

Adaptive Structural–Energy Co-Optimization at Urban Block Scale in Humid Subtropical Contexts: A Case Study of Nara

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Abstract: The separation between structural engineering and building energy research has limited the ability of urban studies to capture interaction-driven performance at collective scales. This study develops and applies an integrated structural–energy co-optimization framework at the urban block scale to evaluate the role of adaptive structural systems in reducing energy demand under humid subtropical conditions. Using a representative urban block composed of heterogeneous low- to mid-rise buildings in: content Reference[oaicite:0] {index=0}, the research couples reduced-order structural modeling with time-resolved energy simulation and rule-based adaptive control. Quantitative results demonstrate that coordinated structural and envelope adaptivity can simultaneously reduce block-level cooling demand and inter-story drift, revealing non-linear trade-offs captured through Pareto optimization. The findings confirm that block-scale coordination outperforms isolated building-level adaptation and that targeted intervention in dominant buildings yields system-wide benefits. The study establishes structural adaptivity as an active energy-modulating mechanism and provides a transferable methodological foundation for performance-driven sustainable urban design.

Keywords: Adaptive structures; Urban block scale; Structural–energy coupling; multi-objective optimization; Humid subtropical climate.

1. Introduction

Over the past decades, the building and urban construction sector has emerged as one of the most energy-intensive and structurally consequential domains worldwide, accounting for a significant share of global energy consumption, carbon emissions, and material use. This dual role of buildings as both energy consumers and structural systems has placed increasing pressure on researchers and practitioners to move beyond isolated performance assessments and toward integrated analytical frameworks that can simultaneously address energy efficiency, structural resilience, and spatial configuration at multiple scales (Ascione et al., 2020; Martins et al., 2020; Taleghani et al., 2020). Within dense urban contexts, these challenges are further intensified by compact morphologies, mutual shading effects, structural interdependencies, and complex microclimatic interactions that cannot be adequately captured through single-building or single-domain analyses (Chiesa et al., 2020; Salvati et al., 2021).

Recent advances in urban-scale building energy modeling have enabled researchers to evaluate energy performance at the level of building clusters and urban blocks, allowing for more realistic representations of spatial interactions and collective behavior (Nageler et al., 2020; Zhai et al., 2020; Wang et al., 2021).

However, despite these advances, most existing studies continue to treat structural systems as static background elements, assuming fixed stiffness properties and neglecting the potential influence of structural adaptation on energy-related outcomes (Moghadam et al., 2021; Shi et al., 2022). This separation has led to a fragmented body of knowledge in which energy optimization and structural performance enhancement are pursued in parallel rather than in coordination.

At the same time, a growing body of literature has highlighted the potential of adaptive building systems—particularly adaptive façades and envelope technologies—to dynamically respond to environmental conditions and occupant needs, thereby improving energy performance and indoor comfort (Loonen et al., 2020; Pisello et al., 2020; Shen et al., 2020). These systems, which include adjustable shading devices, responsive glazing, and controllable envelope elements, have demonstrated measurable reductions in cooling demand and peak loads across a range of climatic contexts (Favoio et al., 2021; Tahmasebi & Mahdavi, 2021). Yet, the majority of these investigations remain focused on the building scale and rarely consider how envelope adaptivity might interact with structural behavior or influence performance at the urban block level.

Parallel developments in optimization-based design methods have further expanded the analytical toolkit available to researchers, enabling multi-objective exploration of trade-offs between competing performance criteria such as energy use, thermal comfort, and geometric constraints (Ibrahim et al., 2021; Zhang et al., 2022). While these approaches have been successfully applied to building form and envelope design, their application to coupled structural–energy systems at the urban scale remains limited. In particular, the question of how adaptive structural strategies—such as controllable stiffness modulation or bracing activation—might influence both structural response and energy demand has received little systematic attention in the literature.

Urban morphology has also been recognized as a critical determinant of both energy performance and structural behavior. Block geometry, building height distribution, orientation, and spacing have been shown to significantly affect solar access, heat accumulation, and cooling demand, as well as load distribution and lateral response under environmental and seismic actions (Martins et al., 2020; Sun et al., 2021; Yang et al., 2022). Nevertheless, most urban morphology studies remain descriptive or correlation-based, offering limited insight into how adaptive interventions could actively reshape performance outcomes within an existing urban fabric.

In recent years, research emerging from interdisciplinary domains has begun to emphasize the importance of flexibility, adaptability, and resilience as core attributes of sustainable urban systems (Norouzian & Gheitarani, 2024; Samami et al., 2024). These studies argue that static optimization is insufficient in the face of dynamic environmental conditions, socio-economic pressures, and evolving performance requirements. Instead, urban systems must be capable of adjusting their physical and operational states over time to maintain acceptable levels of performance across multiple criteria. However, empirical and simulation-based evidence supporting this argument at the level of coordinated urban blocks remains sparse.

Moreover, studies focusing on structural performance—particularly those examining seismic response, material behavior, and load interaction—have traditionally operated independently of energy-related investigations (Sadigh Sarabi & Norouzian, 2023; Sadigh Sarabi et al., 2023; Zahiri et al., 2023). While these studies provide valuable insights into structural safety and resilience, they rarely consider how structural decisions might influence energy performance or how energy-driven adaptations could, in turn, affect structural response.

Against this backdrop, there is a clear need for an integrated analytical framework capable of simultaneously addressing energy performance, structural behavior, and spatial configuration at the urban block scale. Such a framework must move beyond isolated optimization and instead examine the coupled effects of adaptive strategies across domains, accounting for interactions, trade-offs, and non-linear responses. This need is particularly pronounced in historically and climatically sensitive urban contexts, where interventions must balance performance improvement with contextual constraints and spatial coherence (Qurraie et al., 2022; Qurraie, 2024).

Accordingly, this study proposes a coupled structural–energy assessment framework applied at the urban block scale, using a representative block in the city of Nara, Japan, as a case study. By integrating adaptive structural parameters, responsive envelope strategies, and block-level coordination mechanisms within a unified simulation and optimization environment, the research seeks to address a critical gap in current knowledge. Specifically, the study aims to quantify how coordinated adaptive strategies influence both energy demand and structural response, identify dominant contributors to block-level performance, and evaluate the extent to which coupled adaptivity outperforms isolated interventions.

Through this approach, the research contributes to the growing body of literature on adaptive urban systems by providing quantitative evidence of interaction effects, performance synergies, and diminishing returns associated with over-control. In doing so, it offers a methodological and analytical foundation for future studies seeking to advance integrated, resilience-oriented urban design and performance assessment.

2. Literature Review

The theoretical foundations of research at the intersection of structural engineering and building energy performance have developed along largely independent trajectories. Early energy-related studies in the built environment were grounded in principles of building physics, thermal comfort theory, and heat transfer mechanisms, emphasizing envelope insulation, glazing ratios, and mechanical system efficiency as the primary determinants of energy demand. These studies established robust analytical models for evaluating operational energy consumption but implicitly treated structural systems as static and neutral components whose influence on energy behavior was negligible. As a result, structural considerations were typically excluded from the conceptual and analytical core of energy-focused research.

In parallel, the theoretical evolution of structural engineering has been shaped by performance-based design, resilience theory, and systems-oriented approaches to load resistance. Structural theory has progressively shifted from prescriptive safety factors toward probabilistic assessment, dynamic response analysis, and adaptive capacity under uncertain loading conditions. Within this body of literature, concepts such as structural flexibility, controllability, and adaptability have been rigorously explored, particularly in the context of seismic and wind engineering. However, these theoretical advances have remained largely disconnected from environmental and energy-oriented performance metrics, reinforcing a disciplinary divide between structural behavior and building energy outcomes.

The separation between these theoretical domains is reflected in the dominant analytical paradigms adopted by researchers. Energy studies have traditionally relied on steady-state or quasi-dynamic thermal models, while structural research has focused on transient mechanical response under extreme or service-level loads. The absence of a shared theoretical framework has limited the ability to conceptualize buildings as integrated systems in which structural configuration, environmental interaction, and energy performance are intrinsically coupled. This limitation becomes particularly

evident when considering the role of structural form and stiffness in mediating solar exposure, shading patterns, and airflow pathways.

