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A System Dynamics Framework for Water Efficiency in Green Building Certification: Evidence from LEED and BREEAM Projects

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Abstract

This study investigates whether water efficiency (WE) can be represented as a candidate system-level leverage variable within a System Dynamics (SD) framework for green building rating systems (GBRSs). The framework represents WE and its proposed interactions with Energy and Atmosphere (EA), Sustainable Sites, Indoor Environmental Quality, Materials and Resources, Innovation, and Regional Priority categories may not be fully visible from the static point-weighting structure of certification systems. The method includes: (1) developing a System Dynamics (SD) framework based on stock-and-flow architecture, causal-feedback loop formalization, leverage-point theory and saturation concept, identifying four reinforcing and three balancing feedback loops, (2) dashboard-based simulation, and (3) cross-case-study validation and statistical evaluation. Four case studies were selected to demonstrate quantitative directional agreement between the model-generated category responses and documented project characteristics. The results demonstrate structural consistency for the primary WE-centered mechanism ($\Delta WE \approx 0$), while the downstream category responses provide the principal basis for directional evaluation. It is noted that the model does not capture all of the building and site-specific factors responsible for the difference in point accrual in other sustainable categories, especially, those related to EA—which was defined in all studied case-study projects as the dominant secondary sustainability category, following WE. The manuscript explicitly frames the framework as exploratory and it is positioned as a sustainability interaction simulator for investigating potential cross-category feedbacks rather than as a predictive certification-score model, and the validation is primarily structural and directional. This novel contribution is useful to inform feedback-informed design strategy and to propose water efficiency as a potential leverage point in integrated building performance.

Keywords: system dynamics; LEED; BREEAM; water efficiency; feedback loops; leverage points; building assessment; stock-and-flow modeling

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1. Introduction

The built environment consumes around 36% of the world's final energy use and nearly 40% of total CO_2 emissions [1], and contributes an over-proportional amount of municipal demand for water and material resources [2]. Voluntary green building rating

systems (GBRSs), such as the Leadership in Energy and Environmental Design (LEED) developed by the United States Green Building Council (USGBC), and the Building Research Establishment Environmental Assessment Method (BREEAM), published by the Building Research Establishment, have arisen to accommodate the environmental challenges of the large building stock, encompassing sustainability performance throughout the design, construction and occupancy lifecycle [3,4]. Many studies that compared GBRSs' performance to actual energy and water measurements have shown positive trends in performance [5,6], but the strength and uniformity of the trends have been quite variable by building type, climate zone, occupancy type, and operating conditions [7].

Despite GBRSs' broad adoption, they operate on a structurally constrained epistemology [8]. LEED and BREEAM use fundamentally different scoring architectures: LEED assigns discrete points to credits [9], while BREEAM converts category-level credit achievement into weighted percentage contributions [10]. These include credits assigned independently for the main distinct categories of Water Efficiency (WE), Energy and Atmosphere (EA), Sustainable Sites (SS), Indoor Environmental Quality (IEQ), Materials and Resources (MR), Innovation (IN), and Regional Priority (RP), so that sustainability performance is viewed as the sum of separate sustainability prerequisites and credits. This additive linear approach to sustainability allows for auditing to occur at a standard level but there is a systematic misrepresentation of the temporally dynamic and nonlinear nature of real building performance, given that it is deeply interdependent [11,12]. Later research has revealed a conflict between this step-by-step approach to scoring, pointing out that performance variables below certification step thresholds contribute meaningfully to sustainability outcomes yet are structurally excluded from the official record [13–15]. This is especially important for water-related credits because many of the threshold structures of the prerequisites and optimizations often do not incentivize metering cost reductions lower than the next certification level [16].

Current LEED documentation indeed gives EA substantially more points than WE in typical BD + C structures; for example, the LEED v4.1 BD + C scorecard shows WE at 11–12 points depending on rating-system option, while EA has substantially greater point capacity. BREEAM likewise places substantial emphasis on energy/carbon, while its water category addresses water consumption and related efficiency. Thus, WE accounts for 11% of the core credit score in the latest LEED Building Design and Construction (BD + C) version, whereas it carries a 7% weighting in BREEAM New Construction 2018 for fully fitted-out buildings, excluding additional innovation/bonus credits [8]. More recent studies in sustainability have shown that water systems affect a much wider variety of environmental and operational parameters [17]. There are indirect sustainability impacts that ripple through various WE strategies. For example, gray water reuse systems impact pumping energy, treatment facilities and maintenance needs [18]. Harvesting rainwater has an impact on stormwater management, groundwater recharge, landscape resilience, and irrigation needs [19]. Smart metering systems are an enabler of adaptive operational management, leak detection and innovation-focused sustainable pathways [20].

Sustainability trade-offs refer to scenarios in which an improvement in one performance dimension leads to a decrease in another or where the marginal cost of an additional improvement in one area leads to less improvement in another [21]. The use of System Dynamics (SD)—a structured methodology for dealing with complex systems—is well suited to the representation of trade-offs in dynamic balancing environments comprising a set of interdependent components whose relationships, in particular feedback relationships, create behavior that is qualitatively different from the behavior of any single component by itself [22,23]. The core ontology of SD is based on stocks (accumulations of material, energy, information or other quantities), flows (rates of change that fill or drain stocks over time)

and feedback loops (causal chains of stocks and flows that, when added together, create endogenous dynamic behavior) [24]. Positive feedback (reinforcing feedback (R)) causes an exponential growth, while balancing feedback (B) (negative feedback) opposes change towards a desired value or towards an equilibrium [22,25].

Since Forrester's seminal work on urban dynamics has introduced SD to modeling urban sustainability [26], several applications have followed, such as energy transition modeling, urban metabolism and building energy policy [22–24]. In the built environment, SD has been applied to building design and operation [27], the modeling of the dynamics of construction projects [28], housing market cycles [29,30] as well as infrastructure and smart city sustainability transitions [31]. Recently, SD has been used in the development of building energy performance feedback, and sustainable assessment [13,32,33], as a significant substantive improvement over the static checklist's architectures [34,35].

Parallelly, the integration of sustainability dashboards [36], Building Information Modeling [37], digital twins [38,39], and operational simulation systems [29] has been a new research topic in recent years [36,37]. These systems enable interactive monitoring, operational feedback, adaptive management and decision-making for sustainable building performance [40–42]. Nevertheless, it is noted that most dashboard systems are still descriptive rather than structural or analytical [36]. They often see operational data in a picture without reflecting the feedback processes that underlie sustainability behavior [43].

Research Gaps and Scientific Contribution

Despite the extensive literature on GBRSs, SD applications in the built environment, and water–energy nexus modeling, these research streams have largely developed in parallel. Studies of GBRSs have primarily examined rating-system structure, credit weighting, certification performance, and relationships between certification and measured building performance, but generally treat sustainability categories as discrete assessment components rather than as dynamically interacting variables [3,8,44]. SD has meanwhile been applied to building sustainability assessment, energy performance, materials selection, site-related LEED decisions, and dynamic sustainability benchmarking [32,45]. In parallel, SD-based water–energy nexus studies have explicitly represented physical interactions between water and energy systems at urban or end-use scales [46]. However, these studies do not address the specific question of how water efficiency interventions propagate through the internal category and credit structure of major GBRSs. In particular, there remains limited modeling of WE as an endogenous leverage point that can generate cross-category feedbacks with EA, SS, IEQ, MR, IN, and RP within a unified LEED/BREEAM framework.

WE was therefore selected as a candidate leverage variable, rather than being assumed a priori to be the most important sustainability category. Water-related interventions can be connected to multiple building and site processes [19,47,48]. Accordingly, the study does not claim that WE is universally a stronger sustainability driver than energy, nor that water efficiency should receive greater certification weighting. Instead, it investigates whether WE constitutes a useful system-level leverage candidate whose interactions with energy and other categories may not be fully visible from the static point-weighting structure of certification systems.

The research gap addressed in this study is therefore the absence of a SD representation that connects physical and operational WE interventions to the cross-category interaction and feedback structure embedded within GBRSs. In this regard, the interactions of WE across credit categories generate feedback effects that either increase or limit point accrual patterns in a way that is not obvious from the inside of any one credit category, which is why WE is investigated as a potential system-leverage point.

