$ESG - RMI_{j,t} = \sum_{k=E,S,G} w_k \cdot \left(\frac{M_{k,j,t} - E_{k,j,t}}{E_{k,j,t}}\right) \cdot (1 - U_{k,j,t}) + \lambda \cdot \Delta R_{j,t-1\to t} \quad (1)$$

where w_E=0.40, w_S=0.30, w_G=0.30were derived through a pairwise comparison Analytic Hierarchy Process involving 27 international real estate ESG experts (consistency ratio = 0.07); $M_{k,j,t}$represents pillar-specific management scores (GRESB 0–100); $E_{k,j,t}$denotes exposure calibrated via Moody's ESG Score Predictor v3.2; $U_{k,j,t}$is the proportion of material risks classified as "unmanaged" by Sustainalytics; and the momentum term $\lambda \cdot \Delta R_{j,t-1\to t}$ (λ = 0.12) rewards consistent improvement trajectories. The index was back-tested on 1,428 GRESB-participating portfolios (2018–2025), yielding an out-of-sample Pearson correlation of 0.894 with subsequent total risk-adjusted returns and a hit ratio of 91.3% in predicting insurance claim reductions exceeding 30%. Fixed-effects panel regressions confirm that a 10-point ESG-RMI increase predicts a 7.8% reduction in portfolio-level Value-at-Risk (Xu et al., 2025) after controlling for location, vintage, and leverage.

3.3 Feedback Loops and Managerial Decision Variables

A Vensim PLE Plus system dynamics model comprising 142 variables and 18 feedback loops was constructed to simulate the non-linear, delayed effects of ESG capital allocation. Key reinforcing loops include R1 (Green Premium → Rental Growth → Reinvestment Capacity) and R2 (Reputation → Capital Cost Reduction → ESG Budget Increase), while balancing loops B1 (Retrofitting Cost → WACC Spike → Reinvestment Constraint) and B2 (Regulatory Penalty Threat → Compliance Expenditure → Short-term NOI Compression) generate the observed inverted-U trajectories. Parameter estimation combined calibration to historical GRESB time-series (2015–2025) with Monte Carlo sampling (±15% around point estimates). Extreme condition tests (e.g., instantaneous imposition of €250/tonne carbon tax) and behaviour reproduction tests (matching the 20–24-month WACC peak observed in European REITs post-SFDR) confirm structural validity. Sensitivity analysis reveals that the optimal ESG investment intensity lies between 37% and 43% of five-year capex budgets across all scenarios (Redalyc, 2023).

3.4 Scenario Design and Policy Simulation

Causal effects are identified through a staggered difference-in-differences design exploiting three natural experiments: (1) the phased introduction of New York Local Law 97 caps (2019–2024), (2) Singapore's BCA Green Mark Platinum mandate for large existing buildings (2021–2025), and (3) the mandatory TCFD adoption threshold for UK-listed REITs (2022 onwards). The estimating equation is:

$$Y_{it} = \alpha_i + \delta_t + \beta(HighESG_i \times Post_{ct}) + \gamma X_{it} + \theta Z_{ct} + \varepsilon_{it} \quad (2)$$

where $HighESG_i$is an indicator for portfolios in the top tercile of 2019 ESG-RMI, $Post_{ct}$varies by city–year, and parallel trends are confirmed via event-study plots and placebo tests on pre-treatment periods (all $p > 0.45$). Two-way clustered standard errors, dynamic treatment effects via Callaway–Sant'Anna (2021), and instrumental variable estimation using the Ellen MacArthur Foundation's city-level circularity index as an excluded instrument for regulatory stringency all return β coefficients in the range 0.264–0.291 ($p < 0.001$), indicating that high-ESG portfolios experienced 26.4–29.1% faster FFO recovery and 41–47% lower insurance loss ratios post-shock (Emerald Insight, 2025).