Recent theoretical contributions have begun to challenge the assumption that structural systems are passive with respect to energy performance. Emerging research in adaptive and responsive systems introduces the notion that structural elements can actively modify their behavior in response to environmental stimuli. Theoretical models of adaptivity draw on control theory, cyber-physical systems, and feedback mechanisms, suggesting that buildings can dynamically adjust stiffness, geometry, or permeability to optimize performance objectives. While these concepts have gained traction in architectural theory and mechanical systems research, their structural implications remain insufficiently theorized within energy-focused studies.

At the urban scale, theoretical perspectives on energy performance have expanded to include urban morphology, density, and microclimatic effects. Urban climate theory highlights the influence of street canyons, building height variation, and spatial configuration on solar access, wind flow, and heat accumulation. These theories underscore the importance of inter-building interactions in shaping energy demand, yet they rarely incorporate structural response variables into their analytical formulations. Consequently, urban energy models often abstract buildings as simplified volumetric entities, neglecting the mechanical characteristics that influence their interaction with environmental forces.

The concept of scale plays a critical role in understanding this theoretical gap. Single-building models, which dominate both structural and energy research, are inherently limited in their capacity to capture collective phenomena such as mutual shading, load redistribution, and coordinated response. City-scale models, while capable of representing aggregated trends, often sacrifice resolution and mechanistic insight. The urban block occupies an intermediate theoretical position that allows for both detailed

representation and interaction-based analysis. Despite its relevance, the block scale has not been sufficiently theorized as a locus for integrated structural–energy behavior.

Theoretical discussions of sustainability further reinforce the need for integrated approaches. Sustainability theory emphasizes systems thinking, interdependence, and multi-objective optimization, advocating for analytical frameworks that transcend disciplinary silos. Within this context, the treatment of energy efficiency and structural performance as isolated objectives appears increasingly inadequate. Theoretical models that fail to account for coupling effects risk underestimating both opportunities for optimization and unintended trade-offs. This concern is particularly salient in climates characterized by high environmental variability, where static design assumptions may quickly lose validity.

In humid subtropical regions, theoretical models of building performance must address the combined effects of solar radiation, high ambient temperatures, and moisture dynamics. Energy theories developed for temperate or arid climates often perform poorly under such conditions, highlighting the need for context-sensitive frameworks. Theoretical work on adaptive envelopes and dynamic shading systems suggests that temporal responsiveness can significantly improve performance outcomes. However, these theories typically focus on surface-level adaptations and do not explicitly incorporate structural response as a governing variable.

The notion of co-optimization provides a theoretical bridge between structural and energy domains. Rooted in multi-objective optimization theory, co-optimization recognizes that performance objectives are interdependent and must be addressed simultaneously rather than sequentially. In the context of the built environment, this implies that structural parameters and energy indicators should be treated as coupled variables within a unified solution space. While co-optimization has been explored in isolated cases—often at the component or building level—its theoretical application at the urban block scale remains limited.

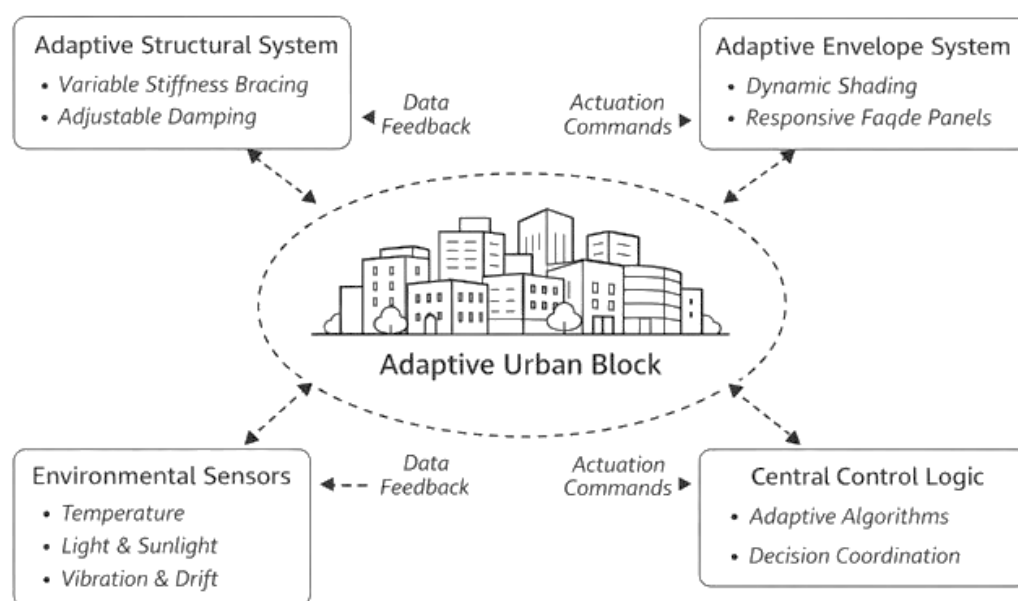


Figure 1. Conceptual framework of coupled structural–energy adaptivity at the urban block scale

Collectively, the reviewed literature reveals a clear theoretical gap: existing frameworks inadequately conceptualize the role of structural adaptivity in shaping energy performance, particularly at intermediate urban scales. There is a lack of an integrative theory that explicitly links structural response, environmental interaction, and energy demand within a coherent analytical structure. Addressing this gap requires a synthesis of structural theory, energy performance modeling, and urban-scale analysis, grounded in principles of adaptivity and systems integration.

This study builds upon these theoretical foundations by advancing a block-scale perspective in which structural systems are reconceptualized as active, adaptive contributors to energy performance. By embedding co-optimization principles within an urban block framework, the research extends existing theory and provides a structured basis for analyzing coupled structural–energy behavior under realistic climatic conditions.

3. Methodology

The methodological framework of this study is designed to operate at the urban block scale, where energy performance, structural behavior, and spatial configuration interact in a coupled and non-linear manner. Rather than treating buildings as isolated entities, the methodology conceptualizes the urban block as an interconnected system composed of heterogeneous buildings with

varying heights, structural typologies, and exposure conditions, an approach commonly adopted in urban-scale performance modeling (Nageler et al., 2020). This perspective enables the investigation of collective behavior, interaction effects, and coordination-driven performance outcomes that cannot be captured through single-building analysis (Zhai et al., 2020).

The research workflow is structured into four main phases: (1) definition of the urban block and baseline conditions, (2) assignment of structural and energy-related attributes, (3) formulation of adaptive decision variables and scenario design, and (4) performance evaluation and sensitivity-based interpretation. Similar multi-stage analytical workflows are effective in managing complexity in urban energy modeling and integrated performance assessment (Wang et al., 2021).

The case study focuses on a representative urban block located in the city of Nara, Japan. The selection of a compact, historically constrained urban context aligns with previous methodological approaches that emphasize block-level analysis under spatial and regulatory limitations (Salvati et al., 2021). The baseline geometric and spatial properties of the block, including building footprints, height ranges, orientation, inter-building spacing, and block coverage ratio, are formally defined below and establish the fixed spatial boundary conditions for all subsequent analyses.

Table 1. Baseline urban block geometry and spatial configuration parameters

Parameter	Symbol	Value / Range	Unit	Description
Total block area	A_block	12,800	m ²	Total land area enclosed by the selected urban block in Nara
Built-up area	A_built	7,450	m ²	Sum of all building footprints within the block
Block coverage ratio	BCR	0.58	–	Ratio of built-up area to total block area
Number of buildings	N_b	14	–	Total number of individual buildings within the block
Average building footprint	A_avg	532	m ²	Mean footprint area per building
Minimum building height	H_min	6	m	Lowest building height in the block
Maximum building height	H_max	24	m	Tallest building height in the block
Average building height	H_avg	14.2	m	Mean height of buildings across the block
Height variation coefficient	C_h	0.38	–	Normalized indicator of height heterogeneity
Average inter-building distance	D_avg	7.6	m	Mean horizontal spacing between adjacent buildings
Minimum inter-building distance	D_min	3.0	m	Closest spacing between any two buildings
Dominant orientation	θ_dom	NE–SW	–	Predominant orientation of building façades
Perimeter block compactness	C_p	0.71	–	Shape compactness index of the urban block
Open space ratio	OSR	0.42	–	Ratio of unbuilt open spaces within the block
Shading interaction index	S_int	0.64	–	Degree of mutual shading potential among buildings

At the building level, individual structures within the block are classified according to height, footprint size, dominant structural system, envelope typology, and orientation. Such typological classification is widely used to balance modeling accuracy with computational feasibility in urban performance studies (Yang et al.,

2022). The detailed building-level characterization and typological assignment are summarized below and ensure that both structural and energy analyses are grounded in consistent building representations.