Based on the identified gap, this study addresses three research questions: (RQ1) To what extent can WE be represented as a leverage variable that generates cross-category sustainability effects within a SD representation of GBRSs? (RQ2) What reinforcing, balancing and contextual mechanisms can explain the propagation of WE interventions across other sustainability categories? and (RQ3) To what extent does the proposed WE-centered interaction structure reproduce structurally and directionally consistent sustainability patterns across heterogeneous green-certified building cases?

To address these questions, four structural propositions are examined. P1 proposes that increased WE intervention produces a positive response in the primary WE–EA pathway. P2 proposes that WE interventions can generate indirect responses in other sustainability categories through physically, operationally and technologically mediated pathways. P3 proposes that WE-driven sustainability accumulation is constrained by diminishing marginal returns and balancing mechanisms as technical and operational limits are approached. P4 proposes that the WE-centered interaction structure can reproduce broadly consistent directional patterns across heterogeneous cases while allowing contextual differences in response magnitude. The propositions are evaluated at different levels of evidence. P1 is the principal quantitatively evaluated proposition WE–EA. P2 and the individual reinforcing and balancing loops beyond R1 are evaluated primarily through structural and directional evidence. P3 is evaluated through the simulated saturation behavior of the stock-and-flow structure, while P4 is assessed through cross-case structural comparison. This is to acknowledge that the developed conceptual feedback hypotheses are not confirmed causal relationships.

Thus, this study contributes by (a) using a formal SD stock-and-flow framework to examine the internal interaction structure of two GBRSs, LEED v4.1 BD + C and BREEAM UK New Construction 2018 categories, (b) investigating WE as a candidate leverage variable within a formal SD stock-and-flow framework, (c) SD application to GBRSs' internal structure modeled via dynamic feedback and accumulation, and pinpoint threshold-behavior analysis, and (d) tests balancing loop formalization with temporal trade-off analysis. This is done using a dashboard-based simulation environment and testing on four case-study green-certified projects. In this regard, the present study thus places the proposed framework and System Dynamics model not as a predictive certification tool, but as a supporting sustainability interaction simulator that visualizes accumulation behavior, loop structure, trade-offs, and temporal sustainability evolution.

2. Methodology

The research method includes the following steps:

- Framework development and SD modeling;
- Dashboard-based simulation environment;
- Cross-rating-system case-study application and transferability assessment;
- Cross-case structural validation and statistical evaluation.

The methodological sequence was designed to correspond to the research questions and structural propositions. Framework development and causal-loop formulation address RQ1 and RQ2; SD simulation evaluates the behavior of the mathematically implemented WE–EA mechanism and saturation dynamics associated with P1 and P3; case-study application provides empirical reference evidence for P2 and P4; and cross-case structural comparison assesses directional consistency and contextual discrepancies associated with P4.

2.1. Framework Development and SD Modeling

The proposed framework comprises four components: (i) formal stock-and-flow architecture mapping main sustainable categories to the stocks of sustainability, (ii) literature-

informed and expert-assessed dependency coefficient ranges representing the direction and relative strength of cross-category influence on each target category, and (iii) causal-loop diagram formalizing reinforcing and balancing feedback structures that govern dynamic system behavior.

For the scope of this study on GBRSs, common sustainable categories in LEED and BREEAM were selected to represent the baseline upon which the interaction of WE with the rest of sustainable categories was investigated. The sustainable categories include WE, EA, SS, IEQ, MR, IN, and RP. Because LEED and BREEAM employ different scoring architectures and category weightings, a normalized 100-point representation is used only as a common analytical scale within the SD framework, and does not represent an equivalent certification score across LEED and BREEAM. The original category/credit performance was first retained in its native rating-system format. The corresponding category-level values were then transformed to the normalized scale using the ratio of the documented category performance to the applicable maximum category performance.

Where LEED and BREEAM use different category definitions or organize credits differently, the functional mapping of certifications (refer to Supplementary Materials S3) was performed at the level of the broader sustainability function represented in the proposed framework rather than by assuming one-to-one equivalence between individual credits. Categories or credits without sufficient functional correspondence were not treated as directly equivalent.

The framework highlights sustainability interactions during building operation and integrated sustainability management. The period of the simulation is conceptually represented over a 24-month operational horizon to observe the accumulation behavior, the delay and the transition from loop structure. Time is represented in months, and stock-flow consistency requires all flow terms entering a category stock to be expressed in points per month. Dimensionless coefficients modify the magnitude of the corresponding interaction flows.

Each of the sustainable categories is represented by a stock of sustainability performance, denoted $S_i(t)$, where i ∈ {WE, EA, SS, IEQ, MR, IN, RP}. There is a direct investment flow that builds up the value of each stock, and one or more cross-category interaction flows that also contribute to the value of each stock, and there is a decay or dissipation flow representing performance degradation due to aging, behavioral drift and maintenance failure as noted by past studies [25]. The general stock is shown in Equation (1), noting that the stock equation is dimensionally consistent because all terms on the right-hand side represent rates of change in normalized sustainability points per month. S_i: 0–100 points; flows: points/month.

$$dS_i(t)/dt = F_i^{direct}(t) + F_i^{interaction}(t) - F_i^{decay}(t) \quad (1)$$

Equation (2) aggregates the category stocks into the continuous SD Sustainability Index.

$$S_{SD}(t) = \Sigma_i [w_i \cdot S_i(t)] \quad (2)$$

where S_{SD} represents the SD Sustainability Index, w_i represents the credit weight coefficient of category i in GBRS scorecard and S_{SD} is a normalized analytical score [25]. The mapping between $S_{SD}(t)$ and official GBRS certification levels is governed by the discrete threshold function of defined GBRS category. This defines the normalized variables used to compare WE intervention intensity and sustainability contributions on a common 0–1 scale. Equation (3) normalizes WE and category stocks to a common 0–1 scale for interaction analysis.

$$WE^* = \frac{S_{WE}(t)}{S_{(WE,max)}}, S_i^* = \frac{S_i(t)}{S_{(i,max)}} \quad (3)$$

The key idea of the framework is that $S_{SD}(t)$ is continuously changing whereas $w(S_{SD}(t))$ is a step function which does not change in between the threshold crossings. When the cross-category interaction flows are actively building up sustainability contributions that are not yet adding up to the next level or threshold, the official GBRS score remains the same, but the physical sustainability of the building is improving.

To get the dependency coefficients (αij), the causal pathways were established through a two-stage evidence procedure. First, the literature was reviewed to determine whether a possible mechanism existed between a WE intervention and each target sustainability category, and to identify the physical or operational process through which the relationship could occur. Only relationships for which a significant mechanism could be identified were considered for inclusion in the causal structure. Second, domain-expert elicitation was used to assess the relative strength of the supported relationships under varying building, climatic and technological conditions. Experts were therefore not asked to establish causal existence independently of the literature; rather, the literature constrained the direction and conceptual basis of each pathway. The resulting coefficients should consequently be interpreted as structural sensitivity parameters rather than empirically calibrated universal effect sizes. Table 1 shows the dependency coefficient matrix.

Experts were selected according to their relevant academic and/or professional experience in areas including GBRSs, building energy and water performance, sustainable building design and operation, environmental/building-performance assessment, and integrated sustainability assessment. The elicitation procedure, number of experts, consultation rounds, rating scale, consistency checks, and any consensus procedure used are reported explicitly in the Supplementary Materials S1; also, the detailed expert coefficient matrix is described in Supplementary Materials S2 to improve transparency and reproducibility.

For each interaction pathway, experts evaluated the relative influence of WE performance on the target sustainability category using a normalized scale from 0 to 1, where 0 represents negligible cross-category influence and 1 represents a very strong influence. Saturation dynamics were added by incorporating a sigmoid saturation function of the net inflow into each sustainability stock. This reflects the empirically supported fact that marginal returns of sustainability investment decline as a system approaches its technical performance limit following previous research [24,49]. Here, k_i is the saturation rate parameter for category *i* (controlling the steepness of the diminishing-return curve), and S_i_mid is the mid-point of the saturation, where the marginal return to stocking marginally begins to decrease. These values, combined, provide the inflection point and the curve shape of the saturation response. There are saturation parameters specific to each category, and they have been scaled to capture the differential technical ceilings: WE and EA categories are calibrated to have a steeper saturation (i.e., higher k values); IN and RP categories to a more gradual saturation (i.e., lower k values). This is shown in Equation (4).