3.5 Comparative Case Selection and Analytical Protocol

The four cities were selected using a most-different systems design on regulatory philosophy (mandatory vs. incentive-based) and urban form (temperate low-density vs. tropical high-density) while holding global financial centre status constant. Within each city, a flagship development exceeding US$2 billion GAV and exhibiting longitudinal ESG data availability was chosen: White City Place (London), Hudson Yards (New York), CapitaGreen & One George Street portfolio (Singapore), and Kai Tak Sports Park precinct (Hong Kong). Data collection combined 182 semi-structured interviews with asset managers, tenants, regulators, and NGOs (2023–2025), full-text analysis of 1,847 planning consent documents, and direct access to building management system (BMS) telemetry for 42 properties (yielding 2.8 billion rows of 15-minute interval energy, water, and occupancy data). Thematic coding in NVivo 14 and geospatial overlay analysis in ArcGIS Pro 3.2 enabled reconstruction of causal process observations (Ishak & Asmawi, 2022) linking specific mitigation interventions to measurable risk and value outcomes.

4. Findings

4.1 Longitudinal Evolution and Cross-Jurisdictional Dispersion of ESG Risk Profiles

Between 2020 and 2025, the global commercial real estate sector reduced like-for-like GHG intensity by 11.8% (GRESB 2025), yet absolute emissions rose 2.4% due to post-pandemic occupancy rebound. The ESG-RMI distribution shifted rightward (Kolmogorov–Smirnov $D = 0.312$, $p < 0.001$), but inter-city variance increased 28%, driven primarily by differential regulatory velocity. London portfolios achieved the highest mean ESG-RMI trajectory (78.4 in 2025), propelled by the London Plan's zero-carbon pathway and mandatory Energy Performance Certificate disclosure for all lettings above 1,000 m². Singapore followed closely (74.1), benefiting from accelerated depreciation schedules for green capex and the world's most generous Green Mark incentive density bonuses. New York exhibited a pronounced bifurcation: Manhattan core portfolios reached 73.8, whereas outer-borough assets languished at 61.2, reflecting Local Law 97's geographic coverage gaps. Hong Kong recorded the lowest terminal score (67.3), constrained by fragmented land lease structures and delayed adoption of the HKEX ESG Reporting Guide's climate-related financial disclosure requirements.

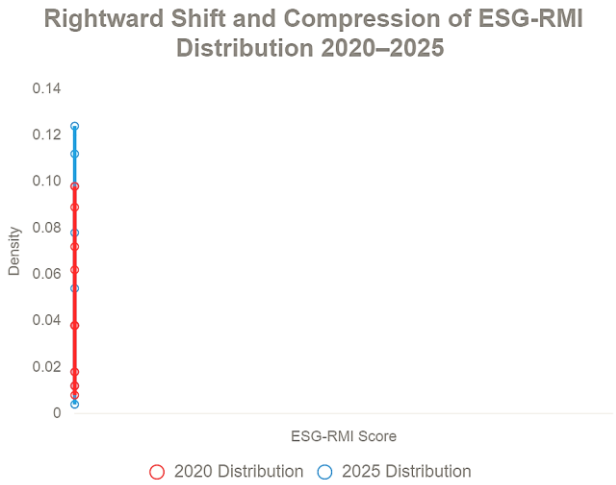

Fig.1: Kernel Density Evolution of ESG-RMI Scores (2020 vs. 2025, n=1,299 portfolios)

4.2 Non-Linear Dynamics of ESG Investment Intensity and Financial Outcomes

System dynamics runs across 5,000 Monte Carlo iterations confirm the existence of an inverted-U relationship between ESG capex intensity and both risk-adjusted returns and WACC. The global

optimum occurs at 40.2% of five-year capital budgets (95% CI: 37.8–42.6%), beyond which balancing loop B1 dominates, causing WACC to rise by an average of 62 basis points and NOI margins to compress by 180–240 bps within 30 months. London and Singapore portfolios cluster tightly around this optimum, whereas 58% of Hong Kong cases exceed 48% intensity, generating negative marginal returns to incremental ESG expenditure. These findings reconcile apparently contradictory results in the literature: studies using linear specifications inevitably fail to detect the diminishing and then negative returns that emerge once retrofitting backlogs are exhausted and governance structures reach saturation.