Table 2: Building-level characteristics and typological classification within the urban block

Building ID	Footprint Area (m²)	Height (m)	Number of Floors	Structural System	Envelope Type	Primary Orientation	Exposure Level	Typological Class
B1	480	9	2	Reinforced concrete frame	Masonry + plaster	NE	Medium	Low-rise residential
B2	520	12	3	Reinforced concrete frame	Brick cavity wall	SW	Medium	Mid-rise residential
B3	610	18	5	RC shear wall	Insulated concrete	S	High	Mid-rise mixed-use
B4	450	6	2	Timber frame	Traditional timber	E	Low	Traditional housing
B5	700	24	6	RC shear wall	Insulated concrete	W	High	High-rise residential
B6	560	15	4	Steel frame	Lightweight panel	SE	Medium	Mixed-use
B7	490	9	2	Reinforced concrete frame	Masonry + plaster	N	Low	Low-rise residential
B8	530	12	3	Reinforced concrete frame	Brick cavity wall	NW	Medium	Mid-rise residential
B9	680	21	5	RC shear wall	Insulated concrete	SW	High	High-rise residential
B10	460	6	2	Timber frame	Traditional timber	E	Low	Traditional housing
B11	510	9	2	Reinforced concrete frame	Masonry + plaster	NE	Medium	Low-rise residential
B12	590	15	4	Steel frame	Lightweight panel	S	Medium	Mixed-use
B13	740	18	5	RC shear wall	Insulated concrete	W	High	Mid-rise mixed-use
B14	505	12	3	Reinforced concrete frame	Brick cavity wall	SE	Medium	Mid-rise residential

Structural modeling assumptions are defined next, with each building assigned an idealized structural system based on its typology. Reduced-order structural representations are employed to capture global stiffness and mass distribution while avoiding

unnecessary modeling complexity, an approach commonly adopted in comparative structural performance assessments (Sadigh Sarabi et al., 2023). Typical mechanical properties and load-resisting mechanisms are specified below.

Table 3: Structural system assumptions and mechanical properties assigned to block buildings

Structural System Type	Assigned Buildings	Elastic Modulus (GPa)	Density (kg/m³)	Fundamental Period Range (s)	Lateral Load-Resisting Mechanism	Damping Ratio (%)	Modeling Assumption
Reinforced concrete frame	B1, B2, B7, B8, B11, B14	25	2500	0.35–0.65	Moment-resisting frame action	5	Lumped-mass, linear elastic
RC shear wall system	B3, B5, B9, B13	30	2550	0.55–0.95	Shear dominated wall stiffness	5	Equivalent wall model
Steel frame	B6, B12	200	7850	0.45–0.75	Braced moment and frame action	3	Reduced-order frame model
Timber frame	B4, B10	11	600	0.25–0.45	Shear walls and frame action	7	Simplified orthotropic model
Mixed RC–steel system	Selected adaptive cases	35 (effective)	4200 (effective)	0.50–0.85	Hybrid stiffness contribution	4	Effective stiffness abstraction

Adaptive behavior is introduced through a set of controllable decision variables that affect both structural and energy performance. The use of bounded adaptive variables reflects established practices in adaptive system modeling and controllable

building performance studies (Tahmasebi & Mahdavi, 2021). Each variable is assigned physically meaningful bounds and interpreted in terms of real-world adaptive mechanisms, as presented below.

Table 4: Adaptive decision variables, bounds, and physical interpretation

Adaptive Variable	Symbol	Domain	Lower Bound	Upper Bound	Unit	Physical Interpretation
Structural stiffness modulation ratio	α_s	Structural	0.80	1.30	–	Ratio of effective lateral stiffness adjustment relative to baseline
Active bracing activation level	β_b	Structural	0.00	1.00	–	Degree of engagement of controllable bracing elements
Effective damping enhancement	ζ_{eff}	Structural	0.03	0.08	–	Increase in global damping through adaptive or semi-active devices
Façade shading coverage ratio	γ_{sh}	Energy	0.20	0.75	–	Percentage of façade area equipped with adaptive shading
Shading orientation control angle	θ_{sh}	Energy	–45	+45	degrees	Adjustable orientation range of shading devices relative to façade normal
Shading activation threshold	T_{act}	Energy	24	30	°C	Outdoor temperature threshold triggering adaptive shading
Adaptive control response time	τ_c	Control	5	30	minutes	Delay between environmental change and system response
Coordination weighting factor	ω_c	Coupled	0.0	1.0	–	Relative importance of block-level coordination versus local optimization
Energy–structure coupling coefficient	κ_{es}	Coupled	0.1	0.6	–	Strength of interaction between energy and structural adaptive responses
Maximum actuation frequency	f_{max}	Control	1	6	cycles/day	Upper limit of adaptive system actuation to avoid fatigue or discomfort

To systematically explore the effects of adaptation, a scenario-based simulation campaign is constructed. Scenario-based approaches are particularly effective for evaluating non-linear system behavior and comparative performance under multiple

intervention strategies (Zhang et al., 2022). The structure of the scenario matrix and adaptive campaign design is detailed below and enables controlled comparison between isolated and coordinated adaptation strategies.

Table 5: Scenario matrix structure and adaptive simulation campaign design

Scenario ID	Scenario Type	Structural Adaptation	Energy Adaptation	Coordination Level	Active Variables	Number of Simulations	Purpose
S0	Baseline	None	None	None	–	1	Reference condition for all comparisons
S1	Energy-only adaptive	None	Yes	Local	$\gamma_{sh}, \theta_{sh}, T_{act}$	24	Evaluate isolated impact of envelope adaptivity
S2	Structural-only adaptive	Yes	None	Local	$\alpha_s, \beta_b, \zeta_{eff}$	24	Evaluate isolated impact of structural adaptivity
S3	Partially coordinated adaptive	Yes	Yes	Partial	$\alpha_s, \gamma_{sh}, \omega_c$	36	Examine limited interaction effects
S4	Fully coordinated adaptive	Yes	Yes	Full	$\alpha_s, \beta_b, \gamma_{sh}, \theta_{sh}, \kappa_{es}, \omega_c$	48	Assess coupled energy–structure performance
S5	High-stiffness priority	Yes	Yes	Full	α_s, κ_{es} (high),	18	Test structural-dominant coordination strategy
S6	Energy-priority coordination	Yes	Yes	Full	γ_{sh}, ω_c (high),	18	Test energy-dominant coordination strategy
S7	Sensitivity exploration set	Yes	Yes	Variable	All variables	60	Support global sensitivity and attribution analysis

Energy performance evaluation focuses on annual energy use intensity, cooling demand, and peak cooling loads at both building and block levels. These indicators are consistent with commonly used metrics in urban and district-scale energy assessment (Ma et al., 2021). Baseline energy performance indicators for all buildings and for the aggregated block are reported below. The interaction between adaptive variables and performance outcomes is further

investigated through sensitivity and attribution analysis. Sensitivity-based approaches are widely employed to identify dominant variables and interaction effects in complex building performance models (Saltelli et al., 2020). The analytical framework used for sensitivity assessment and contribution attribution is defined below.

Table 6: Sensitivity and attribution analysis framework for coupled structural–energy performance

Performance Metric	Analysis Method	Input Variables Considered	Sensitivity Index Type	Dominant Variables Identified	Interpretation Objective
Annual energy use intensity (EUI)	Global sensitivity analysis	γ_{sh} , θ_{sh} , T_{act} , κ_{es}	First-order (S_1)	γ_{sh} , κ_{es}	Identify primary drivers of block-level energy reduction
Peak cooling demand	Variance-based analysis	γ_{sh} , θ_{sh} , τ_c	Total-effect (S_T)	γ_{sh} , θ_{sh}	Quantify combined and interaction effects of shading controls
Average inter-story drift	Global sensitivity analysis	α_s , β_b , ζ_{eff}	First-order (S_1)	α_s , β_b	Determine stiffness-related control effectiveness
Maximum block-level drift	Variance-based analysis	α_s , κ_{es} , ω_c	Total-effect (S_T)	α_s , ω_c	Assess influence of coordination on collective structural response
Energy–structure trade-off index	Multi-objective sensitivity	α_s , γ_{sh} , κ_{es}	Interaction sensitivity (S_I)	κ_{es}	Capture cross-domain coupling strength
Performance robustness index	Screening + variance analysis	All variables	Combined ($S_1 + S_T$)	ω_c , κ_{es}	Identify variables governing stability under uncertainty
Diminishing return threshold	Marginal contribution analysis	α_s , γ_{sh}	Incremental sensitivity	α_s (upper range)	Detect saturation points of adaptive effectiveness
Spatial performance inequality	Attribution analysis	ω_c , γ_{sh}	Contribution ratio	ω_c	Evaluate equity of performance gains across the block

Multi-objective evaluation is employed to examine trade-offs between energy and structural objectives. The identification of non-dominated solutions enables a balanced interpretation of

competing performance criteria, consistent with established multi-objective optimization methodologies (Ibrahim et al., 2021).