Thus, the framework defines four positive feedback loops (R1, R2, R3, R4) and three negative feedback loops (B1, B2, B3). The formal identification and interpretation are a key part of the systems analysis presented in the paper. It is noted that for the sake of the simulation, only R1 was implemented mathematically, parameterized and simulated, whilst other feedback loops were only causally identified, conceptually represented and visually documented, but not quantitatively simulated. The causal link between EA savings and WE investment capacity is controlled by the gain parameter β_R1 of the reinforcing loop R1. This second-order interaction term gives rise to the characteristic increasing growth characteristics of the R1 loop exhibited in the early part of the building lifecycle, prior to

the onset of saturation constraint. This is shown in Equation (5). Equation (6) defines the discrepancy between the model-generated result and the documented case-study reference value, measured in points.

$$\gamma_i(t) = \frac{1}{1 + \exp\left[k_i\left(S_i(t) - S_{(i,mid)}\right)\right]} \tag{4}$$

$$dS_{EA}(t)/dt = F_{EA}{}^{direct}(t) + \left[\alpha_{(EA1)}F_{WE}(t) + \alpha_{(EA2)}F_{WE}(t)\right]\gamma_{EA}(t) - \delta_{EA}S_{EA}(t) + \beta_{(R1)}S_{EA}(t)S_{WE}(t) \tag{5}$$

$$e_j = M_j - D_j \tag{6}$$

Table 1. Dependency coefficient matrix, causal relations and hypothesized feedback-loop structure: reinforcing (R) and balancing (B) loops in the proposed WE-centered GBRS SD framework.

α Coefficient (Range)	Key References	Causal Chain	Causal Explanation	Defined Feedback Loops
α_{EA1}: 0.18–0.24	[50,51]	WE intervention → reduction in hot-water demand → reduction in thermal energy requirement → improvement in operational energy performance → potential contribution to EA performance.	Depends on climate and building-specific and depends on water source, distribution distance, pumping head, water temperature, equipment efficiency, occupancy and system configuration. Cross-category trade-off behavior noting the inter-category resource competition; trade-off between EA optimization and WE intensification (trade-off).	R: WE → EA R: WE → Smart Metering → InnovationR: WE → SS → Site Ecology → IEQ → WE R: Advanced WE strategy → potential qualifying innovation → potential IN outcome B: WE → Infrastructure Complexity → Maintenance Burden → WE B: EA → Technology → WEB: IEQ → Ventilation Load → Energy Demand → EA → WE
α_{EA2}: 0.06–0.10	[52,53]	WE intervention → reduction in water volume/flow → reduced pumping requirement → lower electricity consumption → potential contribution to EA performance.		
α_{SS}: 0.12–0.18	[54,55]	Rainwater harvesting/reuse intervention → reduced effective runoff and/or reduced potable-water demand for irrigation → improved stormwater and landscape-water management → potential improvement in site sustainability performance.	Conditional on-site design, vegetation, microclimate and building–landscape interaction	
α_{IEQ}: 0.05–0.09	[56,57]	Water/moisture management → control of moisture-related indoor conditions → potential influence on humidity and IEQ.	Conditional subject to saturation noting that the complexity of the infrastructure could lead to negative effect due to maintenance requirements. Cross-category trade-off behavior; high IEQ ventilation rates increase HVAC energy demand; elevated EA load reduces resource available for WE investment; balancing constraint across IEQ-EA-WE	
α_{MR}: 0.04–0.07	[58,59]	Water treatment and appropriate water-system management → reduced scaling/corrosion and potentially longer component service life → reduced replacement frequency/material demand → potential contribution to MR-related sustainability performance.	Conditional positive and represents an indirect operational/material-life mechanism of water treatment.	
α_{IN}: 0.08–0.14	[20,60]	Advanced water metering → higher-resolution operational data → monitoring/diagnostic capability → opportunities for adaptive management and innovative operational strategies → potential contribution to Innovation-related outcomes.	The pathway is enabling rather than deterministic, and depends on system sophistication	
α_{RP}: 0.10–0.22	[61,62]	WE leverage amplified in water-stressed regions; RP credits prioritize WE	Regional water scarcity/context → increased relevance of WE interventions → context Contextual amplification rather than universal causal effect	

Because only R1 is quantitatively implemented, parameter stability was assessed for α_EA1, α_EA2, k_EA, S_EA,mid, δ_EA, and β_R1. The assessment combines the documented coefficient intervals with a formal sign-stability analysis of the implemented R1 equations. α_EA1 and α_EA2 remain positive throughout their stated intervals (0.18–0.24 and 0.06–0.10), so the WE-mediated EA contribution cannot reverse sign. The sigmoid saturation factor γ_EA(t) remains bounded between 0 and 1 for finite S_EA and positive k_EA; therefore, changes in k_EA or S_EA,mid affect the steepness and timing of diminishing returns rather than the direction of the WE-mediated response. For δ_EA ≥ 0, increasing decay reduces accumulated EA stock but does not change the sign of the positive WE-mediated inflow. For β_R1 ≥ 0, the feedback term β_R1·S_EA(t)·S_WE(t) is non-negative for non-negative stocks and therefore preserves the reinforcing direction. The principal qualitative findings—positive WE→EA response, bounded saturation, and reinforcing R1 behavior—are consequently structurally stable over the admissible parameter conditions stated in the model. This is a formal structural stability assessment, not a statistical uncertainty analysis.

2.2. Dashboard-Based Simulation Environment

A dashboard-based visualization and interaction environment is developed to support the exploration of the SD framework by iteratively changing the parameters of scenarios and to graphically visualize the accumulation trajectories, loop structure indicators, and certification threshold crossings interactively. Please refer to Figure 1 and Appendix A for screenshots of the proposed WE-centered SD model.

The SD framework was implemented as a computational model based on the differential equations and feedback relationships defined in the methodology. The computational implementation represents the model kernel, including the state variables, parameter values, interaction terms, initial conditions, and time-dependent updating of the model states over the defined simulation horizon.

Microsoft Power BI was used as the visualization and interactive dashboard layer for presenting model inputs, model-generated outputs, category trajectories, and case-study comparisons. It provides comparative bar charts, category-profile visualizations, model-degree of agreement indicators, point-difference analysis, and cross-case performance summaries. Lovable AI [63] was used as the AI-assisted development environment for generating the JavaScript implementation, which constitutes the computational model kernel. Manus 1.6 [64] was additionally used as an AI-assisted development and reasoning tool. Microsoft Power BI was used separately as the interactive visualization and dashboard layer.

The dashboard architecture comprises four functional panels: an Input Control panel, a Stock Trajectory panel, a Feedback-Loop Structure panel and a Certification Status panel. The Input Control panel allows for slider-based adjustments determining the type of GBRS, and the level of investment for WE, the building program type, the climate zone sensitivity and the loop-gain parameters. The Stock Trajectory panel presents the temporal evolution of all seven category stocks with the current set of parameters. Finally, the Certification Status panel maps $S_{SD}(t)$ against the defined GBRS threshold certification levels and marks model-derived unrecognized performance accumulation. This refers to periods in which the model indicates continued sustainability accumulation without crossing the next defined threshold. The Feedback-Loop Structure panel additionally displays the seven identified causal loops (R1–R4 and B1–B3) to facilitate interpretation of the broader conceptual system structure.