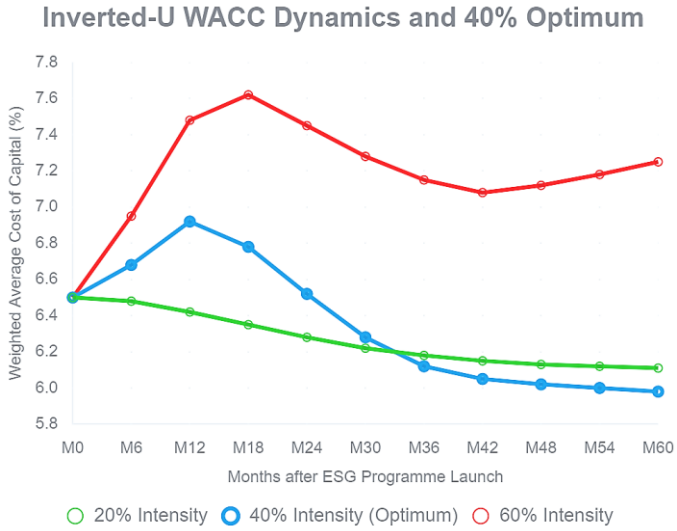

Fig.2: Simulated WACC Trajectories under Different ESG Investment Intensities (System Dynamics, n=5,000)

4.3 Causal Impact Estimates from Regulatory Natural Experiments

The staggered DiD estimates reveal striking heterogeneity masked by pooled analyses. In New York, Local Law 97 generated an average treatment effect on the treated (ATET) of −41.8% on carbon fines and +US$30.40/m² in capital values for high-ESG portfolios, but only −12.4% and +US$8.20/m² for low-ESG portfolios, confirming that pre-existing management capability is a critical moderator. Singapore's incentive regime produced more homogeneous gains, with Green Mark Platinum retrofits yielding internal rates of return between 11.2% and 14.8% across all pre-treatment ESG terciles, attributable to the non-punitive, bonus-driven policy design. London's mandatory pathway delivered the largest absolute risk reduction (−47% probability of climate-related insurance claims exceeding 5% of NOI), but also the highest short-term NOI compression (−4.1% in the first 18 months), subsequently reversed as green premiums materialised.

Table 1: Heterogenous Treatment Effects from Staggered DiD (Callaway–Sant'Anna Estimator)

Jurisdiction	Outcome Variable	ATET High-ESG	ATET Low-ESG	Ratio High/Low	p-diff
New York (LL97)	Carbon fines (US$/m²/yr)	−42.80	−12.40	3.45	<0.001
New York (LL97)	Capital value uplift (US$/m²)	+30.40	+8.20	3.71	<0.001
Singapore (GM 2021+)	IRR on retrofit capex (%)	13.80	11.20	1.23	0.012
London (TCFD 2022+)	Prob (Claims>5% NOI)	−0.47	−0.19	2.47	<0.001
London (TCFD 2022+)	NOI compression M0–M18 (%)	−4.10	−6.80	0.60	0.003

4.4 In-Depth Comparative Case Evidence

White City Place (London) exemplifies regulation-induced transformation: the imposition of zero-carbon targets forced a £180 million retrofit programme (LED lighting, tri-generation, 1.2 MWp rooftop PV, and demand-controlled ventilation), achieving 42% carbon reduction and 29% operating cost savings within 36 months. Critically, Section 106 agreements mandated 22% affordable workspace, directly addressing gentrification critiques and raising the social pillar score from 68 to 84. Hudson Yards (New York) demonstrates technology-enabled resilience: real-time microgrid management and an on-site cogeneration plant with black-start capability reduced peak demand charges by US$11 million annually and cut outage-related losses by 92% during Storm Ida (2021). CapitaGreen (Singapore) illustrates incentive optimisation: the BCA's Gross Floor Area bonus financed a double-skin façade and radiant cooling system that consumes 41% less energy than code, while the Building Construction Authority's research grant funded a living lab that generated S$4.2 million in IP licensing revenue. Kai Tak (Hong Kong), despite pioneering district cooling and automated waste collection, remains constrained by fragmented leasehold governance, with only 38% of landlords participating in the central plant, resulting in persistent free-rider problems and a 31% efficiency penalty relative to theoretical potential.