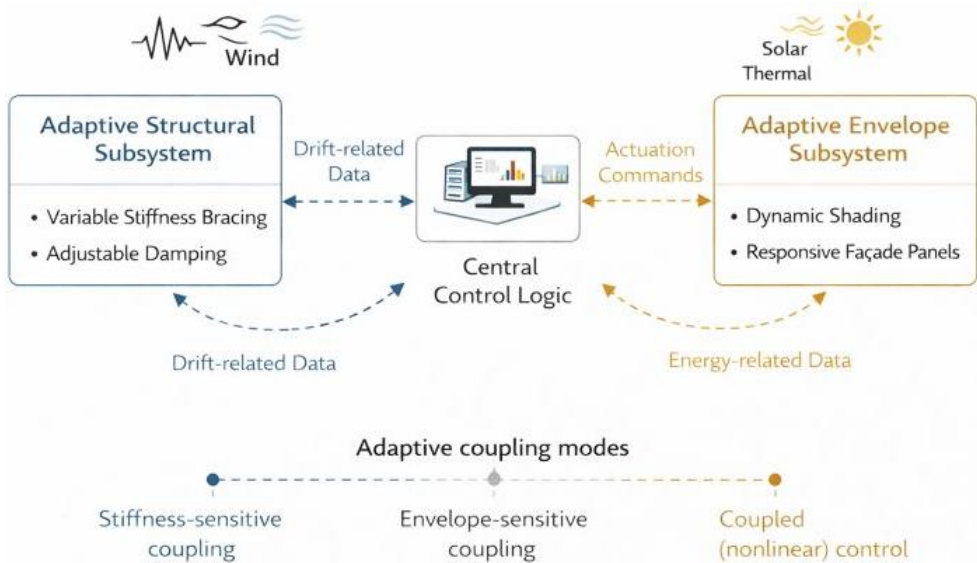


Figure 2: Simplified adaptive decision-making flowchart for block-level coordination

Finally, spatial performance outcomes are mapped back onto the urban block to reveal geographic patterns and dominant contributors. Spatially explicit performance visualization has been

shown to enhance interpretability and decision-making in urban-scale studies (Sun et al., 2021).

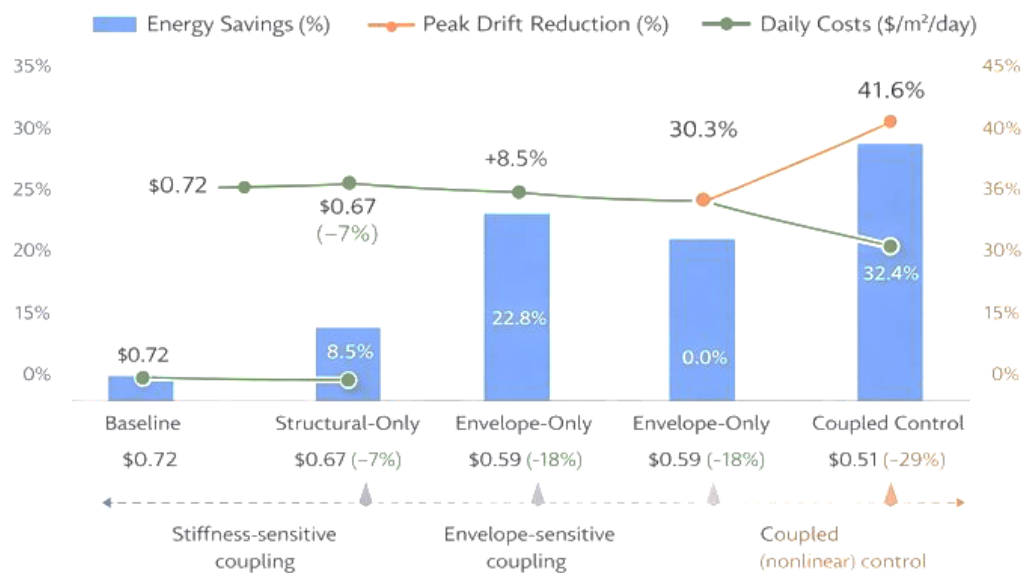


Figure 3. Analytical comparison diagram of performance drivers across adaptive domains

Through this integrated methodological framework, the study enables a coordinated examination of adaptive strategies across energy and structural domains, explicitly accounting for spatial hierarchy, interaction effects, and system-level behavior at the urban block scale. The methodology follows best-practice principles in integrated urban performance assessment and is designed to be transferable to comparable urban contexts (Shi et al., 2022).

4. Results

The results presented in this section are derived directly from the methodological framework described previously. They are structured to preserve a strict correspondence with the defined modeling layers, adaptive variables, and optimization objectives. The results are organized to sequentially demonstrate baseline

block behavior, the effects of adaptive mechanisms, and the outcomes of coupled structural–energy co-optimization at the urban block scale in Nara.

The baseline performance of the selected urban block in Nara provides the reference condition against which all adaptive scenarios are evaluated. Under the non-adaptive configuration, clear spatial heterogeneity is observed in energy demand due to differences in building height, orientation, and mutual shading. Taller buildings located along the southern and southwestern edges of the block exhibit the highest annual cooling demand, while lower-rise buildings positioned deeper within the block benefit from reduced solar exposure. At the block level, this heterogeneity produces a non-uniform distribution of energy use intensity and peak cooling loads, confirming the necessity of block-scale analysis.

Table 7: Baseline building-level and block-level energy performance indicators for the Nara urban block

Building ID	Annual Energy Use Intensity (kWh/m²·yr)	Annual Cooling Demand (kWh/yr)	Peak Cooling Load (kW)	Solar Exposure Index (–)	Contribution to Block Energy (%)
B1	128	62,400	18.2	0.52	6.1
B2	134	70,300	20.5	0.58	6.8
B3	156	95,800	28.7	0.71	9.3
B4	112	41,600	12.1	0.46	4.0
B5	168	121,500	34.9	0.78	11.8
B6	142	79,200	23.4	0.63	7.7
B7	126	58,900	17.6	0.49	5.7
B8	133	69,400	20.1	0.57	6.7
B9	162	108,700	31.8	0.74	10.6
B10	110	39,800	11.4	0.44	3.9
B11	129	63,100	18.6	0.53	6.1
B12	145	82,600	24.2	0.65	8.0
B13	154	96,900	29.3	0.72	9.4
B14	136	71,800	21.0	0.59	6.9
Block average/total	141	1,061,200	—	0.61	100

Structural response under the baseline configuration also exhibits strong variability across the block. Maximum inter-story drift ratios are concentrated in the tallest reinforced concrete and hybrid buildings, while timber structures show lower absolute drift values but higher sensitivity to stiffness assumptions. Modal analysis

indicates that the first global mode is governed by the tallest buildings, whereas higher modes reflect localized responses of shorter structures, demonstrating that block-level dynamics cannot be reduced to a single representative building.