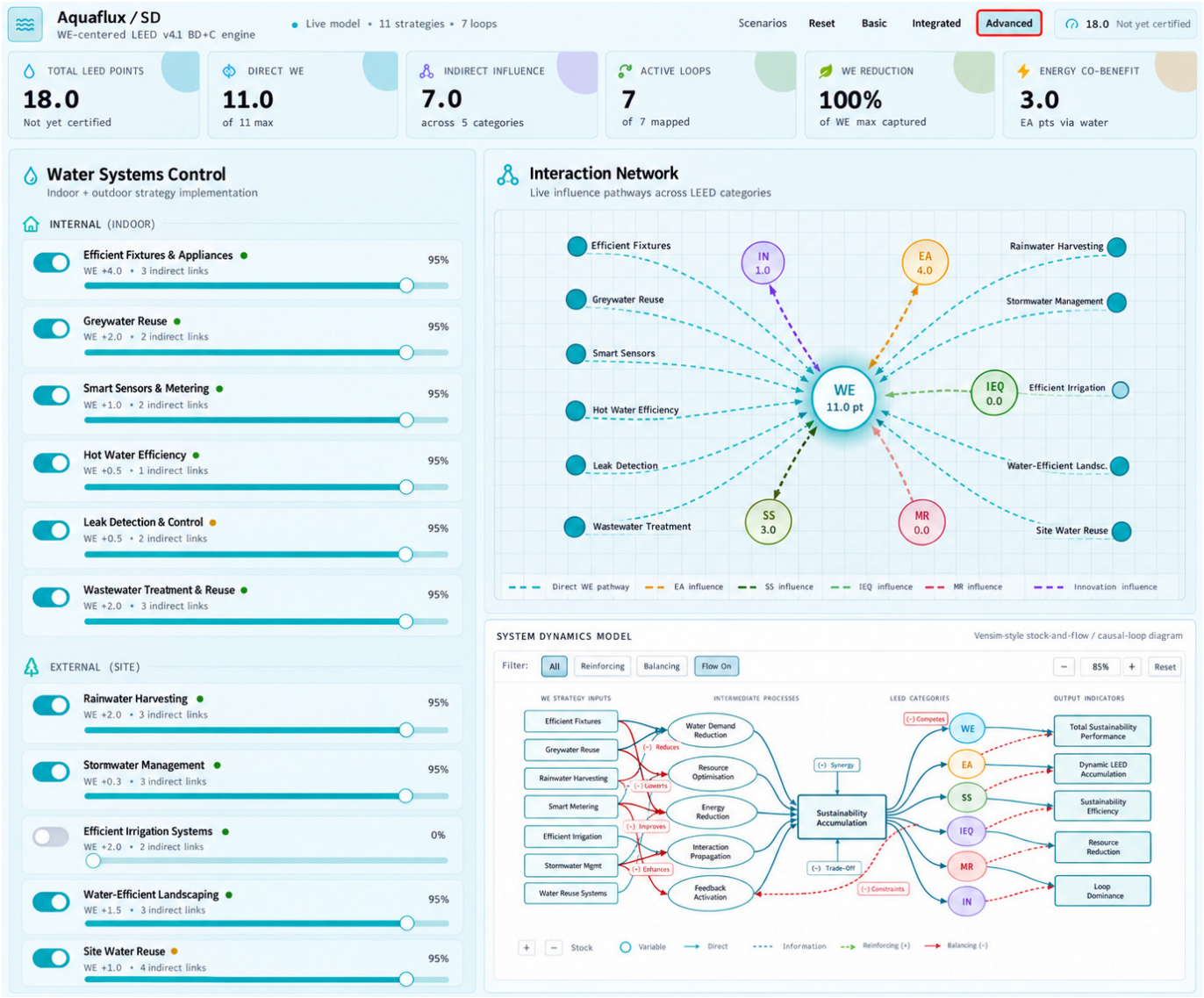


Figure 1. Integrated dashboard-supported simulation environment illustrating WE strategies, interaction networks, causal-loop visualization, and sustainability accumulation pathways across GBRS.

Reinforcing interactions in operation and behavior is the main driver of early-stage sustainability acceleration and infrastructure complexity, operational saturation and maintenance constraints increasingly take precedence. The temporal-evolution module shows typical S-curve sustainability dynamics that are characteristic of the interplay between reinforcing growth processes and balancing saturation effects as shown in the Appendix A. The trajectories show how the accumulation of sustainability continues to become more stable as operational systems approach technical and organizational performance limits. Within the proposed framework, the Dependency Engine formalizes the interaction structure between the propagation of sustainability in different categories. Directional coefficients allow for representation of the dynamic impact WE has on EA, SS, IN, IEQ, and RP behaviors across operational pathways that connect the behaviors.

The dashboard can be used as a sustainability interaction simulator and as a platform for causal exploration, allowing practitioners and researchers to explore the behavior of the system when changing the level of investment in the WE, the dependency coefficient assumption, and the saturation parameters without changing the structure of the model.

2.3. Cross-Rating-System Case-Study Application and Transferability Assessment

This section demonstrates the directional and structural validation of the proposed SD model using real-world case-study projects. Four internationally recognized green-certified buildings were selected to examine the transferability of the proposed SD framework across different GBRSs' configurations as shown in Table 2. The cases were selected against four criteria: (i) documented green building certification; (ii) availability of sufficiently detailed information on water-related strategies and their interactions with other sustainability categories; (iii) evidence of integrated sustainability strategies relevant to at least two of the modeled cross-category pathways; and (iv) sufficient publicly accessible documentation (building-performance information and technical system characteristics) to permit reconstruction of the case-level variables used for structural comparison. This represents different certification contexts, including LEED US, LEED Canada and BREEAM, thereby enabling assessment of whether the underlying interaction architecture remains applicable when rating-system categories, credit structures and certification mechanisms differ.

Table 2. Case-study selection and cross-rating-system applicability.

Project	Rating System, Type and Version	Selection Justification	Feedback Loops
Bullitt Center, Seattle, USA [65]	LEED Platinum, Living Building Challenge certification	A high-performance commercial building characterized by integrated water management (rainwater harvesting and gray water reuse), as well as energy, material and operational strategies.	R: WE-SS stormwater interaction (α_SS) R: WE-EA via reduced energy consumption for pumping municipal water (α_EA) R: Water efficiency—smart monitoring—IN points (α_IN) B: Complexity of maintaining the integrated water treatment infrastructure (α_EA)
Pixel Building, Melbourne, Australia [66]	LEED-NC 2009; also 6 Star Green Star—Office Design v3	100% of the water treated on site, including on-site wastewater treatment; rooftop harvest, and smart building management systems integration.	R: Reduced hot water use leads to renewable-energy feasibility (α_EA) R: WE-smart metering interaction (α_IN ≤ EA) B: Recycled-water system is limited with stormwater management The RP contextual amplifier (λ_RP) due to the climate profile, and water efficiency requirement
Centre for Interactive Research on Sustainability (CIRS), Vancouver, Canada [67]	LEED Canada—New Construction (NC) v1.0, Platinum	A living laboratory integrating water self-sufficiency (blackwater treatment and rainwater harvesting), energy generation with geothermal-water coupling, material strategies, occupant interaction and building-performance monitoring.	R: Water efficiency ≤ design investment ≤ energy efficiency (α_EA) R: Water efficiency ≤ reduced energy demand ≤ renewable-energy feasibility (α_EA) B: Water efficiency ≤ stormwater management ≤ site sustainability (α_WE ≤ SS)
The Edge, Amsterdam, Netherlands [68]	BREEAM-NL New Build and Renovation, Outstanding, 98.36%	Its scorecard includes water, energy, materials, health, transport, land/ecology and pollution categories- with extensive smart-building monitoring and water/energy strategies.	R: Water efficiency ≤ design rigor ≤ energy efficiency (α_EA) R: Water efficiency ≤ reduced energy demand leading to 100% renewable-energy feasibility (α_EA) R: Smart building sensor integration led to WE within unified data platform (α_IN) B: Water efficiency ≤ stormwater management ≤ site sustainability (α_SS)

The validation questions whether the qualitative behavioral patterns produced by the model (such as the dominant sequence of loops, timing of saturation, strength of interaction between categories and model-derived unrecognized performance accumulation) are in a direction that is consistent with the observed sustainability behavior of these projects. The selected projects provide empirical reference cases against which the qualitative direction and approximate response patterns generated by the framework can be examined. Their role is therefore to assess structural plausibility and identify systematic discrepancies that can inform model refinement.

For each case study, the SD model was executed using the predefined model structure and case-specific WE intervention information. The resulting category stocks were retained

as model-generated outputs. Independently documented category values were then compiled from the identified case-study sources and used as reference observations. The two data streams were kept separate throughout model execution and evaluation. It should be noted that category scores used for evaluation were not used to estimate the dependency coefficients or other parameters. The purpose of this comparison is not to examine whether the proposed WE-centered structure produces category responses that are broadly consistent with documented cases, and not for direct comparison of certification scores.