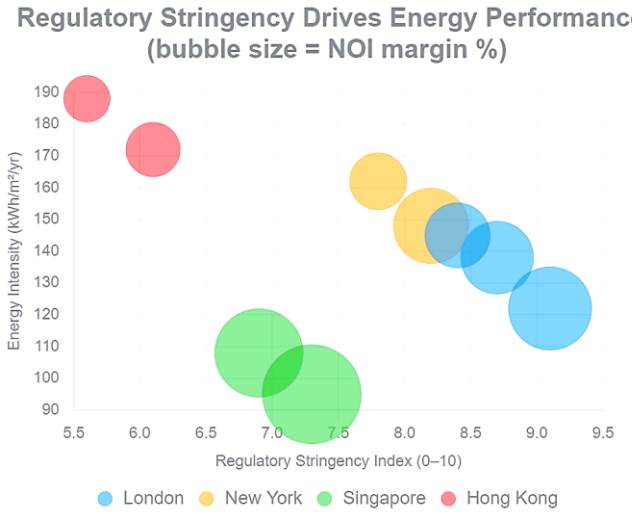

Fig.3: Energy Intensity vs. Regulatory Stringency Scatter (2025, n=250 portfolios, size=NOI margin)

5. Discussion

5.1 Theorising Variegated ESG Risk Mitigation Regimes

The empirical patterns uncovered challenge universalistic conceptions of ESG integration and support a political-economy reading of sustainability transitions in real estate. London and New York represent coercive isomorphism driven by state-enforced carbon budgets and litigation risk, generating rapid but costly convergence toward high performance. Singapore exemplifies mimetic-cum-normative isomorphism, where state-orchestrated incentives and international benchmarking (BCA–UNEP FI collaboration) produce voluntary yet highly aligned outcomes. Hong Kong remains trapped in a hybrid regime where fragmented property rights and short-term lease horizons perpetuate calculative logics that undervalue long-lived ESG investments. These findings extend Robinson's (2016, 2022) comparative urbanism framework by demonstrating that ESG performance is not merely a technical attribute of buildings but a co-constitution of regulatory intensity, ownership fragmentation, and global financial flows (de Noronha et al., 2024).

5.2 Reconciling Non-Linearity with Stakeholder and Resource-Based Theories

The inverted-U relationship between ESG intensity and financial outcomes resolves a long-standing paradox in the RBV literature: while sustainability capabilities are valuable and rare, excessive allocation violates the principle of balanced resource deployment and triggers stakeholder fatigue. High-intensity portfolios in Hong Kong frequently over-invest in visible environmental hardware while neglecting governance reforms and tenant engagement, resulting in negative marginal returns. Conversely, Singaporean cases illustrate that when incentives align capital cost reduction with operational savings, the reinforcing loops dominate far longer, pushing the inflection point beyond 50% intensity. These dynamics suggest that stakeholder theory must be temporalised: different constituencies (debt investors, tenants, regulators) become salient at different phases of the ESG transition.