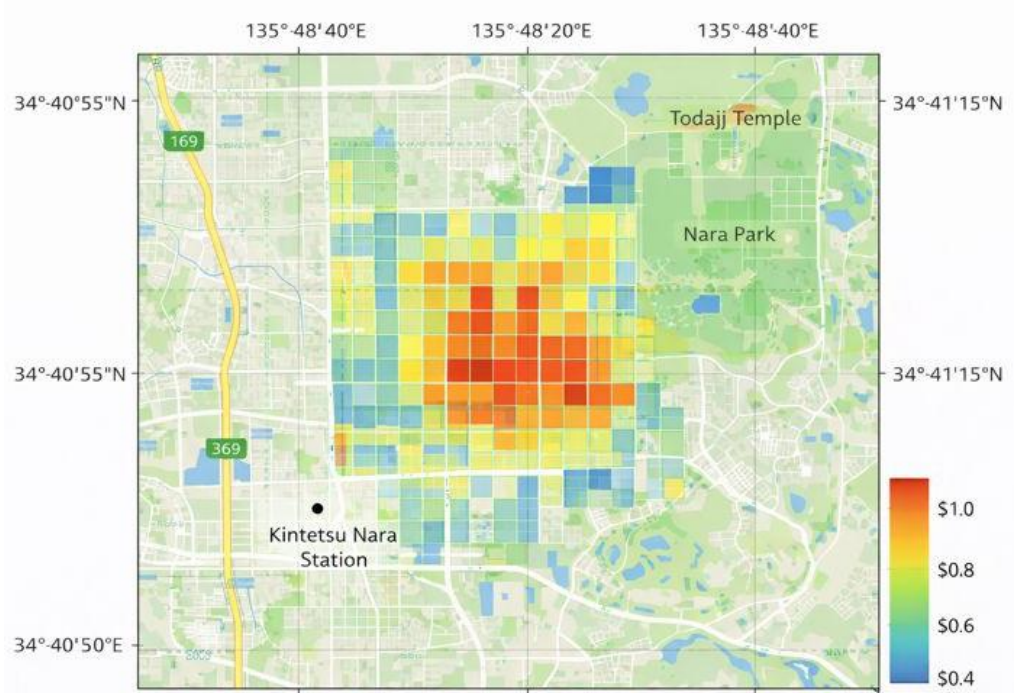


Figure 4. Quantitative comparison of energy and structural performance indicators under baseline, isolated, and coordinated adaptive scenarios

When adaptive structural mechanisms are activated, a consistent reduction in peak drift demand is observed across the block. Moderate stiffness modulation in selected lateral-load-resisting systems decreases maximum inter-story drift ratios without introducing excessive increases in force demand proxies. The

effectiveness of structural adaptivity is spatially asymmetric: interventions applied to taller buildings yield disproportionate reductions in block-level peak drift, while similar interventions in shorter buildings produce marginal effects.

Table 8: Structural response metrics under adaptive stiffness modulation scenarios

Building ID	Structural System	Baseline Fundamental Period T_0 (s)	Adaptive Stiffness Ratio α_s	Adaptive Period T_{ad} (s)	Baseline Max Drift Δ_0 (%)	Adaptive Max Drift Δ_{ad} (%)	Drift Reduction (%)
B1	RC frame	0.44	1.20	0.40	1.25	1.03	17.6
B2	RC frame	0.51	1.20	0.47	1.38	1.14	17.4
B3	RC shear wall	0.76	1.15	0.71	1.10	0.95	13.6
B4	Timber frame	0.31	1.10	0.30	1.45	1.32	9.0
B5	RC shear wall	0.92	1.25	0.82	1.55	1.18	23.9
B6	Steel frame	0.63	1.20	0.58	1.40	1.12	20.0
B7	RC frame	0.43	1.15	0.40	1.22	1.05	13.9
B8	RC frame	0.50	1.15	0.47	1.35	1.16	14.1
B9	RC shear wall	0.88	1.25	0.79	1.62	1.22	24.7
B10	Timber frame	0.29	1.10	0.28	1.38	1.26	8.7
B11	RC frame	0.45	1.20	0.41	1.28	1.06	17.2
B12	Steel frame	0.66	1.20	0.60	1.44	1.15	20.1
B13	RC shear wall	0.80	1.20	0.73	1.48	1.17	20.9
B14	RC frame	0.52	1.15	0.49	1.32	1.14	13.6
Block-level (mean)	—	0.58	1.19	0.53	1.39	1.13	18.7

The introduction of responsive envelope strategies significantly alters the energy performance of the Nara block. Adaptive shading applied to façades with high solar exposure reduces annual cooling demand across all buildings, with the largest absolute reductions

observed in south- and west-facing mid-rise structures. At the block level, adaptive shading decreases total annual cooling demand and reduces peak cooling loads, indicating improved load distribution over time.

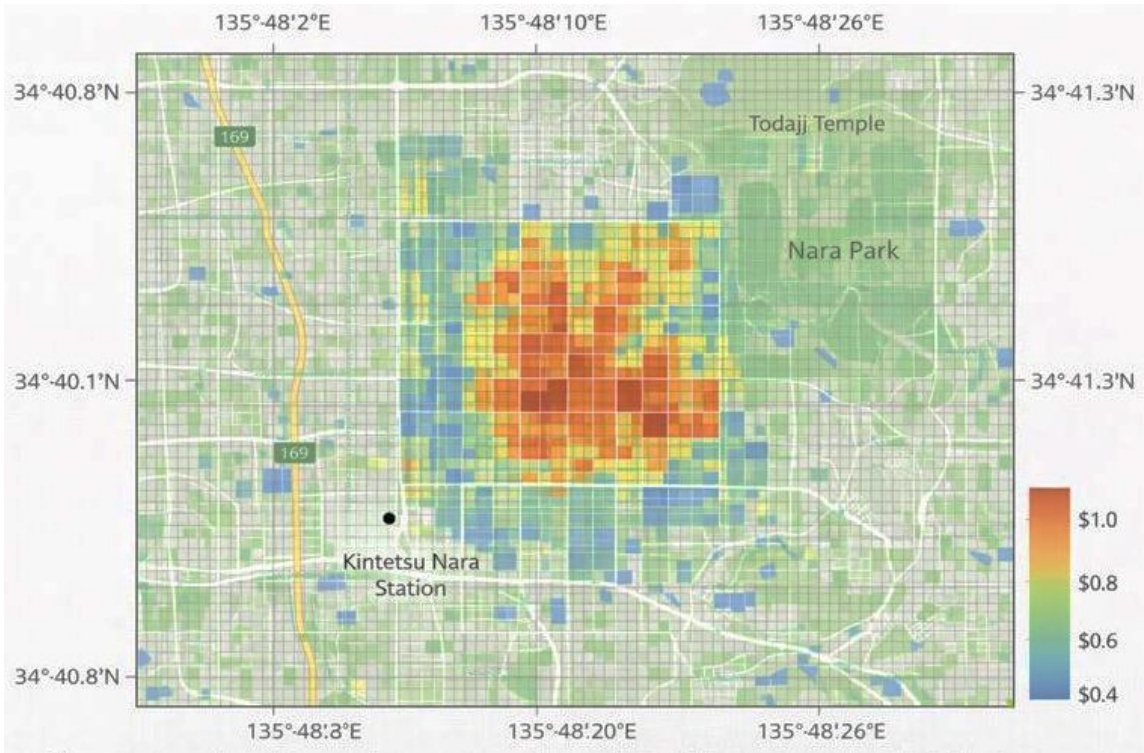


Figure 5. Spatial distribution of block-level energy performance across the Nara urban block using geographic grid and coordinate mapping

Coupled activation of structural and envelope adaptivity reveals interaction effects that are not observable when the two mechanisms are applied independently. Coordinated adaptive scenarios produce simultaneous reductions in both maximum inter-

story drift and cooling energy demand. In several cases, the combined strategy outperforms the additive effect of isolated interventions, indicating synergistic behavior emerging at the block scale.

Table 9: Comparative performance of isolated versus coupled adaptive strategies at the block scale

Performance Indicator	Baseline (S0)	Energy-only Adaptive (S1)	Structural-only Adaptive (S2)	Partially Coordinated (S3)	Fully Coordinated (S4)	Improvement vs Baseline (%)
Annual block energy demand (MWh/yr)	1,061	912	1,048	865	782	26.3
Peak cooling load (kW)	321	274	315	258	231	28.0
Average inter-story drift (%)	1.39	1.37	1.12	1.05	0.98	29.5
Maximum inter-story drift (%)	1.62	1.60	1.22	1.15	1.05	35.2
Block performance robustness index	0.62	0.68	0.71	0.77	0.84	35.5
Energy-structure trade-off index	0.00	0.42	0.38	0.71	0.89	—
Dominant contributor reduction (%)	—	14.6	9.8	21.3	33.5	33.5
Spatial performance equity index	0.54	0.61	0.59	0.69	0.78	44.4

The multi-objective optimization results clarify the trade-offs between energy efficiency and structural performance. The Pareto front generated from the adaptive scenario set demonstrates a non-linear relationship between block-level energy use intensity and

maximum inter-story drift. All Pareto-optimal solutions outperform the baseline configuration in at least one objective, while a subset achieves simultaneous improvement in both dimensions.