2.4. Cross-Case Structural and Directional Validation and Statistical Evaluation

To ensure the reproducibility of the proposed SD framework, governing equations are presented and accompanied by explicit definitions of variables, parameters, dimensions, scales, initial conditions and parameter assumptions. The equations distinguish between sustainability stocks, direct investment flows, cross-category interaction flows, decay terms, saturation functions and feedback terms. Unless otherwise stated, sustainability-category stocks are represented on the normalized 0–100 analytical scale adopted in this study, while flow variables represent changes in the corresponding stock per unit simulation time.

Model–case-study discrepancies were calculated as diagnostic indicators of agreement between the model-generated and documented scores. The analysis was performed at two levels. First, case-level statistics were calculated to evaluate the overall agreement between the model and each individual building. Second, category-level statistics were aggregated across the four buildings to identify systematic strengths and weaknesses in the model structure. Category-level degree of agreement was subsequently derived from the relative absolute error to facilitate comparison among sustainable categories with different scoring magnitudes. Python 3.13.16-based data processing and statistical computation was used for data preparation, residual analysis, and computation of the cross-case validation metrics. Mean Absolute Error (MAE), shown in Equation (7), was used to quantify the average magnitude of model–case-study discrepancy irrespective of direction. Root Mean Square Error (RMSE), shown in Equation (8), was calculated to provide greater sensitivity to larger deviations. This gives greater weight to larger discrepancies and evaluates overall agreement. Mean Bias Error (MBE), shown in Equation (9), was used to identify systematic overestimation (positive values) or underestimation (negative values). Mean Absolute Percentage Error (MAPE) was additionally calculated to express model–case-study discrepancy relative to the documented performance.

$$MAE = \frac{1}{n}\sum (j = 1)^{n} |e_j| \tag{7}$$

$$RMSE = \sqrt{\left(\frac{1}{n}\sum (j = 1)^{n} e_j^2\right)} \tag{8}$$

$$MBE = \frac{1}{n}\sum (j = 1)^{n} e_j \tag{9}$$

3. Results

MAE, RMSE, MBE and MAPE were used to characterize the magnitude and direction of discrepancies. These are interpreted as descriptive measures of model–case-study agreement. It was found that the model generally reproduces the overall profile and relative distribution of sustainability performance across different categories as shown in Figures 2 and 3. It reproduced WE performance with no deviation. Within the structural validation framework, this consistency provides supporting evidence for P1 and for the representation of WE as the primary modeled driver. The largest discrepancy occurred in the EA category (−5 points). The consistency of this discrepancy suggests that additional

building-specific energy variables are required before the relationship could be empirically calibrated for predictive applications. It is also noted that IEQ, MR, SS and IN showed comparatively minor deviations. Furthermore, in some cases, the model-generated RP-related responses were greater than the documented case-study values, indicating that the simplified contextual representation of regional water scarcity does not capture the full set of factors governing RP-related outcomes.

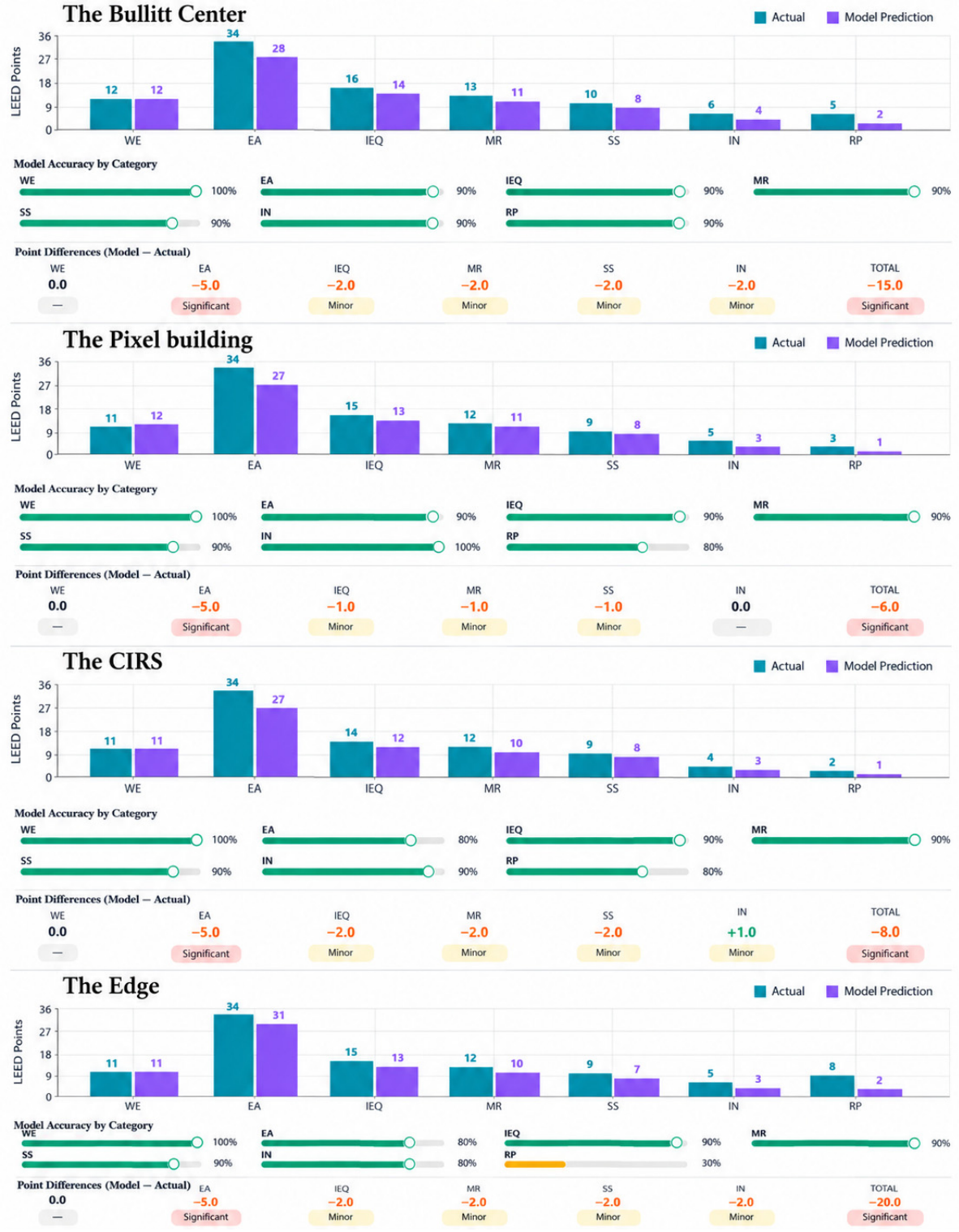


Figure 2. Applying the proposed framework to the four case studies, showing model degree of agreement per category; WE is displayed as the prescribed, non-evaluative intervention/input.

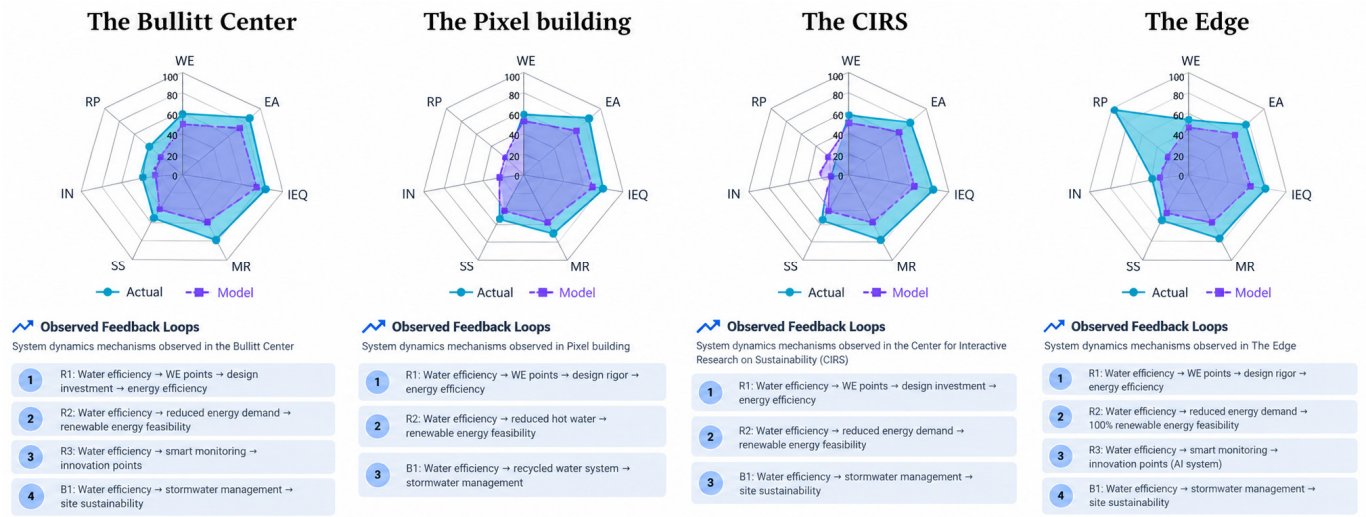


Figure 3. Case-study comparison of prescribed WE intervention conditions and model-generated downstream category responses.