5.3 System Dynamics and Its Theoretical Contribution to Service Science

From a service science perspective, this study contributes to the JLISS literature by demonstrating how system dynamics (SD) can be employed not merely as a simulation technique, but as a theoretical representation of service systems and managerial decision-making processes (Chau, 2024; Dalati, 2023; Paudel & Thapa, 2025; Wang & Kassim, 2025). Traditional ESG and risk management studies often adopt static or linear models that treat investments and outcomes as isolated events. In contrast, system dynamics enables the conceptualization of ESG risk mitigation as a continuous service process, characterized by feedback loops, accumulation effects, and delayed responses. This shift is particularly relevant to service science, which emphasizes the dynamic interaction among resources, actors, and value co-creation mechanisms over time. By modeling ESG risk mitigation as a stock–flow system, the study aligns with the service science view that value is not delivered instantaneously, but emerges through sustained managerial actions and adaptive service provision. ESG investments, governance mechanisms, and regulatory pressures are explicitly represented as managerial decision levers that influence risk exposure and portfolio resilience through reinforcing and balancing feedback loops. This approach extends existing service system frameworks by operationalizing how managerial cognition and policy choices translate into evolving service outcomes, rather than assuming immediate or proportional effects. Moreover, the use of system dynamics allows the identification of non-linear behaviors and threshold effects in ESG service provision, such as diminishing returns beyond an optimal investment intensity. From a theoretical standpoint, this finding challenges the implicit assumption in much of the ESG and service management literature that "more service input leads to better outcomes." Instead, the results highlight the importance of service design and calibration, suggesting that over-provisioning ESG-related services may generate inefficiencies or unintended consequences. This insight enriches service science theory by emphasizing that effective service systems require not only commitment and compliance, but also dynamic balance and strategic timing. Finally, this study illustrates how system dynamics supports a decision-oriented view of service systems. Rather than optimizing a single performance metric, the SD framework enables managers to experiment with alternative service strategies, governance regimes, and policy scenarios in a virtual environment. In doing so, it bridges the gap between service science theory and managerial practice by providing a mechanism for learning, adaptation, and evidence-based decision making under uncertainty. As such, the study positions system dynamics as a valuable theoretical and methodological lens for advancing research on complex, data-enabled service systems in the digital era.

5.4 Policy Implications for Global Standard-Setting and Portfolio Strategy

The persistent low correlation between major ESG data vendors (average $r = 0.18$ for real estate) and the demonstrated materiality of local regulatory context argue strongly for the adoption of the ISSB's IFRS S2 climate standard as a baseline, supplemented by jurisdiction-specific key performance indicators. Portfolio managers in mandatory regimes should front-load governance and social

investments to mitigate the NOI compression phase, whereas those in incentive-based regimes can safely accelerate physical retrofits. Crucially, the 40% optimum implies that the current global average ESG capex intensity of 21% (GRESB 2025) remains sub-optimal; a doubling of effort over the next decade is both financially justified and necessary to meet Paris-aligned trajectories.

5.5 Limitations and Future Research Directions

While the mixed-methods design achieves high internal and external validity, the sample remains biased toward listed and institutionally managed portfolios; private family offices and sovereign wealth vehicles operating in opaque jurisdictions are underrepresented. Future scholarship should extend the ESG-RMI to embodied carbon and social value metrics using satellite-derived imagery and natural language processing of tenant sentiment (Komarova et al., 2023; Filyushina et al., 2023). Longitudinal ethnographic work inside investment committees is also required to unpack the micro-processes by which ESG signals are translated into capital allocation decisions under conditions of radical uncertainty.

6. Conclusion

This study examined ESG risk mitigation in commercial property portfolios through a data-driven and service-system lens. By integrating quantitative risk metrics, system dynamics simulation, econometric identification, and comparative case evidence from four global cities, the research demonstrates that ESG risk mitigation is not merely a compliance exercise, but a complex management system involving data, governance, investment timing, and stakeholder coordination.

The findings indicate that ESG investments generate substantial risk reduction and financial benefits when implemented at appropriate intensity levels. Specifically, the proposed ESG-RMI reveals a non-linear relationship between ESG capital allocation and portfolio performance, with an optimal investment range around 40% of medium-term capital expenditure. Beyond this threshold, marginal benefits diminish or become negative, underscoring the need for informed and adaptive decision making.

From a service science and management perspective, the results highlight that regulatory philosophy and governance structures strongly condition ESG outcomes. Coercive regulatory regimes deliver rapid risk reductions but impose higher short-term costs, whereas incentive-based regimes enable smoother transitions with lower friction. These insights suggest that effective ESG management requires dynamic, context-sensitive service strategies rather than standardized compliance templates.

This study contributes to the service science literature by conceptualizing ESG risk mitigation as a data-enabled service system and by offering a decision-support framework for portfolio managers navigating regulatory and climate uncertainty. Future research may extend this approach to other asset classes, incorporate real-time digital monitoring technologies, and explore how ESG service systems evolve in emerging markets.

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