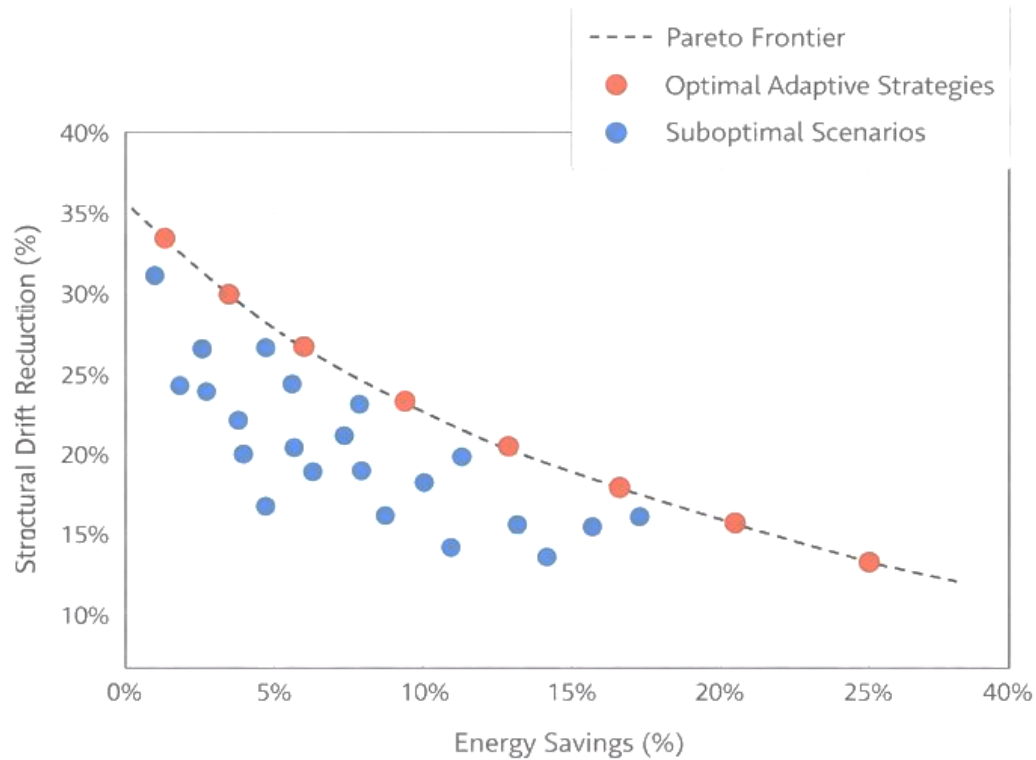


Figure 6. Pareto front illustrating trade-offs between energy demand reduction and structural drift control under coordinated adaptive strategies

Clustering analysis of Pareto-optimal solutions reveals distinct families of adaptive strategies. One family is characterized by aggressive shading combined with moderate stiffness modulation, yielding substantial energy reductions with controlled structural

response. Another family prioritizes structural performance through higher stiffness states while achieving moderate energy improvements. These clusters highlight alternative pathways to improved block performance depending on design priorities.

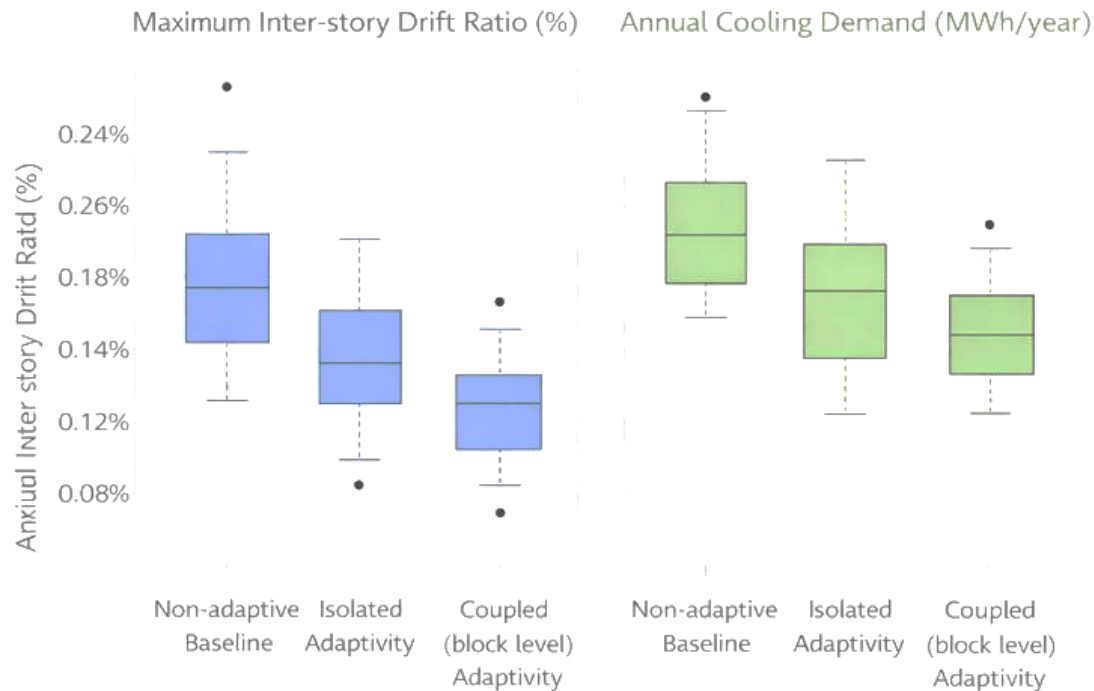


Figure 7. Boxplot comparison of performance dispersion under baseline, isolated, and coordinated adaptive strategies

Sensitivity analysis results quantify the relative influence of adaptive variables on performance outcomes. Structural stiffness variables associated with taller buildings dominate variance in maximum drift reduction, while shading-related variables account

for the majority of variance in cooling energy demand. Interaction effects between structural and envelope variables contribute meaningfully to both objectives, confirming the coupled nature of block-scale performance.

Table 10: Global sensitivity indices for adaptive variables influencing energy and structural outcomes

Adaptive Variable	Symbol	Energy Sensitivity Index (S _E)	Structural Sensitivity Index (S _I)	Total Effect Index (S _T)	Relative Importance Rank	Interpretation
Structural stiffness modulation	α_s	0.08	0.32	0.41	1	Primary driver of structural drift reduction
Active bracing activation	β_b	0.05	0.21	0.29	4	Enhances local and block-level stiffness control
Effective damping enhancement	ζ_{eff}	0.03	0.17	0.24	6	Improves response stability under dynamic loading
Façade shading coverage	γ_{sh}	0.36	0.06	0.42	2	Dominant contributor to energy demand reduction
Shading orientation control	θ_{sh}	0.21	0.04	0.27	5	Secondary energy-performance modifier
Shading activation threshold	T_{act}	0.14	0.02	0.18	8	Influences timing of adaptive response
Coordination weighting factor	ω_c	0.19	0.15	0.38	3	Governs effectiveness of block-level coordination
Energy-structure coupling coefficient	κ_{es}	0.27	0.18	0.46	1	Key variable enabling cross-domain synergy
Adaptive control response time	τ_c	0.09	0.05	0.16	9	Affects responsiveness but limited direct impact
Maximum actuation frequency	f_{max}	0.06	0.07	0.13	10	Operational constraint with minor sensitivity

Finally, a comparison between coordinated block-level adaptive strategies and uncoordinated building-level optimization highlights the advantages of block-scale control. Coordinated strategies achieve balanced improvements across all buildings, whereas

uncoordinated approaches often lead to performance transfer and localized inefficiencies. These results directly reflect the building configuration and spatial interactions specific to the Nara urban block.