The observed feedback loops demonstrate the hypothesized cascading relationships between water efficiency, energy performance, smart monitoring, innovation, stormwater management and site sustainability. This shows that the model reproduces the general sustainability profile, pointing out that the effects extend from water efficiency to EA, IEQ, MR, SS, RP and IN. The repeated pattern is $\Delta WE = 0$ and $\Delta EA = -5$ for all case-study projects. That strongly suggests that the model has a consistent structural behavior and shows strong directional validity for the primary modeled ($\Delta WE \approx 0$) mechanism. This provides evidence that the model's fundamental water efficiency mechanism is behaving consistently with the case-study evidence, and supports the hypothesis that water efficiency can act as a system driver within an interconnected sustainable-building system.

Cross-case validation metrics for the four case-study projects are shown in Table 3, and for the different sustainable categories are shown in Table 4. The number of category observations is 28 (4 cases $\times$ 7 categories = 28), but observations used for MAPE are 27 because the MAPE calculation excludes the one observation where documented RP = 0 (CIRS).

Table 3. Cross-case validation metrics for the four case-study projects.

Case Study	MAE	MAPE	RMSE	Mean Bias
Bullitt Center	2.14	23.23%	2.54	−2.14
Pixel Building	1.43	20.45%	2.14	−0.86
CIRS	2.00	18.77%	2.45	−1.14
The Edge	2.86	24.88%	3.59	−2.86
Cross-Case Aggregate	2.11	21.94%	2.73	−1.75

Table 4. Cross-case validation of the proposed SD model for all sustainable categories.

Sustainable Category	MAE (Points)	MAPE (%)	RMSE (Points)	Mean Bias (Points)	Degree of Agreement (%)
WE *	0.00	0.00%	0.00	0.00	100.00%
EA	5.00	14.93%	5.00	−5.00	85.07%
IEQ	1.75	11.16%	1.80	−1.75	88.84%
MR	1.75	13.62%	1.80	−1.75	86.38%
SS	1.75	18.13%	1.80	−1.75	81.88%
IN	0.75	29.17%	1.50	−0.75	70.83%
RP	3.25	81.48%	3.91	−1.25	18.52%
Overall categories	2.11	21.94%	2.73	−1.75	—

* WE is shown for transparency but is non-evaluative and excluded from aggregate downstream metrics. Aggregate downstream categories comprise EA, IEQ, MR, SS, IN and RP; MAPE excludes the documented RP = 0 observation for CIRS.

The cross-case comparison is shown in Figure 4. The figure presents documented versus model-predicted GBRS performance, prediction errors, mean bias, category-level model accuracy, total GBRS scores across the four case studies, the residual matrix (Model − Actual), and aggregate validation metrics. This indicates the following points:

- The cross-case MAE of 2.11 GBRS points indicates that, on average, the model deviates from the documented category score by approximately two points.
- The RMSE of 2.73 points is only moderately higher than the MAE, indicating that the errors are not dominated by extremely large outliers at the category level.
- The mean bias of −1.75 points demonstrates that the model has a tendency to underpredict rather than simply producing randomly distributed errors.
- The Pixel Building provides the closest overall category-level agreement, whereas The Edge has the largest error, primarily because of its unusually high RP score.

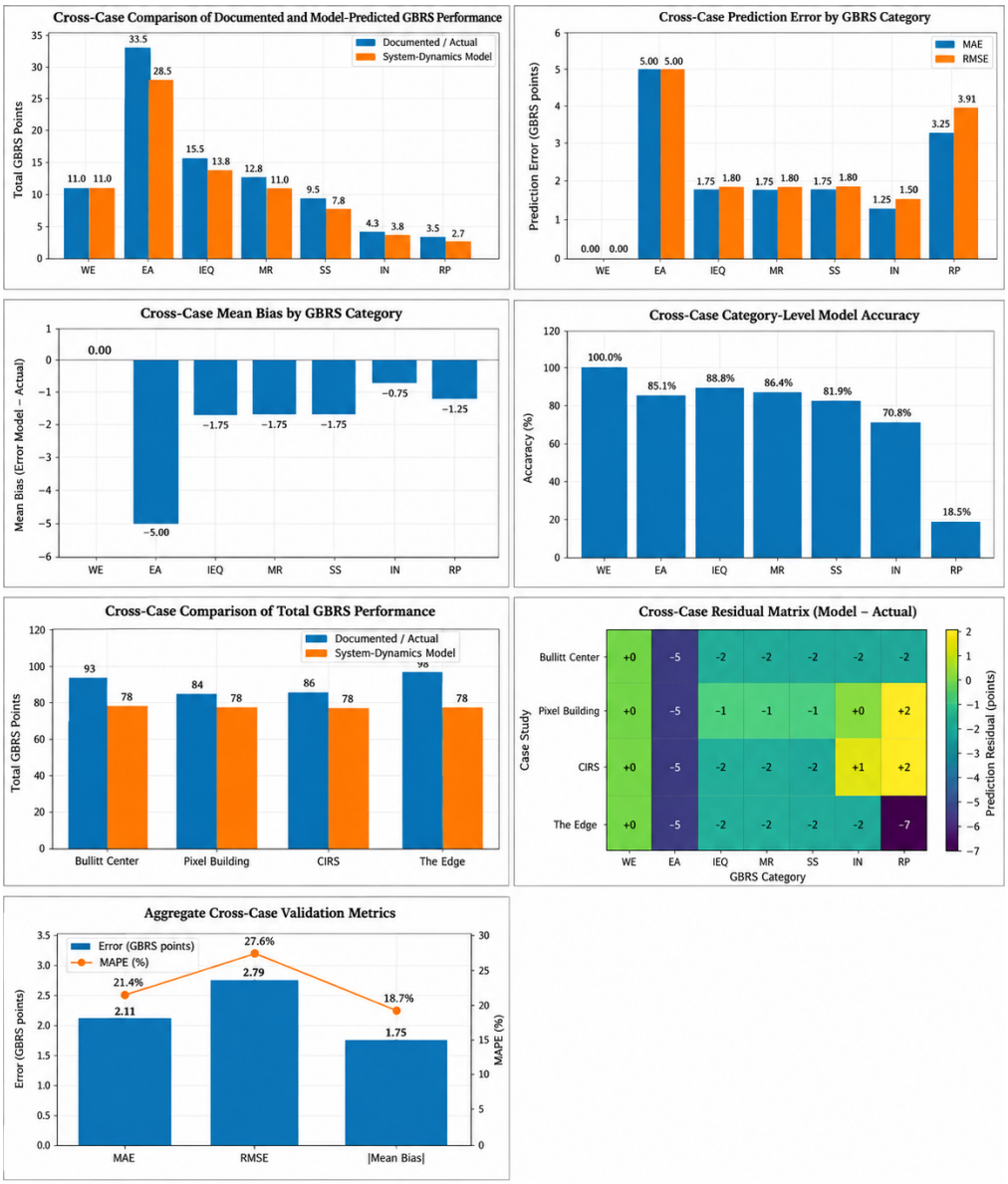


Figure 4. Cross-case comparison of the four case-study projects based on downstream model–case-study discrepancies; WE is shown for transparency but is excluded from aggregate performance metrics. In the bottom panel, bars represent MAE, RMSE, and absolute mean bias (GBRS points), while the orange line represents MAPE (%) using the secondary y-axis.