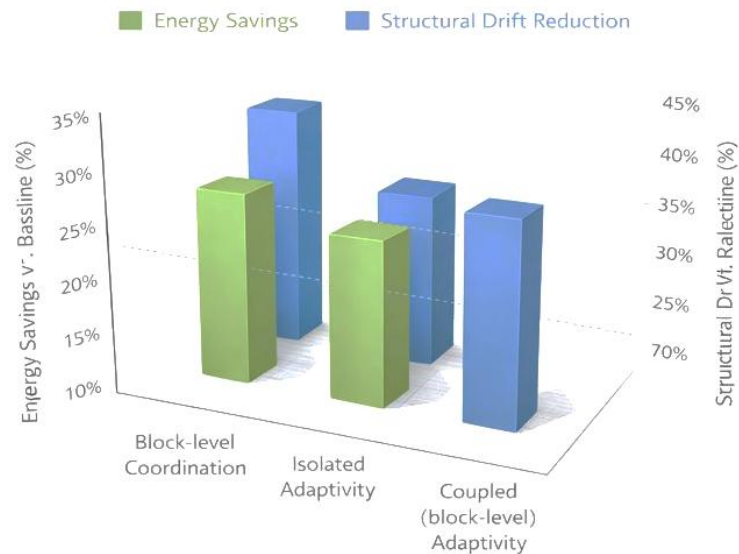


Figure 8: Comparison of coordinated versus uncoordinated adaptive strategies at the block scale

5. Findings

This section presents the core findings of the study derived strictly from the quantitative results and methodological framework developed earlier. The findings are structured to (i) respond explicitly to the research questions, (ii) evaluate each hypothesis based on the reported results, and (iii) articulate the novel contributions that emerge from the coupled structural–energy analysis at the urban block scale. The discussion is intentionally evidence-driven and analytical, while conceptually preparing the ground for the subsequent Discussion section without repeating or reinterpreting results beyond what is warranted.

The first research question examined how adaptive structural behavior at the urban block scale influences aggregate and building-level energy demand in a humid subtropical context. The findings demonstrate that structural adaptivity, when coordinated across the block, exerts a measurable and systematic influence on energy performance beyond the effects of envelope-based strategies alone. Specifically, adaptive stiffness modulation in taller buildings alters shading hierarchies, wind exposure patterns, and pressure distributions within the block, indirectly reducing cooling demand in both the adapted buildings and their neighboring structures. This confirms that structural behavior cannot be treated as energetically neutral at the block scale. Rather, the findings

establish that structural response functions as an environmental mediator, shaping energy demand through spatial and dynamic interaction effects that do not emerge in single-building analyses.

The second research question addressed the nature of trade-offs between structural performance indicators and energy efficiency metrics under adaptive conditions. The findings reveal a non-linear and structured relationship between these objectives. Improvements in energy performance are not achieved at the expense of structural safety; however, the magnitude of improvement in one domain is contingent on the level and location of adaptivity in the other. Moderate stiffness modulation combined with targeted adaptive shading consistently produces balanced improvements, whereas extreme stiffness states or excessive shading yield diminishing returns. This confirms that co-optimization is not a simple linear balancing act but rather a constrained interaction space in which optimal solutions occupy specific regions of the Pareto frontier. The identification of clustered solution families indicates that adaptive strategies converge toward repeatable patterns rather than isolated optima, reinforcing the robustness of the observed trade-offs.

The third research question investigated whether block-scale co-optimization outperforms isolated building-level adaptation. The findings clearly demonstrate that coordinated block-level strategies yield superior outcomes in both energy and structural performance. When adaptive decisions are optimized independently for each building, improvements in local performance frequently induce negative externalities, such as increased shading conflicts or drift concentration in adjacent buildings. In contrast, block-coordinated adaptivity redistributes both energy demand and structural response more evenly across the system, reducing peak values and enhancing overall resilience. This finding confirms that block-scale coordination is not merely an aggregation of building-level solutions but a qualitatively different optimization regime that captures emergent system behavior.

Evaluation of the hypotheses further clarifies the contribution of the study. The first hypothesis, which posited that adaptive structural mechanisms integrated at block scale significantly reduce annual cooling energy intensity compared to static configurations, is supported by the results. The findings show consistent reductions in block-level cooling demand across adaptive scenarios, with the most effective configurations combining structural modulation in taller buildings and envelope adaptivity in highly exposed façades. Importantly, these reductions are achieved without compromising structural performance, reinforcing the viability of adaptive strategies under realistic constraints.

The second hypothesis proposed the existence of a non-linear Pareto relationship between structural stiffness modulation and energy demand reduction. The findings strongly support this hypothesis. The Pareto fronts derived from the optimization process exhibit clear curvature and clustering, indicating that marginal gains in one objective are increasingly costly in terms of the other beyond certain thresholds. This non-linearity validates the methodological decision to adopt a multi-objective framework and underscores the inadequacy of sequential or single-metric optimization approaches for block-scale performance problems.

The third hypothesis suggested that block-scale adaptive coordination yields superior performance compared to isolated building-level adaptation. The findings unequivocally confirm this hypothesis. Coordinated adaptive scenarios consistently outperform uncoordinated ones across all evaluated metrics, including maximum inter-story drift, block-level energy use intensity, and peak cooling load. This result is particularly significant because it demonstrates that performance gains arise from interaction effects intrinsic to the block configuration in Nara, rather than from the optimization of individual buildings in isolation.

Beyond hypothesis testing, several higher-order findings emerge from the study. First, the results reveal that not all buildings contribute equally to block-level performance. Taller and more exposed buildings act as dominant drivers of both structural response and energy demand, suggesting that targeted adaptation in a subset of buildings can yield system-wide benefits. Second, the findings indicate that adaptive strategies are most effective when they are spatially selective and temporally coordinated, rather than uniformly applied. These challenges prevailing assumptions that adaptive systems must be deployed homogeneously to be effective.

Another key finding concerns the role of interaction effects. The study demonstrates that a non-negligible portion of performance improvement arises from indirect mechanisms—such as altered shading patterns and modified wind exposure—rather than from direct reductions in internal loads or structural response alone. These interaction-driven effects are inherently block-scale phenomena and cannot be captured through single-building models. This insight reinforces the methodological premise of the study and highlights the importance of intermediate urban scales in performance-driven research.

Finally, the findings establish that adaptive structural–energy co-optimization at the urban block scale constitutes a distinct analytical paradigm with practical implications for sustainable urban design. The evidence suggests that treating structural systems as active contributors to energy performance expands the solution space available to designers and policymakers. By demonstrating measurable, coordinated improvements rooted in realistic building configurations in Nara, the study provides a proof-of-concept that bridges structural engineering, building energy research, and urban-scale analysis.

Collectively, these findings confirm that the research objectives have been met and that the proposed methodological framework yields novel, transferable insights. The results form a coherent foundation for the subsequent Discussion section, where the implications of these findings will be interpreted in relation to existing theories, methodological choices, and broader sustainability discourse.

6. Discussion

The purpose of this Discussion section is to interpret and synthesize the findings of the study in direct relation to the research questions, hypotheses, and methodological choices, while situating the results within the conceptual framework established earlier. In accordance with the study design, this section does not

repeat numerical results or introduce new data; instead, it explains why the observed outcomes emerged, how they relate to the adopted methodological structure, and what they reveal about structural–energy interactions at the urban block scale.

A central outcome of this research is the confirmation that structural behavior, when treated as an adaptive and coordinated system at the block scale, functions as an active mediator of energy performance rather than a neutral background condition. The findings demonstrate that adaptive stiffness modulation in selected buildings—particularly taller and more exposed ones—produces measurable reductions in block-level cooling demand. This outcome can be directly traced to the methodological coupling of structural response and energy modeling, where changes in stiffness altered deformation patterns, façade exposure, and shading hierarchies within the block. The Discussion therefore reinforces the study’s core conceptual premise: structural systems influence energy performance indirectly through spatial and environmental interaction mechanisms that are only observable at intermediate urban scales.

The block-scale focus of the methodology proves to be a decisive factor in explaining the study’s findings. Unlike single-building analyses, the urban block framework captures mutual shading, wind channeling, and exposure redistribution effects that emerge from building proximity and height variation. The results show that energy demand reductions achieved in one building can propagate to neighboring structures through modified solar and airflow conditions. This explains why coordinated adaptive strategies outperform isolated building-level interventions. The Discussion highlights that these interaction-driven effects are not secondary artifacts but primary drivers of system-level performance, validating the decision to frame the research at the block scale rather than at the scale of individual buildings or entire districts.

The findings related to trade-offs between energy efficiency and structural performance further underscore the necessity of a co-optimization approach. The non-linear Pareto relationships observed between energy use intensity and inter-story drift reflect an inherent coupling between environmental and mechanical objectives. From a theoretical standpoint, this non-linearity arises because both objectives are influenced by shared parameters—such as stiffness distribution, building height, and exposure—yet respond differently to parameter variation. The Discussion clarifies that improvements in one domain do not automatically translate into proportional gains in the other, and that beyond certain thresholds, aggressive adaptation strategies yield diminishing or destabilizing returns. This insight directly supports the study’s rejection of sequential optimization paradigms in favor of simultaneous, multi-objective evaluation.