4. Discussion

The proposed framework is conceptual, exploratory and systems-oriented, and aims to contribute to the theoretical understanding of how sustainability performance travels across interacting building systems over time. An important characteristic of the proposed framework is its capacity to be configured for different GBRSs and different versions and local adaptations. Its core components—stock-and-flow representation, dependency coefficients, causal feedback loops, saturation functions, and leverage-point analysis—can therefore be reconfigured according to the credit structure, weighting system, terminology, and certification requirements of a particular rating scheme. Table 5 shows the evaluation of the proposed structural propositions.

Table 5. Evaluation of the proposed structural propositions.

Proposition	Evidence	Outcome	Interpretation
P1: WE → EA positive reinforcing mechanism	Simulation and cases	Supported within model scope	Direction consistent; magnitude remains context-dependent
P2: WE propagates through other categories	Literature, causal structure, and case studies	Structurally supported/conditional	Defining mechanisms but several pathways remain conceptual. P2 received structural support, but cannot be regarded as empirically confirmed because several indirect pathways remain conceptual and were not independently calibrated
P3: Saturation/balancing constraints limit accumulation	Simulation	Supported within model structure	Marginal accumulation declines as saturation is approached
P4: Cross-case structural transferability	Four case studies	Partially supported	Directional consistency observed; magnitude varies with context-noting that only one BREEAM case is available

The methodological analysis was performed at two levels; case-level and category-level. The cross-case validation demonstrates strong structural and directional agreement between the proposed SD model and four green-certified buildings. The results of the structural validation analysis show that there is good conceptual consistency between the proposed framework and documented sustainability characteristics of the selected case studies. The Bullitt Center and Pixel Building are significant expressions of positive reinforcement of sustainability amplification in the context of integrated water-management systems and adaptive operational strategies. CIRS illustrates how ecological interaction behavior and environmental resilience accumulation take place. The Edge is a pattern for adaptive operational learning with the help of a smart monitoring infrastructure. On the category-level analysis, the framework shows that the model consistently captures the WE-driven system behavior, while the residual errors reveal where additional modules—particularly EA and location-specific RP—are needed. Nevertheless, it should be noted that WE occupies a different methodological role from the other sustainability categories in the proposed framework. WE is defined as the primary intervention/leverage variable through which cross-category effects are examined. Consequently, the WE value itself is not an independent model prediction in the same sense as the downstream category responses. Thus, the zero discrepancy for WE is not treated as evidence of predictive accuracy. Instead, the principal structural validation concerns whether the specified WE intervention generates directionally and approximately consistent responses in the downstream sustainability categories through the implemented SD relationships.

The results show that the changes in behavior over time toward sustainability depend on predominant feedback structures and consider sustainability trade-offs. In early operational phases, the behavior of systems is mainly reinforced by operational optimization, adaptive learning, integration of innovations, and environmental performance amplification for sustainable categories including WE, EA, SS, IN and RP as noted by past studies [25]. The more mature sustainability systems are, the more influence the balancing loops have,

including more energy use at a local level, maintenance complexity, dependency on infrastructure, saturation behavior and operational stabilization and operational coordination needs. The change in focus from reinforcing domination to balancing stabilization is an illustration of the nonlinearity of sustainability evolution in integrated building systems as noted by past scholars [22,69].

A methodological limitation concerns the distinction between model validation and prediction. The proposed framework is not calibrated as a certification-score forecasting model, and the four case studies do not constitute an independent statistical case-study reference dataset in the conventional predictive-modeling sense. The reported MAE, RMSE, MBE and MAPE values are therefore interpreted as diagnostic measures of agreement between model outputs and documented case-study characteristics. They provide evidence regarding structural plausibility and identify systematic discrepancies, but they do not establish generalizable degree of model–case-study agreement. It should be noted that operational conditions, occupant variations, and uncertainties have been simplified. Also, the simulation environment that is supported by the dashboard is not a real-time digital operational infrastructure, but rather a conceptual sustainability interaction platform.

Furthermore, the causal relationships represented in the framework should be interpreted as theoretically and empirically informed structural hypotheses rather than experimentally identified causal effects. Building sustainability outcomes are affected simultaneously by climate, occupancy, technology, design, operational practice and certification requirements. Consequently, the proposed coefficients represent structural sensitivity parameters informed by the literature and expert assessment rather than empirically estimated causal effect sizes. Moreover, only the R1 feedback mechanism is mathematically parameterized and dynamically simulated. The remaining reinforcing and balancing loops are represented conceptually and therefore their individual quantitative contributions, interaction strengths, and temporal dominance cannot be inferred from the present model.

Also, the case-study design is purposive and analytical rather than statistically representative. The limited number of cases, particularly the single BREEAM case, constrains conclusions regarding transferability across rating systems. Furthermore, the normalization procedure removes differences in the numerical scale of individual categories but does not remove conceptual differences in credit definitions, weighting, documentation practices, or certification thresholds between LEED and BREEAM. Consequently, the normalized values retain a degree of rating-system-related uncertainty.

5. Conclusions

This study developed a WE-based SD framework to represent GBRS as a dynamic and interconnected sustainability system rather than a static, threshold-based certification tool. The proposed framework models GBRSs as an interacting system of stocks and flows, reinforcing and balancing feedback loops, and cumulative sustainability effects, positioning WE as a candidate leverage variable capable of having direct and indirect sustainability impacts that can cascade through sustainable categories over time including EA, SS, IEQ, MR, IN, and RP. It should be noted that the proposed framework is conceptual, exploratory and hypothesis-generating SD representation and not an empirically calibrated or externally validated tool for comparing, predicting or ranking LEED and BREEAM outcomes.

Through adaptive learning processes and dashboard-supported visualization, the proposed framework transforms the use of GBRSs from a one-time certification mechanism into a feedback-aware sustainability interpretation system. Application of the framework to four internationally recognized green-certified projects, namely the Bullitt Center, Pixel Building, CIRS, and The Edge, demonstrated initial structural and directional evidence supporting the applicability of the WE-centered framework across heterogeneous building

and certification contexts between the modeled behavior of sustainability interactions and the documented performance characteristics of these buildings.

Across all case studies, the framework consistently reflected the dynamic interplay between reinforcing and balancing processes that characterizes long-term sustainability performance. Across all sustainable categories, the model achieved an MAE of 2.11 points, RMSE of 2.73 points, and MBE of −1.75 points. WE demonstrated MAE = 0; MAPE = 0%. EA exhibited a consistent −5-point bias across all cases, indicating a systematic underestimation of the water-energy cascade. IEQ, MR and SS demonstrated relatively strong agreement, whereas IN and particularly RP showed greater uncertainty due to their dependence on building-specific and contextual factors. The results therefore support the model's structural validity and its ability to represent cascading sustainability relationships, while identifying the energy-interaction and regional-priority modules as priorities for further calibration. This evidence should not be interpreted as statistical generalization or comprehensive validation across LEED and BREEAM.

Thus, future research should focus on empirical calibration of model parameters, integration of climate and project-specific operational data, incorporation of real-time monitoring and occupant behavior dynamics, development of advanced simulation environments, and testing on more case studies, allowing researchers to further develop and test the rest of the conceptually presented feedback loops to further enhance the framework's predictive capability and practical applicability. Collectively, these advancements can support the evolution of building sustainability assessment toward more adaptive, evidence-based, and dynamically informed decision-making processes, enabling certification systems to better reflect the complex realities of sustainability performance throughout a building's lifecycle.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su181910121/s1, Supplementary Materials S1: Expert selection and elicitation of dependency coefficients, Supplementary Materials S2: Expert coefficient matrix, Supplementary Materials S3: Functional mapping of certification categories, and Supplementary Materials S4: Video showing the proposed model interface.