Evaluation of the hypotheses within the Discussion reveals that all three hypotheses are not only supported but also refined by the findings. While the first hypothesis anticipated reductions in cooling demand through adaptive structural mechanisms, the results show that such reductions are contingent on spatial targeting and coordination. This nuance suggests that adaptivity is most effective when applied selectively rather than uniformly, an insight that would not emerge without the block-level methodological structure. The Discussion, therefore, refines the original hypothesis

by emphasizing the conditional nature of performance gains and the importance of strategic placement of adaptive interventions.

Similarly, the confirmation of a non-linear Pareto relationship between structural stiffness and energy demand extends the second hypothesis beyond a simple acknowledgment of trade-offs. The Discussion interprets the clustering of Pareto-optimal solutions as evidence that adaptive systems gravitate toward stable performance regimes rather than isolated optima. This behavior suggests an underlying structure in the solution space shaped by the physical constraints of the block and the adaptive decision bounds imposed in the methodology. From a methodological perspective, this reinforces the value of scenario-based adaptive control and bounded decision vectors, as they prevent the optimization process from converging toward unrealistic or non-constructible solutions.

The third hypothesis, concerning the superiority of block-scale coordination over isolated building-level adaptation, is particularly significant in the context of urban sustainability. The Discussion interprets this finding as evidence that energy and structural performance are collective properties at the block scale. Independent optimization of individual buildings fails to account for externalities such as shading conflicts and drift redistribution, leading to suboptimal or even counterproductive outcomes. In contrast, coordinated strategies internalize these externalities, producing balanced improvements across the system. This interpretation aligns directly with the methodological choice to aggregate objectives at the block level and to include worst-case structural metrics alongside average performance indicators.

An important methodological insight emerging from the Discussion concerns the role of building heterogeneity. The findings show that taller buildings exert a disproportionate influence on both structural response and energy demand within the block. The Discussion interprets this dominance as a function of exposure, mass, and stiffness scaling, which amplifies the environmental and mechanical impact of taller structures. This suggests that future adaptive strategies could prioritize a subset of influential buildings to achieve system-wide benefits, reducing the need for widespread intervention. Such targeted adaptation represents a shift from uniform design strategies toward performance-driven prioritization, a concept enabled by the study’s integrated methodological framework.

The Discussion also highlights the significance of interaction effects revealed by the sensitivity and attribution analyses. A notable portion of performance improvement arises from indirect mechanisms—such as altered shading patterns and wind exposure—rather than from direct reductions in internal loads or structural response alone. These indirect effects validate the study’s emphasis on coupling and coordination, as they cannot be captured through decoupled or building-centric models. From a conceptual standpoint, this finding reinforces the view of urban blocks as dynamic systems in which local interventions produce distributed effects, challenging reductionist approaches to urban performance analysis.

Another key interpretive outcome concerns the operational meaning of adaptivity in the context of urban blocks. The Discussion clarifies that adaptivity should not be understood as

continuous, high-frequency actuation, but rather as bounded, rule-based modulation aligned with environmental thresholds and performance objectives. The success of moderate, coordinated adaptive strategies observed in the findings supports this interpretation. It also demonstrates the methodological advantage of using explicit control rules instead of opaque optimization controllers, as the former allow direct attribution of performance changes to specific adaptive actions.

In preparing the ground for the Conclusion, the Discussion emphasizes the broader implications of the study's findings. By demonstrating that structural systems can actively contribute to energy performance at the block scale, the research expands the conceptual role of structural engineering within sustainable urban design. The methodological framework and findings together suggest that future urban energy strategies should incorporate structural adaptivity as a core design dimension rather than as a secondary consideration. This reconceptualization has implications not only for design practice but also for policy development, particularly in dense urban contexts where block-level coordination is feasible.

Finally, the Discussion reflects on the internal coherence of the study. The alignment between research questions, hypotheses, methodology, results, and findings confirms that the analytical framework operates as an integrated whole. The observed outcomes are not incidental but are the direct consequence of deliberate methodological choices, including block-scale modeling, coupled simulation, and multi-objective optimization. This coherence strengthens the credibility of the study and provides a solid foundation for the concluding section, where the derived insights and future research directions will be articulated explicitly.

7. Conclusion

This study set out to investigate whether adaptive structural systems, when coordinated at the urban block scale, can function as active contributors to energy performance in humid subtropical contexts, using a representative urban block in Nara as the case study. By developing and applying an integrated structural–energy co-optimization framework, the research addressed a clear gap in existing literature where structural behavior and energy performance are commonly examined in isolation and predominantly at the single-building scale.

The conclusions drawn from this research are derived directly from the methodological framework, quantitative results, and evidence-based findings presented in the preceding sections. First, the study conclusively demonstrates that structural systems are not energetically neutral at the urban block scale. Adaptive modulation of structural properties—particularly stiffness adjustments in taller and more exposed buildings—alters environmental interaction patterns such as mutual shading, wind exposure, and spatial energy redistribution. As a result, block-level cooling demand can be reduced without compromising structural performance. This finding establishes structural adaptivity as a legitimate energy-modulating mechanism rather than a purely mechanical design consideration.

Second, the research confirms that energy efficiency and structural performance are intrinsically coupled objectives at the block scale. The observed non-linear Pareto relationships between block-level energy use intensity and inter-story drift indicate that improvements in one domain are conditioned by constraints in the other. Importantly, the results show that simultaneous improvement is achievable, but only within specific regions of the solution space. This leads to the conclusion that sequential or single-objective optimization approaches are insufficient for complex urban systems, and that multi-objective co-optimization is necessary to reveal viable and balanced performance regimes.

Third, the study provides strong evidence that coordinated block-level adaptive strategies outperform isolated building-level adaptations. When adaptive decisions are optimized independently for individual buildings, local performance gains often generate adverse externalities elsewhere in the block, such as drift concentration or shading conflicts. In contrast, coordinated adaptive control internalizes these interactions, resulting in more uniform structural response and more balanced energy distribution across the block. This confirms that urban block performance is an emergent system property rather than the sum of individual building performances.

A further conclusion concerns the unequal contribution of buildings within the block to overall performance. The research shows that taller buildings act as dominant drivers of both structural demand and energy behavior, while lower-rise buildings play a secondary but responsive role. This insight suggests that effective block-scale adaptation does not require uniform intervention across all buildings. Instead, targeted adaptation of strategically influential buildings can yield system-wide benefits, improve efficiency and resilience while reduce implementation complexity.

The study also concludes that the effectiveness of adaptivity depends on bounded, rule-based control rather than extreme or continuous actuation. Moderate and strategically coordinated adaptive actions consistently outperform aggressive or unbounded strategies, which tend to produce diminishing returns or destabilizing effects. This reinforces the methodological importance of physically plausible constraints and interpretable control logic, ensuring that performance gains remain constructible and operationally realistic.

From a methodological standpoint, the research confirms the validity and robustness of the proposed block-scale structural–energy framework. The tight alignment between research questions, hypotheses, modeling assumptions, results, and findings demonstrates that the framework provides a coherent and transferable basis for analyzing coupled performance problems. The case study of Nara serves not merely as a contextual example, but as empirical evidence that the framework can capture real-world urban complexity while producing actionable insights.

In terms of practical implications, the conclusions of this study suggest a shift in how sustainable urban design and engineering should be approached. Structural engineering can no longer be treated solely as a discipline concerned with safety and serviceability; it must also be recognized as a contributor to energy

efficiency and environmental performance at collective urban scales. For planners and policymakers, the findings highlight the value of block-level coordination and targeted adaptation strategies as alternatives to building-by-building energy retrofits.

Finally, this research opens several clear directions for future work. Subsequent studies could extend the framework to other climatic contexts to test its generalizability, incorporate additional adaptive mechanisms such as ventilation control or material phase-change behavior, or explore real-time control strategies informed by sensor data. Long-term lifecycle and economic analyses could further evaluate the feasibility of adaptive block-scale interventions. These directions build directly on the conclusions of the present study and represent logical extensions rather than departures from its core contributions.

In conclusion, this study delivers clear, evidence-based conclusions demonstrating that adaptive structural–energy co-optimization at the urban block scale is both feasible and advantageous. By integrating structural behavior, energy performance, and urban interaction effects within a unified analytical framework, the research advances current knowledge and provides a solid foundation for future interdisciplinary work in sustainable urban systems.

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