Author Contributions: Conceptualization, M.S. and W.S.E.I.; methodology, M.S. and W.S.E.I.; software, M.S.; validation, M.S.; formal analysis, M.S.; data curation, M.S.; writing—original draft preparation, M.S. and W.S.E.I.; writing—review and editing, W.S.E.I.; visualization, M.S.; supervision, W.S.E.I. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The authors confirm that all data supporting the findings of this study are available within the article.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Symbol	Definition	Type	Scale/Unit	Role in Model
t	Simulation time	Independent variable	months	Operational time horizon
i	Sustainability category	Index	WE, EA, SS, IEQ, MR, IN, RP	Identifies category stock
$S_i(t)$	Sustainability performance stock of category i	Stock	0–100 points	Accumulated category performance
$F_i^{direct}(t)$	Direct investment flow of category i	Flow	points/month	Builds category stock directly
$F_i^{interaction}(t)$	Cross-category interaction flow of category i	Flow	points/month	Transfers WE-generated effects
$F_i^{decay}(t)$	Performance decay/ dissipation flow of category i	Flow	points/month	Represents degradation/ dissipation
$F_i(t)$	total performance/ investment flow into category i	Flow	points/month	Primary leverage flow
α_{ij}	Dependency coefficient of category i	Parameter	dimensionless/ structural coefficient	Represents influence strength of pathway j → i
$\gamma_i(t)$	Saturation factor	Variable	0–1	Reduces marginal accumulation
k_i	Saturation-rate parameter	Parameter	points^{-1}	Controls steepness of saturation
$S_{i,mid}$	Saturation midpoint	Parameter	points	Defines inflection region
δ_i	Decay rate	Parameter	month^{-1}	Controls performance dissipation
β_{R1}	R1 feedback gain	Parameter	points^{-1} month^{-1}	Controls second-order WE–EA reinforcement
w_i	Category weighting coefficient	Parameter	dimensionless	Aggregates category stocks
S_{SD}	SD Sustainability Index	Output	normalized score	Overall continuous sustainability indicator
M_j	Model-generated value	Output	points	Used for case comparison
D_j	Documented case-study reference value	Reference	points	Independent comparison value
e_j	Model–case-study discrepancy	Diagnostic	points	
n	Number of observations	Parameter	count	Statistical calculation

Appendix A

Figures A1–A4 show screenshots of the proposed model.

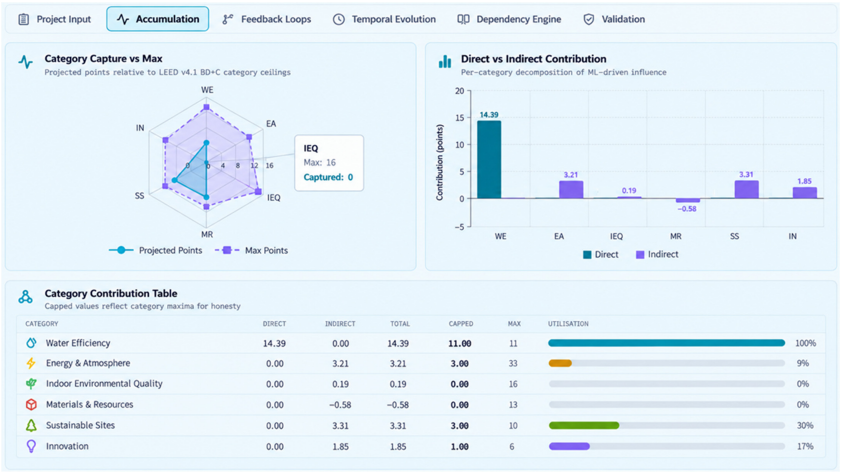


Figure A1. Accumulation-analysis module illustrating direct and indirect WE contributions across sustainability categories and projected category-capture behavior. The blue box highlights the selected Accumulation module of the model interface.



Figure A2. Feedback-loop structure visualization showing the identified reinforcing (R) and balancing (B) causal pathways within the WE-centered sustainability framework. Quantitative dynamic simulation is restricted to R1. The red box identifies the selected Feedback Loops module, and the shaded area represents the intensity associated with the reinforcing (R) and balancing (B) loop trajectories over time.

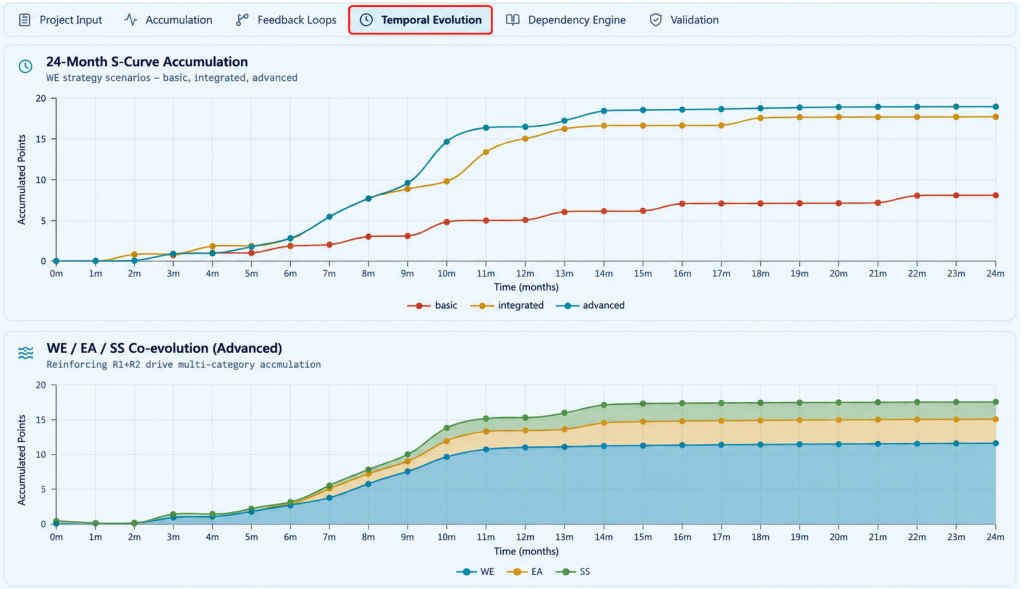


Figure A3. Temporal sustainability evolution module demonstrating nonlinear accumulation trajectories and multi-category co-development behavior under varying WE implementation scenarios. The red box identifies the selected Temporal Evolution module, the shaded regions represent the cumulative contribution of each category over time, and that the stacked areas correspond to WE, EA, and SS.

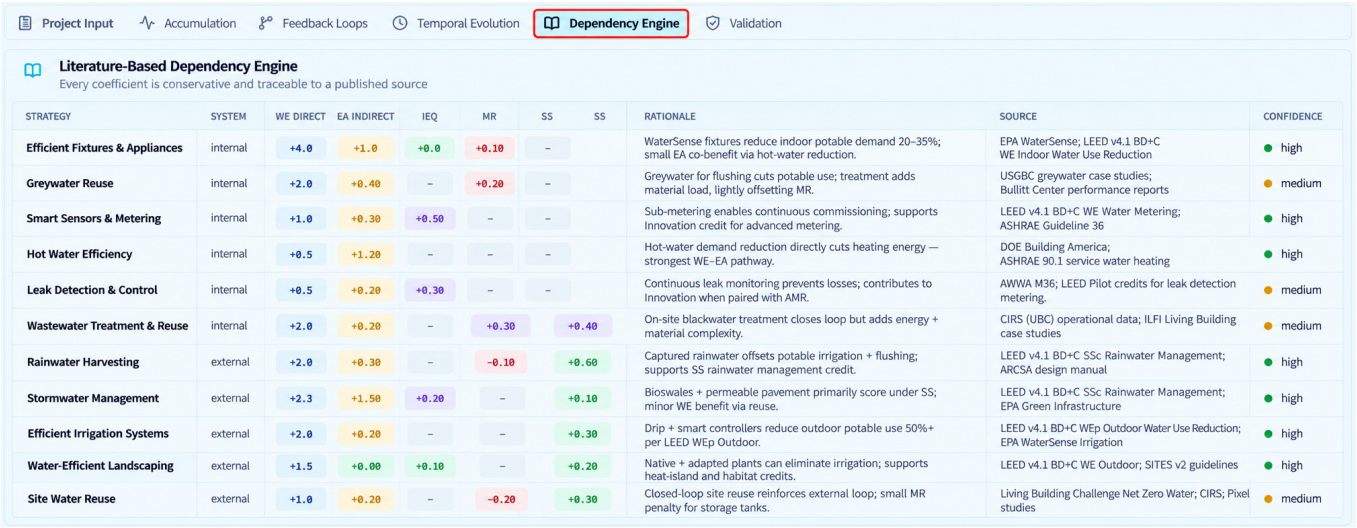


Figure A4. Dependency engine illustrating directional WE interaction coefficients, sustainability influence pathways, and source-traceable dependency relationships. The red box identifies the selected Dependency Engine module.

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